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EXTINCTION CROSS SECTION OF HERRING: NEW MEASUREMENTS AND SPECULATION

by

Kenneth G. Foote
Institute of Marine Research
5024 Bergen, Norway

ABSTRACT

Acoustic abundance estimation of dense, vertically extended aggregations of fish requires knowledge of the extinction cross section. An established method based on a comparison of the area backscattering coefficients of fish and underlying flat bottom is exercised for herring in Ofotfjorden, January 1994, as observed with the SIMRAD EK500/38 kHz scientific echo sounder and Bergen Echo Integrator. Variability in the measurement results both for the present period and with respect to earlier years is viewed in the light of the optical literature. This suggests that the extinction cross section of finite but complicated physical scatterers may be as sensitive to details of orientation as is the backscattering cross section. The possibility of exploiting this property is considered.

RESUME: SURFACE ACOUSTIQUE D'EXTINCTION DU HARENG: NOUVELLES MESURES ET ANALYSE

L'estimation acoustique d'abondance dans le cas de concentrations de poissons, denses et à extension verticale, exige des connaissances sur la surface d'extinction acoustique des cibles concernées. Une technique basée sur la comparaison des coefficients de réflexion du poisson se trouvant au-dessus d'un fond plat est expérimentée pour du hareng dans Ofotfjorden en décembre 1993 et janvier 1994, en utilisant le sondeur SIMRAD EK500/38 kHz et le "Bergen" écho-intégrateur. La variabilité dans les mesures entre la période concernée et les années précédentes est examinée à la lumière des techniques optiques. On en tire que la surface d'extinction d'un nombre fini mais physiquement complexe de diffuseurs peut être sensible à des légères variations de l'orientation comme l'est l'index de réflexion. La possibilité d'exploiter cette propriété est considérée.

INTRODUCTION

Wintering of Norwegian spring-spawning herring (Clupea harengus) in the Ofotfjorden-Tysfjorden system in northern Norway presents an exceptional opportunity for surveying much of the stock, especially the spawning component, in a confined and protected marine area. The state of fish concentration is consequently often very high, with number densities occasionally in the approximate range 1-10 fish/m^3. Given layer thicknesses of 100-200 m, the effect of such densities on extinction is substantial, and compensation for extinction becomes necessary. Knowledge of the extinction cross section is crucial to general compensation algorithms (Foote 1990).

Earlier measurements of the extinction cross section of wintering herring apply to the stock in a different stage of development, justifying new measurements. The very circumstances required to make the measurement, namely occurrence of a substantial layer over a flat bottom (Foote et al. 1992), are sufficiently rare to encourage their exploitation, the more so when they arise during the conduct of an acoustic survey to estimate stock abundance.

In fact, during research cruises in December of 1991, 1992, and 1993, conditions simply did not allow the measurement to be made. In January 1994, however, conditions were satisfactory. New measurements of the extinction cross section of herring are the subjects of this paper.

THEORY OF MEASUREMENT AND METHOD OF CALCULATION

Measurement of the extinction cross section is based on a comparison of echo energy due to a fish layer with that due to the underlying flat bottom. The echo energy is the time-integral of the received signal intensity after application of "20 log r + 2αr" time-varied gain in order to correct for ordinary propagation losses due to scattering by a layer or planar surface. The described echo energy is thus proportional to the area backscattering coefficient, the standard measure of acoustic area density used in modern echo integrators (Bodlholt et al. 1989, Knudsen 1990).

According to an earlier work (Foote et al. 1992), the respective area backscattering coefficients are linearly related to each other. Denoting the coefficient associated with the fish layer by $s_{A,F}$ and that associated with the bottom by $s_{A,B}$,

$$s_{A,B} = a\, s_{A,F} + b \quad . \tag{1}$$

In the absence of fish, $s_{A,B}$ assumes its maximal value. In the presence of fish, $s_{A,B}$ is generally diminished by extinction of sound energy passing through the fish layer both in transit to the bottom and in transit back to the transducer after reflection or scattering from the bottom.

Because the bottom is generally not a uniform target, either in flatness or in scattering properties, and because its echo is generally very substantial, especially compared to that from fish, it requires unusual conditions for the particular method to succeed. These occur at times, however, for the spawning stock of Norwegian spring-spawning herring when wintering in Ofotfjorden. The outer part of Ofotfjorden, at about $68^o24'$N and $16^o10'$-$16^o40'$E is exceptionally flat, and dense, extended concentrations of herring occasionally appear over this area in a distinct mid-water scattering layer.

Inhomogeneities both in the density of fish concentration and scattering properties of flat bottom require a number of simultaneous measurements of $s_{A,B}$ and $s_{A,F}$ and use of linear regression analysis to extract the significant dependences in equation (1). If this is treated as a regression equation, then the estimated regression coefficients $\hat{a}$ and $\hat{b}$ determine the extinction cross section σ_e, here expressed relative to the fish backscattering cross section σ_b:

$$\sigma_e/\sigma_b = -1852^2\hat{a}/(2\hat{b}) \quad . \tag{2}$$

To express the confidence limits, equation (1) is transformed by substituting y for $s_{A,B}$ and x for $s_{A,F}$. Thus, y=ax+b, or, with respect to the n individual paired measurements (x_i,y_i),

$$y_i = \hat{a}x_i + \hat{b} + \varepsilon_i \quad , \tag{3}$$

where ε_i is the error term, which is minimized in a least-squares sense by performance of the linear regression analysis. The confidence limits of σ_e/σ_b are

$$\frac{1852^2}{2} [(\bar{x}-d_1)^{-1}, (\bar{x}-d_2)^{-1}] \quad , \tag{4}$$

where $\bar{x}$ is the mean value of x, and d_1 and d_2 are the respective lesser and greater solutions of the quadratic equation (Seber 1977)

$$d^2[\hat{a}^2 - s_e^2 F^{\alpha}_{1,n-2}/\sum_i (x_i-\bar{x})^2] - 2d\bar{y}\hat{a} + (\bar{y}^2 - s_e^2 F^{\alpha}_{1,n-2}/n) = 0 \tag{5}$$

where s_e^2 is the squared standard error of regression, $\bar{y}$ is the mean value of y, and $F^{\alpha}_{1,n-2}$ is the F-statistic at significance level α with degrees of freedom 1 and n-2. The statistic is widely available in tabulated form, for example, in Hald (1952) and Zelen and Severo (1965), although not always identified by the same name.

The extinction cross section is expressed in relative terms in equation (2). Its absolute value is derived by substituting for the backscattering cross section σ_b. For Norwegian spring-spawning herring, this is given by the equation (Foote 1987):

$$TS = 10 \log \frac{\sigma_b}{4\pi r_o^2} = 20 \log \ell - 71.9 \quad , \tag{6}$$

where r_o is the reference distance of 1 m, and ℓ is the root-mean-square fish length in centimeters. Thus, in units of square centimeters, σ_e is derived by multiplying the ratio σ_e/σ_b in equation (2) by the constant factor $4\pi 10^{-3.19}\ell^2$.

EXPERIMENTAL METHODS

The measurements were made with the SIMRAD EK500 echo sounder (Bodholt et al. 1989) and Bergen Echo Integrator (Foote et al. 1991) during the cruise with R/V "JOHAN HJORT" 6-17 January 1994. The purpose of the cruise was abundance assessment of that part of the herring stock that winters in the Ofotfjorden-Tysfjorden system. At times, a dense, thick concentration of herring appeared in mid-water, in the depth range 200-400 m, in outer Ofotfjorden, over regions where the bottom is quite if not exceptionally flat. In addition to measurements made during ordinary conduct of the survey, special measurements were made to determine the extinction cross section. The periods of these are summarized in Table 1.

Table 1. Periods of data collection on the extinction cross section, including number N of 0.1-NM intervals over which the depth changes by no more than 1 m. The total depth range $[z_{min}, z_{max}]$, average depth z_{ave}, and standard deviation Δz are also given.

Series	Start		End		Ship's log		Depths (m)			
no.	Date	UTC	Date	UTC	interval (NM)	N	z_{min}	z_{max}	z_{ave}	Δz
1	0109	0748	0109	1740	0281.0-0337.5	295	517	540	530	5
2	0111	0852	0111	1023	0561.6-0575.7	70	524	545	536	7
3	0112	0823	0112	1536	0740.0-0785.0	293	530	545	540	3
4	0114	0017	0114	1403	0935.7-0998.3	300	529	546	541	3
5	0115	1600	0115	1733	1210.8-1223.3	42	530	544	538	5
6	0116	0428	0116	0717	1305.3-1324.0	75	520	545	533	7
7	0116	1220	0116	1448	1370.2-1385.1	8	539	570	556	10

During the described period of measurements, the amount of daylight increased steadily, although the sun does not rise for the first time of the year until 15 January. The total period of nautical twilight is very roughly 0900-1500.

Measurements were made simultaneously at each of four frequencies, 18, 38, 120, and 200 kHz. Only the measurements at 38 kHz are reported here. The SIMRAD ES38B split-beam transducer was used strictly as a single-beam device for purposes of echo integration. The pulse duration was 1 ms and receiver bandwidth, 3.8 kHz. The pulse repetition frequency was about 1/s. The vessel speed was about 7-8 knots, the same as during execution of the acoustic survey.

The echo sounder and echo integrator were calibrated by the standard-target method recommended by ICES (Foote et al. 1987). The target at 38 kHz was the 60-mm-diameter copper sphere.

Data were stored ping by ping. During postprocessing, results of integration of the fish-layer and bottom echoes were stored with the highest standard resolution, namely 0.1 nautical mile (NM). Data on the depth of detected bottom were also condensed. For each 0.1-NM integration interval, the average depth and extrema were stored, three values in all, allowing criteria on depth and depth stability to be imposed in selecting subsets of data for analysis. Some statistics of the bottom depth for the various measurement series are shown in Table 1.

Acoustic data were supplemented by biological data derived from catching operations. Data from a total of 12 fish capture stations in outer Ofotfjorden are available for the period 5-15 January 1994. Results from these stations are expressed in Table 2 in terms of the mean length $\bar{\ell}$ and standard deviation $\Delta\ell$ of sampled distributions of total fish length ℓ. The overall measures of total length are formed by weighting the station data equally: $\bar{\ell}$=33.9, $\overline{\ell^2}^{1/2}$=34.0, and $\Delta\ell$=3.2 cm.

Table 2. Fish capture stations performed in outer Ofotfjorden during the period 5-15 January 1994, with sample size n_s, mean $\bar{\ell}$, root-mean-square $\overline{\ell^2}^{1/2}$, and standard deviation $\Delta\ell$ of empirical distributions of total fish length.

Vessel	Date	n_s	$\bar{\ell}$(cm)	$\overline{\ell^2}$(cm)	$\Delta\ell$(cm)
"INGER HILDUR"	[0105]	100	33.7	33.8	2.8
"INGER HILDUR"	0105	100	33.9	34.0	2.5
"FRANTZEN JR"	0106	155	34.2	34.4	3.1
"INGER HILDUR"	0107	100	33.5	33.6	2.6
R/V "JOHAN HJORT"	0109	100	35.1	35.2	3.0
"FRANTZEN JR"	0111	100	34.1	34.2	2.6
"INGER HILDUR"	0112	100	33.7	33.8	2.7
R/V "JOHAN HJORT"	0114	100	34.1	34.3	3.8
R/V "JOHAN HJORT"	0114	100	33.7	33.9	3.7
"INGER HILDUR"	0114	100	33.3	33.4	3.0
"INGER HILDUR"	0114	100	31.3	31.5	3.2
R/V "JOHAN HJORT"	0115	100	36.1	36.2	2.6

RESULTS

The described linear regression analysis was performed for each of the seven data series for each of four different criteria on depth stability. These are that the total variation in depth dz during any one 0.1-NM interval not exceed 0, 1, 2, or 5 m. Corresponding results are shown in Table 3 for the first six data series. Results for the seventh series are omitted because of insufficient numbers of data.

Table 3. Results of the linear regression analysis for σ_e/σ_b and lower and upper bounds with 95% confidence. The parameter dz indicates the maximum allowable variations in depth over individual 0.1-NM intervals of sailed distance, and n_s is the number of such intervals.

Series no.	dz (m)	n_s	σ_e/σ_b	$(\sigma_e/\sigma_b)_-$	$(\sigma_e/\sigma_b)_+$	σ_e (cm^2)
1	0	142	2.78	2.47	3.07	26.1
1	1	295	2.56	2.30	2.82	24.1
1	2	315	2.57	2.31	2.82	24.1
1	5	330	2.59	2.33	2.85	24.4
2	0	39	3.15	1.07	5.05	29.6
2	1	70	3.07	1.28	4.75	28.9
2	2	75	2.97	1.18	4.64	27.9
2	5	84	2.83	1.49	4.10	26.6
3	0	183	1.97	1.79	2.15	18.5
3	1	293	2.02	1.87	2.16	18.9
3	2	303	2.03	1.90	2.17	19.1
3	5	322	2.05	1.92	2.17	19.2
4	0	207	2.48	2.00	2.94	23.4
4	1	300	2.65	2.17	3.11	24.9
4	2	314	2.82	2.33	3.29	26.5
4	5	326	2.96	2.44	3.45	27.8
5	0	21	3.52	2.98	4.04	33.1
5	1	42	3.26	2.88	3.63	30.7
5	2	46	3.71	3.10	4.28	34.9
5	5	47	3.53	2.90	4.13	33.2
6	0	32	3.39	1.95	4.68	31.8
6	1	75	3.06	2.29	3.78	28.7
6	2	82	3.50	2.86	4.11	32.9
6	5	92	2.62	1.67	3.49	24.6

DISCUSSION

The method of data collection, with storage of individual echo time series through values of the volume backscattering strength together with value of detected bottom depth, has made possible a finer-grained analysis than was possible during previous determinations of the extinction cross section of herring in Ofotfjorden (Foote et al. 1992). Thus, it has been possible to separate the data by degree of variation in depth over the basic interval of echo integration, 0.1 NM for the present data. The increased power of discrimination has also increased the complexity of analysis. This is reflected in Table 3, where values of the ratio σ_e/σ_b are observed to vary for the same data series simply due to changing the requirement on bottom depth stability through the parameter dz.

Maintaining dz at a low value presumably ensures a greater flatness, hence homogeneity too of scattering from the bottom. A standard reference target, but one that is distributed over the beam cross section at about 500-m range, is what is sought. The penalty for requiring dz to be small is a reduced number of data.

Here the trade-off between the requirement of flatness over 0.1-NM intervals of sailed distance and numbers of data is resolved by choosing dz=1 m. This corresponds to a bottom slope no greater than one part in 180. Further requirement that there be at least 100 intervals in each data set restricts the results in Table 3 to just three, for series numbers 1, 3, and 4. These results are presented again in Table 4, with results from the previous investigations.

Table 4. Summary of new data compared with previous measurements of σ_e/σ_b. The category of day/night (D/N) for the 1994 data is that of the preponderance. Units of $\hat{b}$ and s_e are those of s_A multiplied by 10^6. The bounds on the ratio σ_e/σ_b apply with 95% confidence.

Year	D/N	$\hat{a}$	$\hat{b}$	s_e	n_s	σ_e/σ_b	Ratio bounds Lower	Ratio bounds Upper	σ_b (cm^2)	σ_e (cm^2)
1988	D	-1.01	1.06	0.144	45	1.64	0.97	2.24	7.7	12.7
1990	D	-1.55	1.16	0.191	324	2.28	2.10	2.46	8.8	20.0
1991	D	-1.30	1.92	0.204	120	1.17	1.06	1.26	9.5	11.2
1991	N	-2.32	1.78	0.169	140	2.24	2.10	2.37	9.5	21.4
1994	D+N	-2.67	1.78	0.378	295	2.56	2.30	2.82	9.4	24.1
1994	D	-1.90	1.62	0.243	293	2.02	1.87	2.16	9.4	18.9
1994	D+N	-3.06	1.98	0.674	300	2.65	2.17	3.11	9.4	24.9

As before, the range of values for the ratio is apparently uncomfortably high. Nonetheless, in the context of the values from 1988-1991, the new data are consistent. It seems reasonable to average the three new values for application in correcting the echo integration data for extinction. The results of this averaging are the following: Ave(σ_e/σ_b)=2.41, s.d.(σ_e/σ_b)= 0.33, and σ_e=22.7 cm^2.

Attempts to explain the variation in values for σ_e/σ_b by day/night effects have failed. There is simply insufficient evidence for such effects. This could reflect the difficulty of making a measurement that requires a large quantity of fish to appear over a flat bottom at the precise time available for investigation.

It might be speculated that the size distribution of fish changed in the course of the three measurement series reported in Table 4. Reference to the biological data contradicts this, however, for there seems to have been no significant change in the length distribution over the duration of the measurements, 9-14 January 1994, described in Table 1.

It is possible that the behavior of the fish changed. The fact that the fish were observed to begin their outwards migration from Ofotfjorden and Tysfjorden during the cruise makes this more plausible.

Two mechanisms for the effect of behavior on the extinction cross section are those of orientation and swimbladder state. Data on these are lacking. The depth range of fish varied slightly, as the fish remained at depths greater than 200 m at all times.

If the orientation distribution were to change, the effect on echo energy would be immediate (Foote 1980, Furusawa 1988). Presumably the extinction cross section would also change. The optics literature may offer particular insight here, for extinction is studied and measured to a much greater degree than in underwater sound. Use of lidar, the light-analog of sonar, as a quantitative instrument, is especially sensitive to extinction relative to backscattering (Hooper 1993), notwithstanding the exception of Raman lidar (Ansmann et al. 1990). The sensitive effect of particle orientation on extinction in addition to backscattering is recognized (Bohren and Huffman 1983). Frequency dependent scattering effects, for both spherical and non-spherical scatterers, are also well recognized (McCartney 1976, Ulaby et al. 1981).

Interest in the optics literature in the dual subjects of backscattering and extinction is current for a number of reasons. Use of lidar has already been mentioned. A second major reason is found in the importance of albedo and absorption due to aerosols on the Earth radiation budget (Lovelock and Kump 1994, Taylor and Penner 1994), for which calculations have been performed for over twenty years (Charlson et al. 1987).

Multiple-frequency measurements in acoustics may be expected to give insight into the connection of extinction and backscattering cross sections, as through inference of the orientation distribution. It requires a scattering model for the fish, however, and for the physostomous herring this is still lacking. Researchers in this area cannot be idle.

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