Aquat. Living Resour. 20, 117–121 (2007)

DOI: 10.1051/alr:2007022
www.alr-journal.org

Aquatic Living Resources

Evaluating uncertainty in measurements of fish shoal aggregate backscattering cross-section caused by small shoal size relative to beam width

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Received 16 April 2007; Accepted 21 May 2007

Abstract – The aggregate backscattering cross-section, σ_{ag}, is the sum of backscattering cross-sections of all fish in a shoal. It is a basic acoustical parameter used for shoal description and biomass estimation. Simulations were undertaken for evaluating the impact of horizontal dimension, density, depth and beam width on measurements of σ_{ag} for shoals with constant abundance. The important factor determining measurement bias is the ratio of shoal size expressed as along cross-section length relative to along ship beam width at mean shoal depth. The results show that $10\log_{10}(\sigma_{ag})$ is underestimated by about 8 dB for a 5 m long shoal located at 200 m depth if detected by a 7° beam. A formula for correcting σ_{ag} estimates for shoal sizes bigger than 1.3 times the beam width is proposed. The negative measurement bias can also be reduced by using transducers with narrower beam widths.

Key words: Bias / Accuracy / Acoustic measurements / Single beam echosounder / Shoal energy / Shoal dimension

Résumé – Evaluation de l'incertitude des mesures de l'énergie agrégée des bancs de poissons occasionnée par la petite taille des bancs relative à la taille du faisceau acoustique. L'énergie agrégée d'un banc, σ_{ag}, est définie comme la somme des énergies réfléchies par tous les poissons du banc. C'est un paramètre fondamental de l'acoustique halieutique pour la description de la géométrie des bancs et pour l'estimation de la biomasse. Une étude de simulation a été menée pour évaluer l'impact de la taille horizontale d'un banc, sa densité et profondeur et l'ouverture du faisceau sur les mesures de σ_{ag} pour des bancs d'abondance constante. Le facteur déterminant du biais de mesure est le rapport entre la longueur du banc et la taille du faisceau à la profondeur moyenne du banc. Les résultats montrent que $10\log_{10}(\sigma_{ag})$ est sous-estimé de 8 dB pour un banc de longueur de 5 m à 200 m de profondeur si le banc est mesuré par un faisceau d'ouverture angulaire de 7°. Une formule est proposée pour corriger les estimations de σ_{ag} pour les bancs de longueur au moins 1,3 fois plus grande que la taille du faisceau. Le biais négatif de mesures peut aussi être diminué par l'utilisation de sondeurs de meilleure résolution angulaire.

1 Introduction

Echo-integration is the common method for abundance and biomass estimation based on acoustic measurements (Simmonds and MacLennan 2005). In the case of fish occurring in shoals, the integration amounts to summing the backscattering strength of all shoals detected within a given survey transect, e.g. a nautical mile. The aggregate backscattering cross-section of a single shoal, denoted σ_{ag}, is therefore an important parameter and any bias in its measurement will lead to biased density and abundance estimates. As demonstrated by Diner (2001), shoal length is overestimated due to border effects created by the finite beam width, hence it can be expected that measurements of σ_{ag} are also biased, but this time underestimated. Muiño et al. (2003) observed an unexplained negative relationship between shoal energy and shoal depth across several species and study areas. This pattern might be, at least partially, explained by an underestimation of shoal density as a function of shoal depth. The physical reasons for the expected biased measurements of σ_{ag} are explained below and the order of magnitude of measurement bias is explored using simulations.

Using standard notation proposed by MacLennan et al. (2002) the aggregate backscattering cross-section of a shoal is defined as:

$$\sigma_{ag} = \sum^{\sigma_{bs}} \quad (1)$$

where σ_{bs} is the backscattering cross-section of an individual target (fish) and the sum is over all targets in the entire volume of the shoal intercepted by the sound beam, that is, it includes all echoes received from the shoal. Based on fish density ρ inside the shoal, σ_{ag} can be expressed as

$$\sigma_{ag} = \sigma_{bs}\rho V \quad (2)$$

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Article published by EDP Sciences and available at http://www.alr-journal.org or http://dx.doi.org/10.1051/alr:2007022

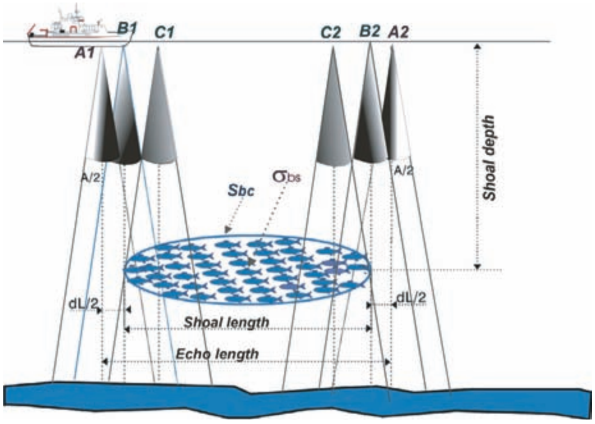

Fig. 1. Diagram in vertical plane of the process of shoal detection by a vertical echosounder.

where V is the total sampled volume of the shoal. However, this equation does not account for the border effect occurring at the beginning and at the end of shoal detection. That is, when the sound beam is not completely occupied by targets, the calculated (sampling) volume V is bigger than the actual shoal volume. The border effect can be seen clearly when decomposing the shoal detection by a vessel-mounted vertical echo sounder into three phases (Figs. 1 and 2):

- C1C2: the beam is fully occupied by the targets; the shoal cross-section surface S_{bc} and σ_{bs} are measured without bias;
- B1C1 (and C2B2): the beam axis is inside the shoal and the targets partially occupy the beam; S_{bc} is unbiased, but σ_{bs} is underestimated; and
- A1B1 (and B2A2): the beam axis is outside the shoal and the targets partially occupy the beam; S_{bc} and σ_{bs} are overestimated due to extrapolation of shoal biomass outside the actual shoal limits.

The data gathered during A1B1 (and B2A2) generally do not compensate perfectly for the underestimation of phase B1C1 (and C2B2). Near perfect compensation occurs when the shoal has very large horizontal shoal dimensions compared to the beam, i.e. when the circle arc FB1F' (Fig. 2b) is close to a straight line.

Thus, underestimation of σ_{ag} by a vertical echo sounder can have two origins: i) shoals with small horizontal dimensions only partially occupy the beam; ii) shoals fully occupy the beam, but have curved edges, not allowing a perfect compensation of underestimation "B1C1" by the complementary data gathered during phase "A1B1".

Given the expected underestimation of σ_{ag} for small shoals, it seems important to first determine the magnitude of the problem and then explore the possibility of deriving an empirical correction formula. When designing an algorithm for the correction of echo trace descriptors (Diner 2001), the relative length of the shoal compared to the beamwidth at the mean depth of the shoal, called Nb_i, was identified as the key parameter. It is calculated using the real detection angle, and allows correction of the measured shoal length though only if $Nb_i > 1.5$; for smaller ratios no correction can be carried out.

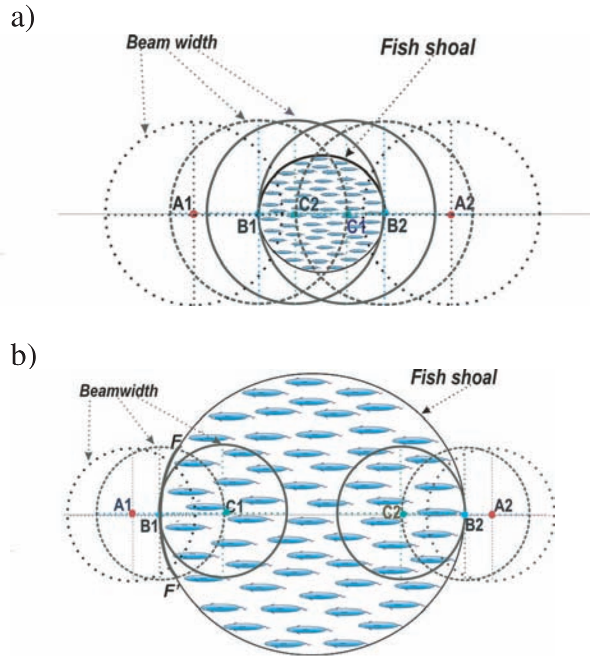

Fig. 2. Diagram in horizontal plane of the process of a shoal detection by a vertical echosounder. a) shoal size is smaller than the beam; b) shoal size is larger than the beam.

As for correcting shoal length, Nb_i is expected to be the key parameter for correcting σ_{ag} measurements.

The detection of a fish shoal by a vertical sounder is a complex process. Simulations allow the process to be analysed in detail, thereby highlighting sensitivities and quantifying likely problems. In addition, true values are known allowing quantification of measurement bias. In this paper, the magnitude of measurement bias of σ_{ag} is estimated based on several simulation scenarios. Finally, an empirical correction formula is derived.

2 Methods

Four simulation scenarios of fish shoals and acoustic measurements were carried out using the acoustic data simulator OASIS (V. Mazauric, pers. comm. for an updated version of the simulator used by Diner 2003). The scenarios are summarised in Table 1. For all scenarios, shoals of various dimensions were placed at different depths between 50 and 200 m. Shoal widths and length were equal in all cases and shoal volume is calculated for an elliptical body.

For scenario 1, single shoals of variable horizontal shoal dimensions and density but approximately the same number of targets per shoal were simulated (Table 2, Fig. 3). For scenario 2, shoal density was kept constant and only horizontal shoal dimensions varied (Table 3, Fig. 4). The number of shoals was set as to fix the total number of fish. Scenario 3 was identical to scenario 2, the only difference being the smaller beam width used, 2° and 3° instead of 7°. Figure 5 shows the simulated shoals. For the final scenario 4, a new range of shoals were simulated to study the relationship between

Table 1. Characteristics of simulation scenarios.

Scenario	1	2	3	4
Number of targets	constant	variable	variable	variable
Number of shoals	1	>1	>1	>1
Shoal density	variable	constant	constant	constant
Horizontal shoal dimension (m)	5–200	4–75	4–75	4–30
Vertical shoal dimension (m)	5	5	5	5
Shoal depth (m)	50, 100, 200	50, 100, 200	50, 100, 150, 200	50, 100, 150, 200
Beam width (°)	7	7	2, 3	2, 3, 4, 7
Target strength (dB)	−40	−40	−40	−40
Signal threshold (dB)	−70	−60	−50	−60

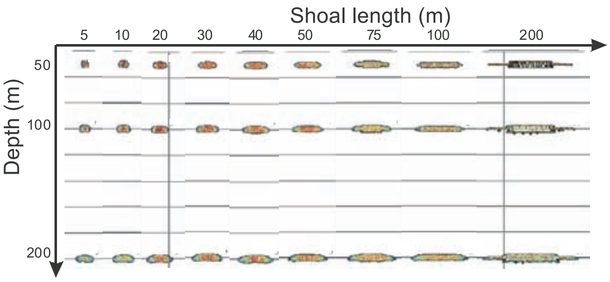

Fig. 3. Echograms of simulated shoals for scenario 1.

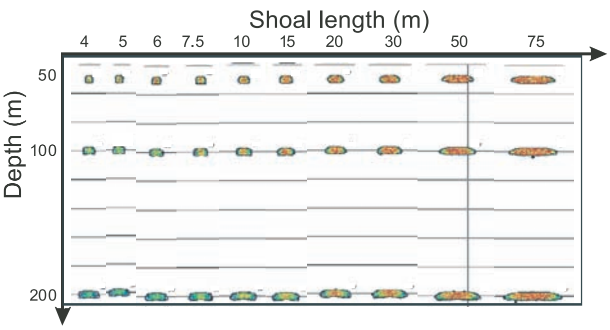

Fig. 4. Echograms of simulated shoals for scenario 2.

relative shoal length with respect to beam width for four different beam widths. To get more precise measurements of shoal echo length, and thus the Nb_i factor, vessel speed and ping rate were adjusted so as to oversample longitudinally (at least 20 pings per shoal for the smallest shoals).

For all simulated acoustic shoals, σ_{ag} was estimated using the shoal echo-integration option of the MOVIES+ software (Diner et al. 2003; Weill et al. 1993). For comparing simulated measures to true values, the estimation bias of the logarithmic measure of σ_{ag} was chosen, which could be called shoal back-scattering strength, as it has the interpretable units dB,

$$\varepsilon = \log_{10}(\hat{\sigma}_{ag}) - 10\log_{10}(\sigma_{ag}) \quad (3)$$

where $\hat{\sigma}_{ag}$ is the estimate from the simulated shoal image, and σ_{ag} is the true value.

3 Results

For scenario 1, with single shoals of different sizes and densities but the same number of targets placed at different

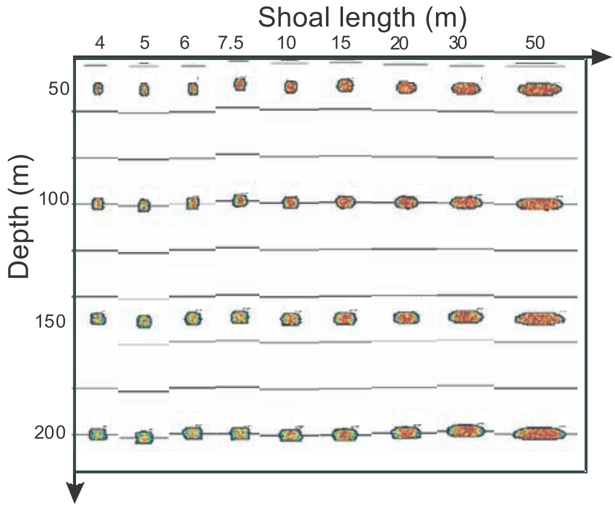

Fig. 5. Echograms of simulated shoals for scenario 3 for 3° beam width.

depths, it appears that at 50 m depth and using a 7° beam, there is no significant bias in measured shoal back-scattering strength ε for shoal lengths above 10 m (Table 2, Fig. 6a). In contrast at 200 m depth, the bias is significant for small shoals, reaching values of –7.5 dB for 5 m long shoals, and only starting to level off at zero for shoals longer than 50 m. The results of scenario 2 show similar bias levels at a given depth as a function of shoal length (Table 3, Fig. 6b). For this scenario several shoals of similar density were simulated. So varying shoal density does not change the relationship between shoal length and bias level which means that the determining parameter is the horizontal dimension compared to the beam width.

For scenario 3, the beam width was reduced from 7° to 2° and 3°. The reduction in bias of the shoal back-scattering strength is most striking at 200 m depth compared to 50 m (Fig. 7). At 50 m depth, underestimation is acceptable for shoal lengths down to 6–7 m for smaller beam widths. At 200 m, a beam width of 3° still leads to an attenuation of about 4 dB for a 6 m long shoal. However, the smaller beam widths leads to a clear improvement compared to 7° for small shoal sizes.

The purpose of scenario 4 was to establish a unique relationship between relative shoal size Nb_i and bias in shoal back-scattering strength independent of beam width. The empirical function fitted to the simulated measurements in Figure 8 is:

$$\hat{\varepsilon} = \frac{-0.6}{Nbi - 1.1} - 0.1.$$

Table 2. Shoal parameter values for simulation scenario 1 with variable dimensions and densities (length, volume, target distance, ρ density, σ_{ag} aggregated back-scattering cross section), but approximately fixed total number of targets N and derived measurements at different depths.

N	Length (m)	Volume (m^3)	Target distance (m)	ρ (m^{-1})	σ_{ag} (m^2)	"measured" σ_{ag}		
						50 m	100 m	200 m
9 771	5	65.4	0.19	148	0.291	0.166	0.110	0.053
9 709	10	261.8	0.30	37	0.145	0.136	0.087	0.042
9 691	20	1 047	0.48	9.2	0.072	0.069	0.075	0.041
9 733	30	2 356	0.63	4.1	0.048	0.041	0.047	0.038
9 757	40	4 188	0.76	2.3	0.036	0.035	0.035	0.031
9 709	50	6 544	0.88	1.5	0.029	0.028	0.033	0.030
9 777	75	14 724	1.15	0.67	0.020	0.020	0.017	0.021
9 727	100	26 176	1.39	0.38	0.015	0.014	0.015	0.014
9 751	200	104 705	2.21	0.09	0.007	0.008	0.008	0.009

Table 3. Shoal parameter values for simulation scenario 2 and 3 with fixed density ($\rho = 8$ m^1), and variable horizontal dimensions L_g and total number of targets N and derived measurements at different depths for scenario 2 (n_{sh} number of shoals, S_{hor} shoal surface in horizontal plane, σ_{ag} aggregated back-scattering cross section).

N	Number of shoals	Length (m)	Shoal surface (m^2)	Volume (m^3)	σ_{ag} (m^2)	Scenario 2 "measured" σ_{ag}		
						50 m	100 m	200 m
1 932 000	5 600	4	13	42	0.013	0.007	0.004	0.002
1 746 000	3 600	5	20	65	0.016	0.010	0.004	0.003
1 832 500	2 500	6	28	94	0.019	0.018	0.007	0.003
1 883 200	1 600	8	44	147	0.024	0.016	0.014	0.006
1 815 300	900	10	79	262	0.031	0.025	0.018	0.011
1 840 400	400	15	177	589	0.047	0.037	0.040	0.020
1 846 125	225	20	314	1 047	0.063	0.058	0.059	0.046
1 856 900	100	30	707	2 356	0.094	0.087	0.089	0.072
1 860 804	36	50	1 963	6 844	0.157	0.157	0.162	0.137
1 864 272	16	75	4 417	14 724	0.236	0.209	0.210	0.231

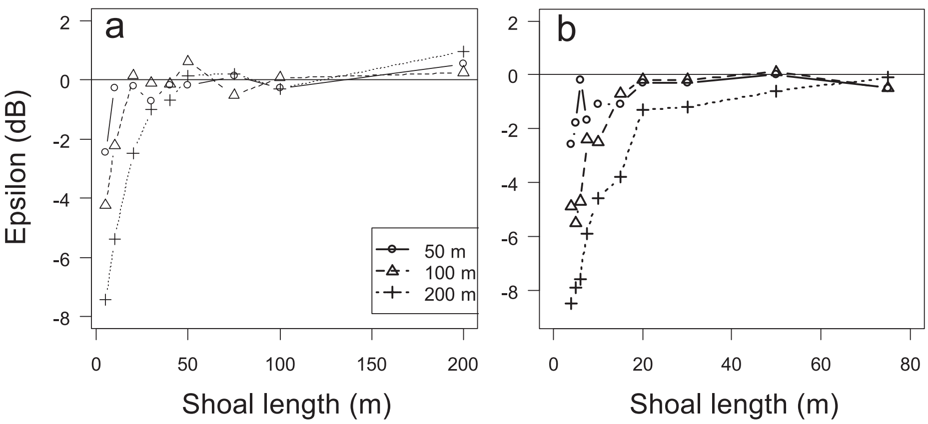

Fig. 6. Impact of horizontal dimension and density on measurement bias $\varepsilon = 10\log_{10}(\hat{\sigma}_{ag}) - 10\log_{10}(\sigma_{ag})$ as a function of shoal length at different depths (50, 100 and 200 m); a) scenario 1 for a single shoal with variable horizontal dimensions; b) scenario 2 for groups of shoals with different horizontal dimensions but same density and overall same total number of individuals.

This function could be applied to correct measurements for shoals with Nb_i values above 1.3. The maximum correction will be 3 dB, which represents a significant bias reduction.

4 Discussion

Using simulations, the bias in measurements of shoal back-scattering strength and thus in the aggregated back-scattering cross-section σ_{ag} of a shoal was found to be substantial for small shoals. The bias was strongly depth dependent. By expressing shoal length relative to beam width, it was possible to obtain a correction function which could be applied for all depths and beam widths, conditional on $Nb_i > 1.3$. A relative shoal size of 1.3 for a beam width of 2–3° corresponds to the category of smaller shoals encountered in the Bay of Biscay which have shoal lengths of about 10 m (N. Diner unpublished

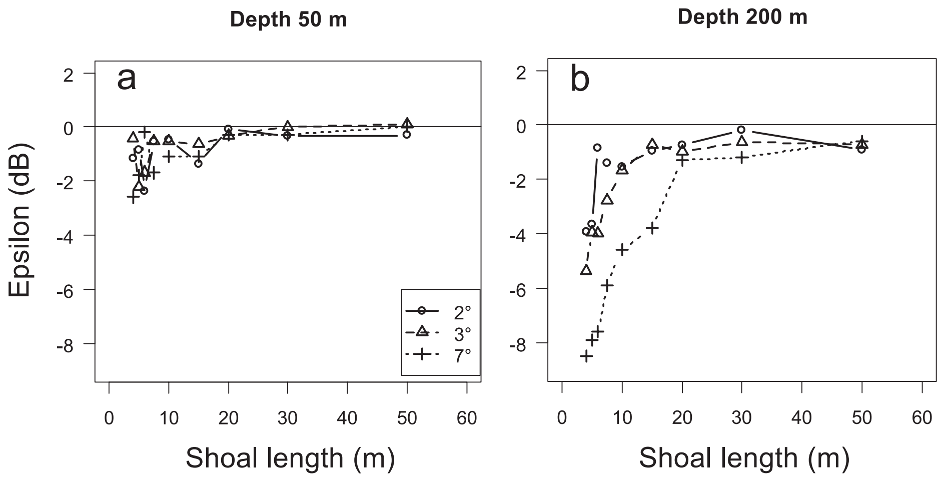

Fig. 7. Impact of beam width on measurement bias $\varepsilon = 10 \log \hat{\sigma}_{ag} - 10 \log \sigma_{ag}$ as a function of shoal length. Results from scenarios 2 and 3 at a) 50 m, b) 200 m.

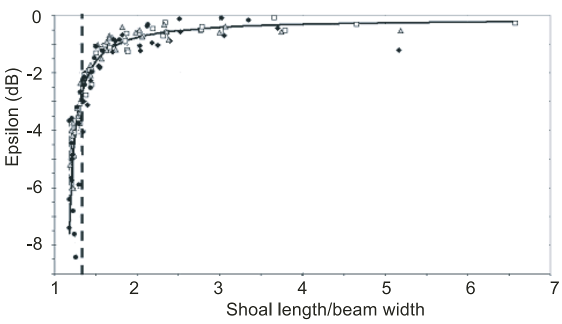

Fig. 8. Measurement bias $\varepsilon = 10 \log_{10}(\hat{\sigma}_{ag}) - 10 \log_{10}(\sigma_{ag})$ as a function of shoal size relative to beam width based on simulations for scenario 4. The vertical line indicates the limit value of 1.3 below which no bias correction is possible.

data). This means shoal back-scattering cross section measurements cannot be corrected if a beamwidth of 7° or more is used. In this context, it is important to note that when using small beam widths for detecting small shoals, the inter ping distance must be also small so as to reduce variability in the estimates of Nb_i and σ_{ag}. Practically, in case of high vessel speed, high ping rates must be used. Correcting measurements of aggregated back-scattering cross-section can also be relevant for species identification based on morphological and energetic shoal parameters (Scalabrin et al. 1996). For example, the corrections could improve the analysis of different species independently changing depth on a diel or seasonal basis as observed in the Bay of Biscay (Scalabrin and Massé 1993).

Acknowledgements. Much appreciation is due to V. Trenkel (Ifremer), for her significant efforts to refine this paper following the author's retirement. D.A. Demer (NOAA/SWFSC) and two anonymous referees are also gratefully acknowledged for their extensive comments on an earlier version.

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