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SOUND LOSSES THROUGH AGGREGATIONS OF FISH

F Armstrong, E J Simmonds and D N MacLennan

Marine Laboratory, P O Box 101, Aberdeen, Scotland

INTRODUCTION

Acoustic extinction or shadowing effects caused by dense shoals of fish have been observed by several investigators e.g. Robinson [1]. Others have developed the theory of this effect while addressing the possibility of multiple scattering in fish shoals [2,3]. Measurements of caged aggregations of fish by Rottingen [4] have indicated a non- linear density dependence of the back-scattered energy as would be expected if acoustic shadowing were significant at high densities. Olsen [5] measured the echo from a metal sphere positioned below free swimming shoals, and he also observed strong shadowing effects.

We have conducted a series of experiments to quantify the attenuation of sound transmitted through high area densities of fish. The results from these experiments are presented here, and we discuss the implications for the interpretation of data collected during acoustic surveys.

EQUIPMENT

Experimental Rig

The experiments were conducted at the Marine Laboratory Field station at Loch Duich, using a rig similar to that described by Edwards & Armstrong [6]. This rig has been modified to allow the use of a 2m deep 2m diameter fish cage. The lower frame with the cameras was removed and replaced by plastic pipe chosen for its low reflectivity. This frame was used to support a 38.1mm tungsten-carbide ball suspended 3.7m beneath the cage. The whole rig was suspended at 15m depth below a raft moored in 90m of water,see Figure 1.

Two transducers, one operating at 120kHz and the other at 38kHz, were placed at the top of the rig and aligned so that the beams were centred on the fish cage.

Data Logging System

The system was operated simultaneously on both frequency channels. Two crystal-controlled transmitters were used to drive the transducers with 0.5ms pulses of 2 kW peak power, the returned echoes were received using constant stepped-gain band-pass receivers. The envelope-detected signals were sampled at 10kHz on each channel by a computer. The sampled data were corrected for range and stored on tape-streaming cartridges.

EXPERIMENTAL PROCEDURES

Two species of fish, mackerel and herring, had been kept in pens 6m in diameter and 5m deep with access to the surface, for a period of 4-6 weeks prior to the experiments, to give the fish time to recover from any damage or stress that had occurred during capture. The mackerel had been caught by hand-lining close to the pens, while the herring had been captured by a commercial purse seiner and transported in the vessel's sea-water tanks from the east coast of Scotland.
The mean and standard deviations of weights and lengths of the fish used can be seen in Table 1. At the beginning of each experiment, many fish were introduced to the cage at the surface. The cage was lowered to a depth of 21m and measurements taken over a period of 2 days. The rig was then lifted to the surface, approximately half the fish were removed and the rig lowered again. The experiment continued for another 2 days, then half of the remaining fish were removed; after a further 2 days all the remaining fish were removed so that final measurements of the empty cage could be recorded. The number and weight of fish removed at each point in the experiment was used to derive the numbers and area densities of fish for the three parts of each experiment, see Table 2.

Table 1
Mean and Standard Deviations for Weights and Lengths of the herring and mackerel used in the experiments.

	Prt 1		Prt 2		Prt 3	
	weight	length	weight	length	weight	length
Mackerel						
mean	155.78	29.63	153.17	28.27	167.27	30.09
std dev	47.80	14.83	44.28	13.93	42.68	12.32
Herring						
mean	144.73	26.30	139.61	25.84	140.62	25.77
std dev	29.06	7.63	29.06	7.91	25.69	7.93

Data Logging

Data were recorded from 1000 acoustic transmissions over 5 minute intervals with 1 minute required after each recording interval to save the data to tape and to produce a summary output. The data from individual transmissions included echo-integrals covering the top target, the fish cage, the lower target and the sea-bed returns for both 38 and 120kHz. The average vertical profile, sampled at 10kHz, was recorded for each group of 1000 transmissions. The samples covering the 60-70m between the lower target and the sea-bed were ignored, although it was necessary to ensure that the time gate for the sea-bed echo integral was long enough to included the whole echo at all states of the tide. To compensate for the change in range of the sea-bed, of about 3.5m in 60m due to tidal rise and fall, a 20logR TVG function was applied to the received sea-bed echo.

Table 2

Correlation coefficients for fish integral and lower target (FI-LT), fish integral and sea-bed echo (FI-SB), lower target and sea-bed echo (LT-SB) for the densities of fish (see Table 2) in each part of the experiments with herring and mackerel.

	herring			mackerel		
	Prt1	Prt2	Prt3	Prt1	Prt2	Prt3
38 kHz						
(FI-LT)	0.03	-0.06	-0.10	-0.02	0.11	-0.02
(FI-SB)	-0.01	0.23	-0.03	-0.11	-0.04	0.01
(LT-SB)	-0.04	0.00	-0.06	-0.01	-0.05	-0.02
120 kHz						
(FI-LT)	-0.01	-0.07	0.03	-0.02	0.01	-0.01
(FI-SB)	-0.02	-0.05	0.02	-0.03	0.00	0.03
(LT-SB)	-0.05	0.00	0.10	0.00	-0.02	0.02

DATA ANALYSIS

Single Ping Relationships

Following a two hour settling time at the start of each experiment, two consecutive blocks of 1000 transmission were selected for each fish density and species. These were analysed for correlation on a ping for ping basis, comparing the cage echo, the lower target and the sea-bed echo, using the following general formula for the correlation coefficient r.

$$r = \sum_{i=1}^{n}(X_i-\bar{X})(Y_i-\bar{Y})/[\sum_{i=1}^{n}(X_i-\bar{X})^2 \sum_{i=1}^{n}(Y_i-\bar{Y})^2]$$

where {X,Y} represent the following pairs of parameters, substituted in the equation in turn

(i) Fish integral and lower target
(ii) Fish integral and sea-bed echo
(iii) Lower target and sea-bed echo

Mean Values

Mean backscattering strengths for the fish, the lower target and the sea-bed were calculated for periods of up to 24 hours for each species and for each fish density. On some occasions when fish mortality occurred, the period over which the average was taken was reduced to ensure that the data did not include any signals from dead fish. The fish mortality rates within the experimental cage were higher than normally encountered, this was possibly due to the initial high density of fish (up to 83 fish per m^3) and to the difficulty of removing fish, for weight and length measurement, without damaging some of the remaining fish. The mean value of the echo integral for the upper target and its calculated target strength at 120 and 38kHz were used to calculate backscattering cross-section of the fish, the lower target and the sea-bed. The number of fish in the cage was used to calculate a mean target strength per individual and E the acoustic cross-section per unit area, defined as:

$$E = \bar{\sigma}_1 \; D_a$$

Where σ_1 is the mean backscattering cross-section per individual
D_a is the area density (number of fish under $1m^2$)

RESULTS

Single Ping Data

The results of the correlation analysis on single ping data are given in Table 2. There was no significant correlation between the integral of the fish echo, the echo from the sphere positioned under the cage or the sea-bed echo.
The extinction of the acoustic signal by the fish aggregation is estimated from the difference in the lower target and the sea-bed echo with and without fish in the cage.

Mean Values

The mean backscattering strength of the fish,the lower target and the sea-bed echo are shown in Table 3 along with the observed target strength per fish at 38 and 120kHz, and area densities for each species calculated from the number of fish and the area of the cage. The extinction is plotted against the acoustic cross-section of the fish per unit area of cage in Figure 2. Data from earlier experiments using a similar rig, when only data from the lower target were recorded are also shown. The 38kHz graph includes regression lines in order to emphasize general trends in the data. It is not suggested that there should be a linear relationship between the acoustic cross-section and the extinction expressed in dB. In the case of the 120kHz data, no clear trend is discernable and no regression line has been included in the figure.

DISCUSSION

The results from the single ping correlation analysis indicate that the measurement of one echo from a fish shoal or another target below the shoal is insufficient to estimate the acoustic extinction and to correct the fish integral for this effect. Only when sufficient samples have been taken to establish an accurate mean value, can the effective extinction be computed either from the fish echo-integral itself, or by reference to the echo from some lower target such as the sea bed.

At 38kHz there is a clear relationship between the extinction and the acoustic cross section of the fish. It appears that fish echo integrals can be reduced by 1 or 2 dB due to the extinction effect when the ratio of the acoustic and geometric cross sections of the shoal is only a few percent. Such values of the cross-section ratio would not be unusual in shoals of herring in the sea.

The extinction derived from the sea-bed echo is about 0.5 dB less than that derived from the lower target for the same fish density. There are two possible explanations for this phenomenon. First the transmitted pulse is forward scattered by the sphere nearest the transducer. When the two spheres are in line with the transducer, the forward scattering amplifies the incident wave at the lower sphere. The returning echo is further amplified as it is also forward scattered by the upper sphere. The lower sphere appears to have a higher target strength than it would have in free field conditions. The effect is complicated by interference between the directly transmitted and the forward scattered fields. If one sphere moves out of line, the forward scattering changes rapidly, and the apparent target strength of the lower sphere apparently decreases. The magnitude of this effect is discussed in MacLennan [7]. It is more significant at the higher frequencies because the phase difference changes more rapidly with the path length of the forward scattered wave. When the targets are out of line the contribution of the forward scattering may not be the same for the lower target echo and the sea-bed return. However more work would be required to establish the significance of this effect. Secondly the presence of distributed fish targets could diffuse the beam transmitted by the transducer, increasing its angular width, thus a point target positioned below the cage will produce an attenuated echo because of the reduced on-axis intensity of the transmitted signal. In the case of a distributed target such as the sea-bed, where the incident energy is totally intercepted even though it is spread over a larger area, the echo will again be attenuated, but by a smaller amount.

Both these phenomena might contribute to the higher extinction of a point target the closer it was to the fish. This could explain

Table 3
Mean backscattering strength in dB of the fish, the lower target and the sea-bed and the observed target strength per individual fish for the numbers of fish and fish densities shown in columns 1 and 2.

	No of Fish	Fish Density (per m^2)	Fish Cage	Lower Target	Sea-bed	Effective TS/Fish
38 kHz						
Empty cage	0	0	-39.48	-43.16	-11.01	
Mackerel	530	165.5	-35.78	-43.89	-11.43	-62.94
	287	91.0	-37.33	-43.93	-10.95	-61.91
	108	34.4	-38.19	-42.85	-10.98	-58.52
Herring	433	147.8	-17.26	-45.85	-13.51	-43.62
	237	75.4	-21.71	-45.50	-12.35	-45.46
	124	37.5	-23.72	-44.17	-11.62	-44.65
120 kHz						
Empty cage	0	0	-35.99	-42.45	-24.96	
Mackerel	530	165.5	-30.15	-43.19	-26.09	-57.31
	287	91.0	-34.01	-42.15	-25.54	-58.59
	108	34.4	-36.30	-42.19	-24.95	-56.63
Herring	433	147.8	-18.17	-43.57	-25.44	-44.53
	237	75.4	-22.61	-45.02	-25.40	-46.36
	124	37.5	-24.40	-43.26	-25.36	-45.33

greater extinction observed in the earlier results included in Figure 2, when the target was positioned closer to the cage. It is the effect on distributed targets that is most important in fisheries acoustics, such as the fish in the lowest layer of a deep shoal rather than a single fish under such a shoal. The extinction measure provided by the sea bed should therefore be more appropriate than that provided by a point target. We suggest that it is generally better to use a measurement of the sea-bed echo in extinction experiments.
The results shown in Figure 2 suggest that a 38 kHz echo-integral of fish about 10m into a shoal containing 10 fish per cubic metre would underestimate the density by 35%.
The 38kHz results give a clear indication of a monotonic relationship between the mean backscattering and the extinction of acoustic signals transmitted through fish shoals. In the case of 120 kHz signals, while extinction undoubtedly occurs, the data are

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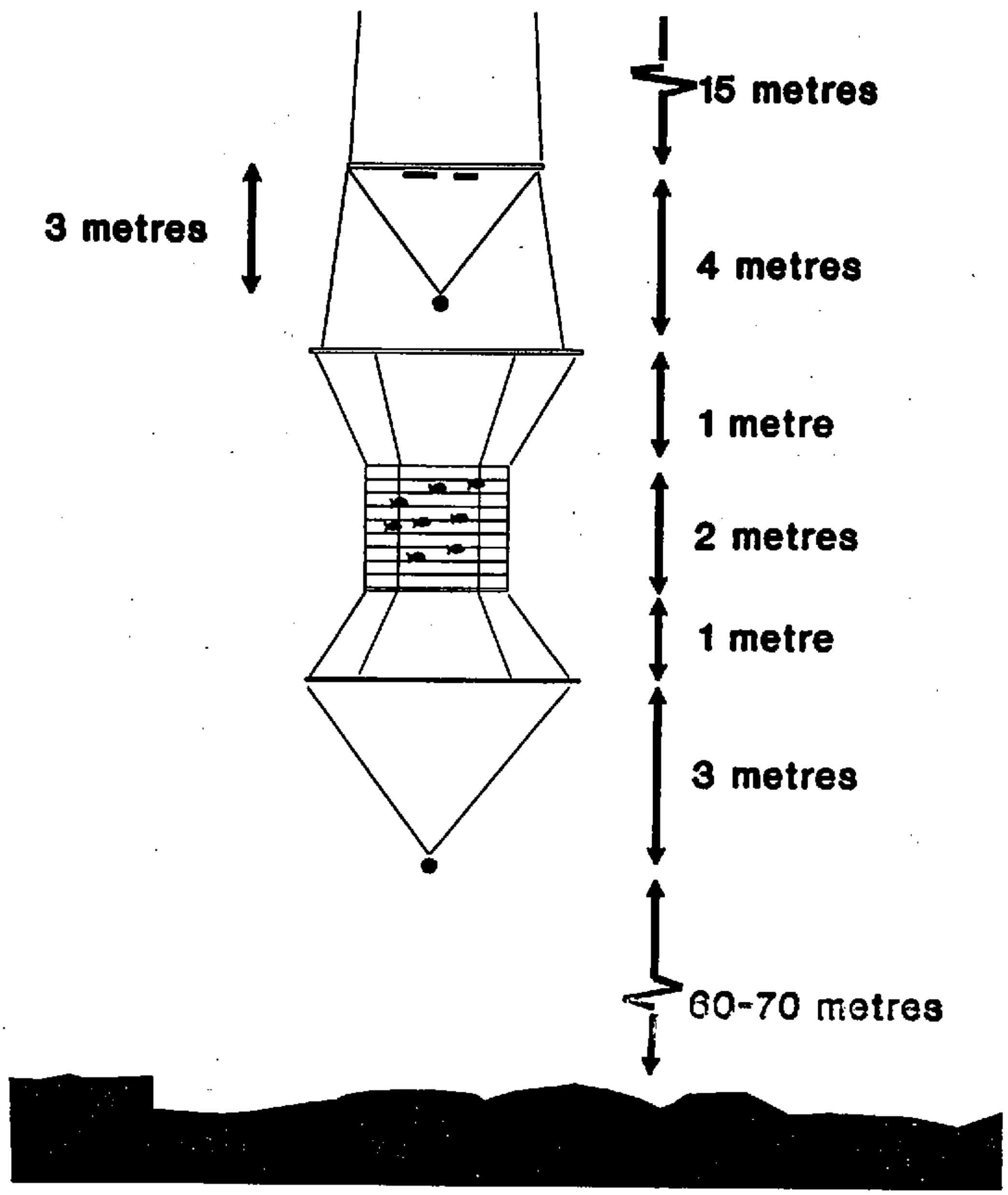

Figure 1
Diagram of the Experimental Rig.
(not to Scale)

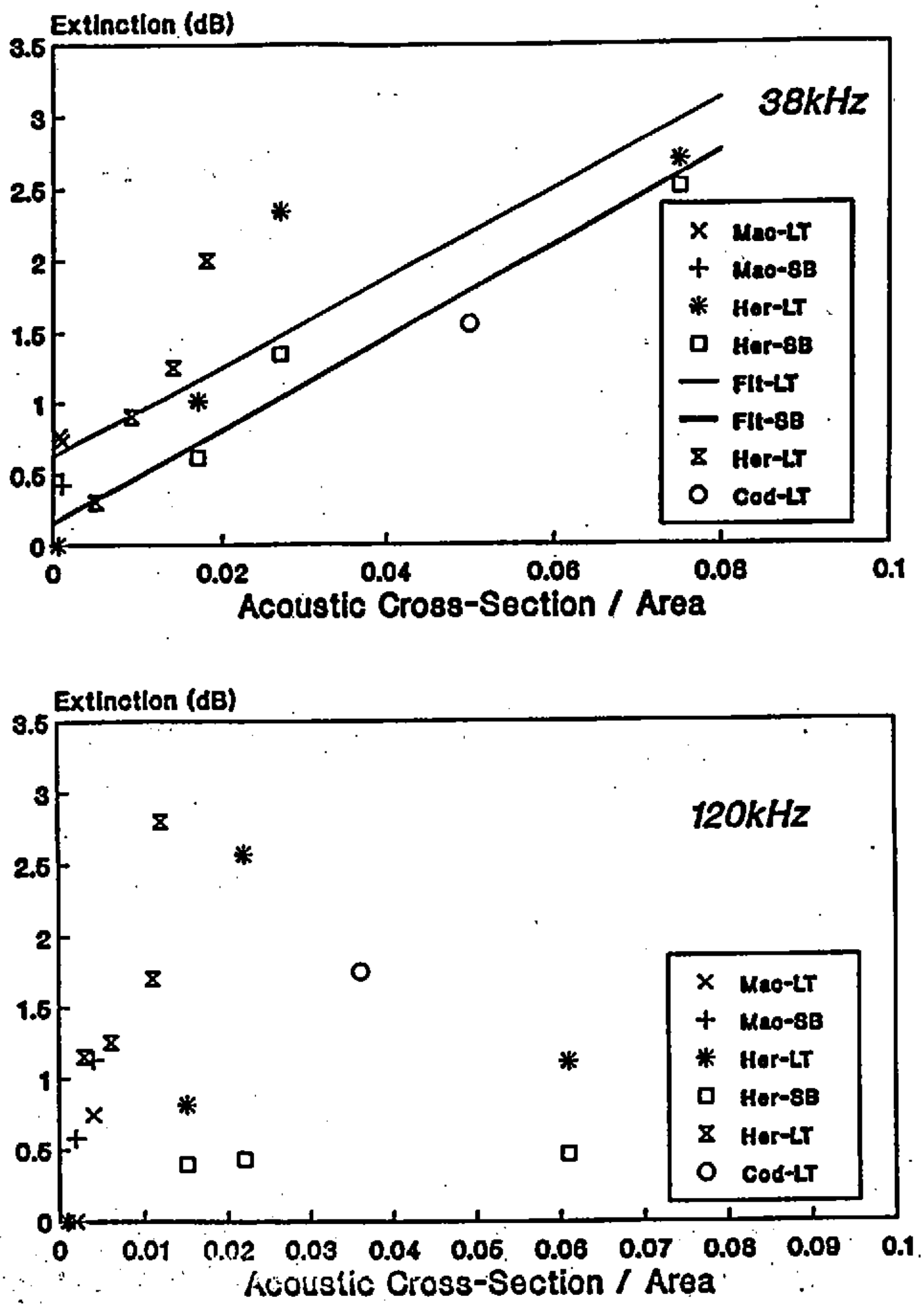

Figure 2
Extinction (dB) plotted against measured Acoustic Cross-Section per unit area at 38 and 120kHz for herring (Her), mackerel (Mak) and cod (Cod) measured using the echo from a target below the cage (LT) and the sea-bed echo (SB). The regressionlines(FIT) are for lower target (LT) and sea-bed (SB) echoes using both herring and mackerel data.

too scattered to suggest any functional relationship. It is difficult to explain this result, and the observation that the lower target echo rose significantly above the level for the empty cage during the mackerel experiment, while the sea-bed echo showed no significant variation with quite large changes in fish density during the herring experiment. We suspect that small changes in the rig geometry are responsible,due to the forward scattering effect discussed above. There were no similar changes in the strength of the sphere echoes at 38kHz , nor in the upper sphere echo at 120kHz. Consideration of the forward scattering properties of the tungsten carbide sphere confirm that this effect should not be significant at 38kHz, but problems could well arise at 120kHz because of the large amplitude of the forward scattered signal and the rapid change of phase associated with small differences in the path length of the direct and forward scattered waves. More work needs to be carried out at 120kHz before the results at this frequency can be fully explained

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