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ON MULTIPLE SCATTERING IN FISHERIES ACOUSTICS

by

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ABSTRACT

The possibility of multiple scattering by dense or extended fish schools has worried some researchers for years. This concern is shown to be unfounded by reference to the larger literature. The sole, non-behavioural effect of aggregation on fish detection and measurement is that of simple shadowing or extinction. A simple addition theorem is stated which is adequate for all fish aggregations of natural occurrence. Empirical evidence for the same is cited.

RESUME: DIFFUSION MULTIPLE EN ACOUSTIQUE HALIEUTIQUE

La possibilité d'une diffusion multiple dans des bancs denses ou de grandes dimensions a inquiété quelques chercheurs depuis des années. Se basant sur une large recherche bibliographique, on montre que cette inquiétude n'a pas été retrouvée ailleurs. Le seul effet non-comportemental dû au groupement des poissons est simplement celui de l'ombre ou de l'extinction acoustiques. On établit une loi d'addition simple, applicable à tout rassemblement naturel de poissons. Des preuves empiriques sont également données sur ce même sujet.

INTRODUCTION

Multiple scattering is a recognized phenomenon in fisheries acoustics. The most striking manifestation of this in echo sounding is the weakening, if not actual loss of bottom signal due to the presence of large, dense schools. Since the numbers of fish and total biomass contained in such schools can be quite large, it is essential for the wider application of the echo integration method that the phenomenon be understood.

There are at least several bodies of literature pertinent to the present discussion. That of fisheries acoustics has been freshly and fully elaborated by MacLennan and Forbes (1982) and Lytle and Maxwell (1982). All of these authors appreciate the importance of the phenomenon. MacLennan and Forbes (1982) advocate further work, at least to disclose the limit of linearity, i.e., the limit of proportionality between integrated echo intensity and fish density.

Lytle and Maxwell (1982) also review the literature, which they find lacking. They have, however, developed their own method for describing multiple scattering from schools of arbitrary density. They additionally describe how this knowledge can be used to correct echo integrator estimates of fish density, especially for high-density schools. This involves application of a special time-varied-gain function which operates over the duration of the returning echo.

Judging from the two cited works, it is reasonable to ask whether or not multiple scattering is still a problem, or in fact has been a problem in the sense of having wanted a solution. It is the purpose of this paper to answer the question by reference to the larger physics literature on multiple scattering.

GERMANE LITERATURE

Contrary to popular belief, the physics literature did not end, or even begin with Foldy (1945), seminal though his work was. A few specific references with reviews and/or bibliographies useful to the discussion are Lax (1951), Twersky (1960, 1977), Waterman and Truell (1961), and Burke and Twersky (1964).

According to the several works, with augmentation by Lax (1952), Twersky (1962, 1976), and Tsang et al. (1982), the problem of multiple scattering can be expressed through the question: What is the propagation constant in a region occupied by scatterers? Alternatively, how does the presence of scatterers change the propagation characteristics of the medium?

WEAK SCATTERING DENSITY

It is a useful exercise to compile a list of expressions for the propagation constant, distinguishing these by the domain or conditions of applicability. As there is general agreement, however, a common expression for the weak scattering density is defined. In terms of the maximum single-scatterer differential scattering cross section σ_{max},

$$\rho << 2\pi\lambda^{-2}\sigma_{max}^{-\frac{1}{2}} \quad , \tag{1}$$

where ρ is the scatterer density and λ is the acoustic wavelength. That is, if the density satisfies the criterion, then multiple scattering is negligible.

To show the significance of Eq. (1) in fisheries acoustics, several cases are considered. In these, σ_{max} is approximated by the maximum backscattering cross section $\sigma_{b,max}$ when normalized in the customary manner by 4π, i.e.,

$$\sigma_{max} \rightarrow \frac{\sigma_{b,max}}{4\pi} \quad . \tag{2}$$

According to the ordinary definition of target strength TS (Urick 1975),

$$\frac{\sigma_{b,max}}{4\pi} = 10^{TS/10} \quad . \tag{3}$$

Substituting in Eq. (1),

$$\rho << 2\pi\lambda^{-2}10^{-TS/20} \quad . \tag{4}$$

For fish whose target strength is described by the regression equation

$$TS = m \log \ell + b \quad , \tag{5}$$

where ℓ is the fish length in centimeters, and m and b are the regression coefficients,

$$\rho << 2\pi 10^{-b/20}\lambda^{-2}\ell^{-m/20} \quad . \tag{6}$$

Since m is equal to 20 in most applications in echo surveying,

$$\rho << 2\pi 10^{-b/20}\lambda^{-2}\ell^{-1} \quad . \tag{7}$$

This equation is evidently amply fulfilled for the same anticipated applications, for the characteristic size-to-wavelength ratio generally lies in the range from 1 to 100 (Foote 1980), while the regression coefficient b very roughly lies in the range from -75 to - 55 dB. For an unfavorable, but still realistic combination of conditions, say $\lambda = 5$ cm, $\ell = 100$ cm, and $b = -55$ dB,

$$\rho << 14100 \text{ m}^{-3} \quad ,$$

if multiple scattering is to be avoided. It is noted in passing that if ρ in Eqs. (6) and (7) is to be expressed in units of fish per cubic meter, then λ must be expressed in meters, while ℓ is expressed in centimeters according to the convention underlying Eq. (5).

As a further example, the empirical relationship for the maximum dorsal aspect target strength of cod (Gadus morhua) at 38 kHz is substituted in Eq. (6). Since m = 25.2 and b = -67.9 dB (Foote 1980),

$$\rho << 1.015 \; 10^{7} \, \ell^{-1.26} \quad .$$

This is clearly satisfied for the applicable length range from 6.7 to 96 cm, for at the extreme lengths, the condition becomes

$$\rho << \begin{cases} 9.24 \; 10^{5} \text{ m}^{-3} & \text{for } \ell = 6.7 \text{ cm} \\ 3.23 \; 10^{4} \text{ m}^{-3} & \text{for } \ell = 96 \text{ cm} \end{cases} \quad .$$

ADDITION THEOREM

The consequence of the fulfillment of Eq. (1) is the addition theorem for cross sections cited in Waterman and Truell (1961). An expression of this in fisheries acoustics is the second, and general addition theorem of Foote (1982). This is tantamount to the statement that the mean echo intensity I_z from fish at depth z in a uniform aggregation whose upper surface is at depth $z_1 < z$ is

$$I_z = I_{z,o} e^{-2\rho\sigma_e(z-z_1)} \quad , \tag{8}$$

where ρ is the fish density, σ_e is the mean extinction cross section, and $I_{z,o}$ is the mean echo intensity due to the same fish of the aggregation at depth z in the absence of higher-lying fish. Thus the sole acoustic effect of propinquity of fish on the echo is an attenuation of both incident and backscattered waves by scattering out of the forward direction. Generalization to the case of spatially inhomogeneous fish distributions is straightforward.

For comparison, the hybrid solution of Lytle and Maxwell (1982) could be consistent with Eq. (8), were the characteristic constants equal. This is not generally the case, however, as Lytle and Maxwell's constant is determined by empirical curve-fitting. It thus depends on simulating or observing the actual survey conditions of interest, and is not easily adapted to new conditions.

EMPIRICAL EVIDENCE

In addition to the theoretical demonstration above, there is a variety of empirical evidence for the validity of the simple interpretation of high-density scattering in terms of extinction. Direct evidence in the fisheries domain is provided by the experiment of Røttingen (1976) and its analysis (Foote 1978).

Other direct evidence for the cited general addition theorem is provided by several classic experiments on sound propagation in bubbly water, viz. Carstensen and Foldy (1947), Fox et al. (1955), and Silberman (1957). Experiments on the propagation of electromagnetic waves in concentrations of styrofoam spheres simulating density states from the gaseous to liquid have been similarly corroboratory of theory (Beard and Twersky 1960), as have been extensions of this work, cf. Beard (1962). A successful theoretical development related to this, but oriented towards fisheries acoustics is described in Prokopets (1982).

SUMMARY

Examination of the larger physics literature has disclosed a general condition for the fish density at which multiple scattering becomes important, cf. Eq. (1). According to the general and specific evaluations, actual densities of natural fish aggregations never support the occurrence of multiple scattering. The sole acoustic effect of the presence of other fish on the echo from any one fish is that of simple extinction, as described briefly in Eq. (8). This is consistent with the principle of linearity as interpreted in Foote (1982). Various empirical evidence both within and outside of fisheries acoustics supports the simple scattering interpretation, hence too the adequacy of existing theory to treat all scattering situations in fisheries acoustics.

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