Correction for an unknown extinction cross section in acoustic fish abundance estimation

Tor Arne Reinen (1), and John Dalen (2)

(1) SINTEF DELAB, N-7034 Trondheim, Norway
(2) Institute of Marine Research, P.O.Box 1870 Nordnes, N-5024 Bergen, Norway

Abstract

A method is suggested for correcting acoustic fish abundance estimates in large and dense fish aggregations for extinction even if the necessary extinction parameter, the ratio between fish extinction cross section and backscattering cross section, is unknown. This is done by estimating the parameter directly from the data. The estimate is obtained by making prior assumptions about the distribution of fish within an aggregation. The method is tested on echo sounder recordings of a large herring layer in a Norwegian fjord. For this data set reliable measurements of the extinction parameter exist. In comparison with the latter one, the estimates for single echoes show an expected large variance, whereas the averaged estimate shows a very small deviation from the reference.

1 Introduction

When fish are schooling they often form very dense aggregations where the linearity between backscattered echo energy and fish biomass breaks down. This is commonly explained by the attenuation or *extinction* of sound energy within the school, as expressed quantitatively by the mean extinction cross section, σ_e, of the fish, and the volume density distribution of the aggregation [1]. It is common practice in acoustic fish abundance estimation by echo integration methods to neglect extinction [2] [3]. This practice is based on the expectance of a low or moderate number of scatterers, as seen by individual pings. In such cases extinction is negligible. In other cases, however, the neglect of extinction is undesired but necessary due to lack of measured σ_e-values. Thus the biomass is consistently underestimated, and the quality of acoustic abundance estimation is limited for fish schools and generally for dense fish aggregations as emphasized in [4].

If the extinction cross section, σ_e, is known, it is known how to compensate for attenuation [5], though such corrections are not yet generally implemented in echo integration algorithms. The present paper investigates the possibilities of compensating for extinction even if σ_e is unknown. This is achieved by making a simple assumption regarding the distribution of fish within an aggregation. Precisely stated an estimate is found of the ratio between σ_e and the corresponding backscattering measure: the backscattering cross section σ_b.

This work is part of a research project that has been initiated at the Institute of Marine Research, Norway, to possibly develop a sonar based system for estimating absolute fish abundance of near surface schooling fish.

2 Estimation of extinction

In the following it is assumed that the fish aggregation of interest extends wide enough transversally to cover the full acoustic beam width. This makes it straightforward to correct the received signal for spherical spreading. After having performed such geometric corrections ("20 log r corrections"), and corrections for sound absorption in water, the backscattered power per volume unit (i.e. the volume backscattering coefficient) can be expressed, as in [6]:

$$s(r) = \sigma_b \rho(r) e^{-2\sigma_e \int_0^r \rho(u) du} \tag{1}$$

where r is the position of the volume element, measured as its distance from the transducer, and $\rho(r)$ is the volume density of scatterers at position r. Output power and directivities are suppressed from the notation in (1). Strictly speaking, (1) expresses the *expected* backscattered power from the given volume element, and actual measurements would show statistical variations around the given mean. This fact is neglected below. However one should bear in mind that deviations from ideal signal levels will occur and will contribute to the overall variance of the estimates of interest.

Assuming that σ_e is unknown, it can be estimated from the received signal $s(r)$ if some apriori knowledge exists about $\rho(r)$. Or, more precisely, the ratio σ_e/σ_b can be estimated from $s(r)$. Such knowledge is conveniently expressed through the relative number of scatterers within different distance intervals, as specified by one or more equations of the form

$$\int_{r_m}^{r_n} \rho(r) dr = \beta \int_{r_o}^{r_p} \rho(r) dr \tag{2}$$

where β is a known constant, and the intervals r_m - r_n and r_o - r_p should be nonoverlapping and large enough to average out details in $\rho(r)$. Suppose that the prior knowledge is such that criteria can be specified for detecting r_m, r_n, r_o, r_p, and β from the form of $s(r)$. Then σ_e/σ_b can be estimated by searching for a value that, when used to correct for extinction, gives partial echo integrals that satisfy the specified equation or equations of the form (2). Of course equations like (2) should only be expected to be correct *on the average* , and averaging of the resulting estimates may be necessary.

In the present paper the following form of (2) is investigated:

$$\int_{r_1}^{r_2} \rho(r) dr = \int_{r_2}^{r_3} \rho(r) dr \tag{3}$$

where r_1 and r_3 are outer limits of the fish aggregation, and r_2 is a point within the aggregation, given by some prior knowledge about what fish distributions to expect. If no detailed knowledge is at hand, a natural choice is $r_2 = (r_1 + r_3)/2$, i.e. r_2 is the midpoint of the aggregation as seen by the acoustic beam. This is equivalent to assuming equal amounts of fish in front of and beyond the midpoint of the school.

To obtain correspondence with computer algorithms, discrete position (time sampled) versions of (1) and (3) are used hereafter. Furthermore the notation is simplified by the variable substitution

$$x(r) = \sigma_b \rho(r) \tag{4}$$

The following discrete versions of (1) and (3) result:

$$s(i) = x(i) e^{-\alpha \sum_{j=0}^{i-1} s(j)} \tag{5}$$

$$\sum_{i=i_1}^{i_2} x(i) = \sum_{i=i_2+1}^{i_3} x(i) \tag{6}$$

where

$$\alpha = 2\frac{\sigma_e}{\sigma_b} \tag{7}$$

i is a discrete distance measure, and i_1, i_2, and i_3 replace r_1, r_2, and r_3 of (3). If α is known, compensation for attenuation is obtained by the simple recursion [5]:

$$\begin{array}{ll} x(0) = s(0) & z(0) = s(0) \\ x(i) = s(i)e^{\alpha z(i-1)} & z(i) = z(i-1) + x(i) \end{array} \tag{8}$$

which is a direct rewriting of (5), included here for convenience.

Using (8) to find x for any given α, (6) is exploited to estimate the true α. Specifically α is estimated as the one and only zero crossing of the function

$$f(\alpha) = \sum_{i=i_1}^{i_2} \hat{x}(i;\alpha) \; - \sum_{i=i_2+1}^{i_3} \hat{x}(i;\alpha) \tag{9}$$

where $\hat{x}(i;\alpha)$ is the signal that results after correction of $s(i)$ according to (8), using a given candidate α. The zero crossing of (9) can be found by any of a number of well known numerical solution methods see e.g. [7]. In the present paper the focus has been put on the basic assumption rather than on the choice of a solution procedure. Thus a simple interval bisection method is chosen for the experiments (see Section 3).

Corrections as described in (8) may be performed for each ping individually, using an individual solution of $f(\alpha) = 0$. On the other hand, if one has reason to believe that a group of echoes are reflected from targets of a common type, α-values may be averaged to reduce the estimation variance.

3 Experiments and discussion

The algorithm has been tested on echo sounder data collected in a Norwegian fjord in January 1990 [8]. A dense concentration of Norwegian Atlantic spring spawning herring was located in the depth interval 150 m to 250 m. 200 pings covering a surface distance of one nautical mile have been analyzed. The horizontal extent of the layer was well beyond this distance.

Echoes were recorded at 0.5 m depth resolution. A trawl catch showed the mean length of the herring to be 32.9 cm.

In [8] the distance integrated bottom areal backscattering coefficient in a large data set including the above aggregation was compared with the corresponding bottom recordings without the fish layer present. This comparison was used in a regression analysis to find an exponential attenuation coefficient corresponding to (7) [8]. An α-value corresponding to the above attenuation coefficient is used for comparison below. This value, 4.4 (i.e. $\sigma_e/\sigma_b = 2.2$), is taken from [9], where the transformation from the results of [8] to the standard σ_e/σ_b-value can be found. Since the results in [8] are found using a very large data set including the above layer, the resulting α-value can be used as a reference for the given data set.

A simple implementation of the algorithm in Section 2 was made as follows: Aggregation boundaries i_1 and i_3 of (6) were determined for each ping individually as limits of the interval containing all $s(i)$-values above 10 % of the maximum value. i_2 was set to $(i_1 + i_3)/2$. To solve for $f = 0$ in (9), the interval bisection method, as implemented in [7] was used. The necessary initial bracketing of the solution was also taken from [7], using the mean α-value calculated from previous echoes as an initial guess. The relative α tolerance used was 0.01.

Corrections as described in Section 2 were performed both using individually estimated α-values and using the 200 ping average α estimate. Corrections were performed in the i_1 - i_3 interval only, and echo integration was restricted to the same interval. Figure 1 shows a typical echo power profile before and after correction using the α-value estimated for the given single ping. The detected aggregation boundaries i_1 and i_3 are indicated as vertical lines, and partial integration is performed for clarity of illustration.

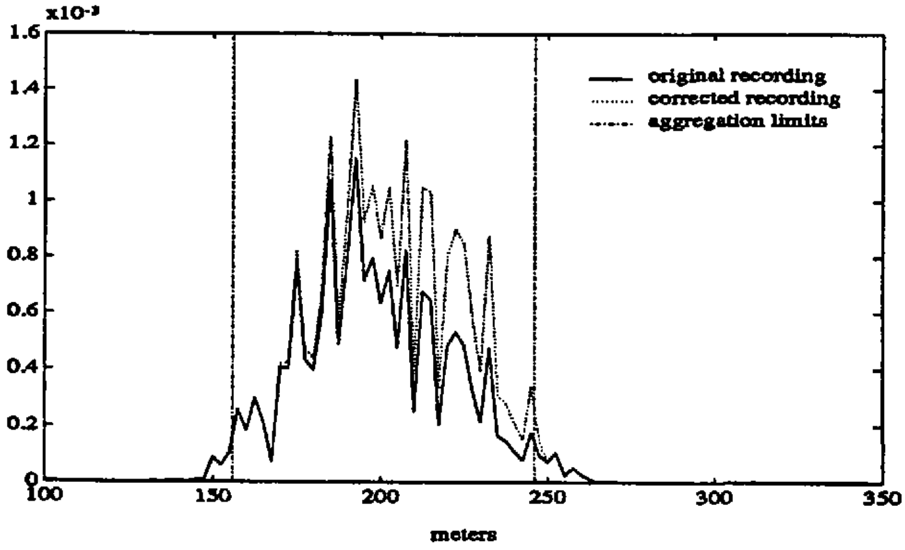

Figure 1: Typical single echo relative volume backscattering coefficient vs. depth, integrated within 2.5 m depth intervals

Figure 2 shows the resulting single ping integral correction factors, $\sum_{i=i_1}^{i_2} x(i)/\sum_{i=i_1}^{i_2} s(i)$, using nonaveraged α-estimates, using the 200 ping average estimate, and using an α-value according to [8].

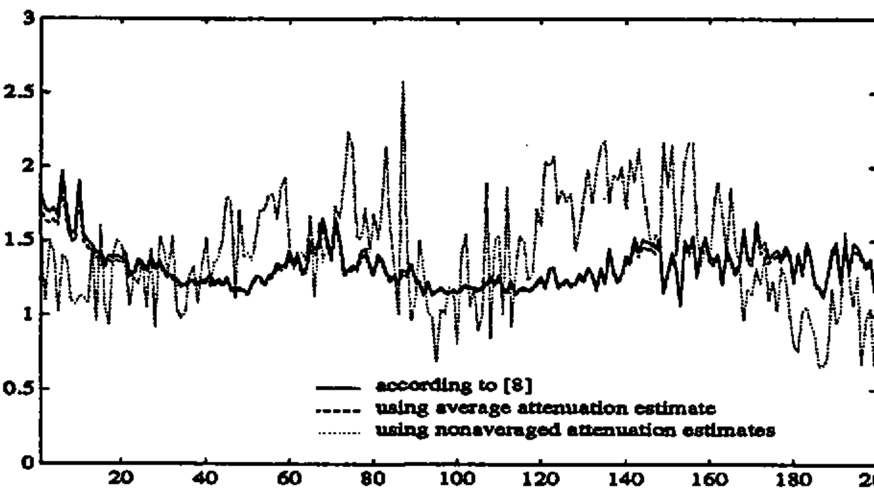

Figure 2: Echo integral correction factor vs ping number

The standard deviation, σ_v, of a variable of interest, v, was calculated with normalization by the desired value, μ:

$$\sigma_v = \sqrt{\frac{1}{200}\sum_{n=1}^{200}\left(\frac{(v(n)-\mu(n))}{\mu(n)}\right)^2} \qquad (10)$$

where n is ping number. $1/\mu$ may be put outside the square root if it does not depend on n. If both v and μ are independent of n, (10) reduces to the absolute value of $(v-\mu)/\mu$.

To identify the different α-values used, an index is useful: In the following the value according to [8] is denoted α_t, the 200 ping average estimate is denoted α_m, and single ping estimates are denoted $\alpha_i(n)$. The following figures, tabulated in Table 1, were calculated to evaluate the algorithm:

- σ_α: The relative deviation of α compared to α_t as defined in (10). For the 200 ping average, this reduces to the absolute value of $(\alpha_m - \alpha_t)/\alpha_t$.
- σ_c: The relative deviation, as defined in (10), of the echo integral correction factors compared to corrections using α_t .
- c_t: Total integral correction factors $\sum_{ping=1}^{200}\sum_{i=i_1}^{i_2} x(i)/\sum_{ping=1}^{200}\sum_{i=i_1}^{i_2} s(i)$ using the different α-values.
- σ_{c_t}: The relative deviations in c_t compared to the value c_{tt} that results from using α_t, i.e. the absolute value of $(c_t - c_{tt})/c_{tt}$

α	σ_α	σ_c	c_t	σ_{c_t}
α_i	1.18	0.31	1.43	0.04
α_m	0.05	0.02	1.35	0.02
α_t			1.38	

Table 1: Comparisons with results according to [8]

As shown in Table 1, σ_e/σ_b-estimates for individual echoes show an average deviation of 118% from the reference value. This large deviation is however reduced to 5% for the averaged estimate. Correspondingly, echo integral correction factors for individual echoes show an average deviation of 31% when individual estimates are used, and only 2% when the averaged estimate is used. In the correction factor for the total 200 echo integral, positive and negative errors tend to cancel, so that this factor deviates only 4% from the reference value even when individual estimates are used. Using the averaged estimate, a deviation of 2% results.

The above results for the total echo integral correction are rather satisfying, indicating that the basic assumptions underlying our estimates are correct *on the average* . However, though the aggregation analyzed was very large, it is still only one observation series, representing one species and one hour of the day. This means that some care should be taken in generalization of the model.

Generally it may be remarked that the basic assumptions are more likely to be correct in large aggregations, where boundary effects play no important role in the overall fish distribution. This is so at least when observing an aggregation directly from above, as is done in the usual echo sounder applications.

4 Conclusion

In traditional fish abundance estimation by echo integration, biomasses are underestimated in aggregations that are extensive and dense, as seen by individual pings. This is due to the sound attenuation or *extinction* within the aggregation, which is neglected in the estimates. Algorithms have recently been introduced to correct for this effect when σ_e/σ_b: the ratio between the extinction cross section and the backscattering cross section, is known [5]. But as often the opposite is the case - the value of σ_e/σ_b is unknown for the fish aggregation of interest.

In the present paper a method is suggested for estimating σ_e/σ_b directly from the echoes, and thus for correcting for extinction even when σ_e/σ_b is unknown. This is done by exploiting prior assumptions about the relative distribution of fish within the aggregation.

The suggested algorithm has been tested on echo sounder recordings of a large layer of herring in a Norwegian fjord. For these recordings reliable measurements of σ_e/σ_b exist [8] [9], so that we have been able to compare the algorithm with results using a known σ_e/σ_b. Though single echo estimates of σ_e/σ_b show a high variance, the overall echo integral correction factor, using an averaged estimate, deviates only 2% from what is obtained by using the above known σ_e/σ_b. This result is rather satisfying, indicating that the basic assumptions underlying our estimates are correct *on the average* .

It may be possible to achieve robustness against distributions that deviate considerably from the simple assumptions used in the present paper, e.g. by excluding extreme distributions, or by a more careful selection of the subintervals used for comparison of partial echo integrals.

References

[1] C. Clay and H. Medwin, *Acoustical Oceanography*. J. Wiley and sons, 1977.

[2] K. Johannesson and R. Mitson, *Fisheries acoustics. A practical manual for aquatic biomass estimation*. FAO.Fish.Tech.Pap. 240, Rome, 1983.

[3] J. Dalen and O. Nakken, "On the application of the echo integration method," *Counc.Meet.Int.Counc.Explor.Sea 1983/B:19*.

[4] T. Stanton, "Multiple scattering with applications to fish-echo processing," *J.Acoust.Soc.Am.*, vol. 73, pp. 1164–69, April 1983.

[5] K. Foote, "Correcting acoustic measurements of scatterer density for extinction," *J.Acoust.Soc.Am.*, vol. 88, pp. 1543–46, Sept 1990.

[6] D. Lytle and D. Maxwell, *Hydroacoustic estimation in high density fish schools*, pp. 157–71. In Symp.Fish.Acoust.,Bergen,Norway, 1982, FAO Report 300.

[7] W. Press, B. Flannery, S. Teukolsky, and W. Vetterling, *Numerical Recipes in C*. Cambridge University Press, 1988.

[8] R. Toresen, "Absorption of acoustic energy in dense herring schools studied by the attenuation in the bottom echo signal," *Fish.Res.*, vol. 10, pp. 317–27, 1991.

[9] K. Foote, E. Ona, and R. Toresen, "Determining the extinction cross section of aggregating fish," *Subm. to J.Acoust.Soc.Am.*, September 1991.