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SUMMARY OF METHODS FOR MEASURING FISH TARGET STRENGTH

by

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ABSTRACT

Methods for measuring fish target strength are intercompared. The consistency of results obtained on the same or related species by different methods is noted.

RESUME: RESUME DES METHODES DE MESURE DES INDEX DE REFLEXION DES POISSONS

Les méthodes de mesure des index de réflexion des poissons sont comparées entre elles. La cohérence des résultats obtenus sur les mêmes espèces ou sur des espèces voisines est notée.

INTRODUCTION

The Working Group on Fisheries Acoustic Science and Technology recommended at its meeting in Seattle, 26-28 June 1987, "that the WG should continue the study of fish target strength, including methods of measurement at the next meeting" (Anon. 1987). This was duly done in Ostende, 20-22 April 1988. Documentation of a particular presentation at the meeting follows.

The subject of target strength measurement has been reviewed generally by Midttun (1984) and with respect to *in situ* techniques by Ehrenberg (1979, 1983a). Since the cited, two most recent reviews, which were prepared for the Symposium on Fisheries Acoustics held in Bergen, 21-24 June 1982, some established methods have been improved and new methods introduced. Thus, a new review may be timely.

This review has several aims. It attempts to classify the various methods in order to show their relationships and suggest ranges of applicability. In addition to summarizing the methods, key references are given for accessing the larger literature. Tabulation of measurement results for the same or similar species, although still relatively few in number, compare very favorably.

PROBLEM DEFINITION

The problem of target strength measurement may be formulated succinctly through a simple equation for the echo energy ε from a number of distinct scatterers,

$$\varepsilon = \sum_j \varepsilon_j = \sum_j g_j \, b^2(\theta_j,\phi_j) \, \sigma_j \quad , \tag{1}$$

where g is a gain factor that may be range dependent, $b^2(\theta,\phi)$ is the product of transmit and receive beam patterns in the direction (θ,ϕ), and σ is the backscattering cross section. Each of the three factors relates to the same, j-th discrete scatterer. The target strength TS is defined in terms of σ thus:

$$TS = 10 \log \frac{\sigma}{4\pi} \quad , \tag{2}$$

where the target strength of an idealized perfectly reflecting sphere of 2-m radius is 0 dB (Urick 1975).

The problem is the following. Either the total energy ε or set of individual constituents $\{\varepsilon_j\}$ is measured. The functional forms of g and b are known *a priori*, as by calibration. How can the set of individual backscattering cross sections $\{\sigma_j\}$, probability density function $f(\sigma)$, or mean value $\bar{\sigma}$, or corresponding target strength quantities, be determined?

CLASSIFICATION OF METHODS

A hierarchy of measurement methods is shown in the figure. The Roman numerals denote particular examples or variants of the methods.

The major division of methods is that of *in situ* and *ex situ*. *In situ* measurements are performed on fish in their natural environment without deliberate disturbance before completing the acoustic measurements, if then. The precise identity of the target is thus generally unknown. *Ex situ* methods remedy this situation by measuring fish constrained in some way after capture. However, the effects of capture and physical constraint on behaviour and target strength are generally unknown.

In situ measurements are indirect or direct insofar as the target strength is determined as a statistical measure for the entire ensemble (indirect) or individually for each resolved, single-fish echo (direct). Alternatively, indirect and direct methods can be distinguished by the way in which the beam pattern factor b in Equation (1) is removed from the measurement of echo energy. This may proceeed numerically (indirect) or electronically by means of simultaneous positioning data (direct).

- IN SITU
  - INDIRECT
    - ECHO SURVEYING
      - PRESEINING ECHO INTEGRATION (I)
      - SIMULTANEOUS INTEGRATION AND COUNTING (II)
    - SINGLE BEAM
      - NONPARAMETRIC
        - LOGARITHMIC DOMAIN (III,IV)
        - INTENSITY DOMAIN (V,VI)
      - PARAMETRIC
        - RAYLEIGH PDF (VII,VIII)
        - RICE PDF (IX)
  - DIRECT
    - DUAL BEAMS (X)
    - SPLIT BEAMS (XI)
- EX SITU
  - TETHERED SINGLE FISH (XII)
  - CAGED FISH (XIII)
  - MORPHOMETRY-BASED COMPUTATION (XIV)

Figure. Hierarchy of target strength measurement methods.

Echo surveying (I,II)

Under suitable conditions, ordinary echo-sounding and integrating equipment may be sufficient for determining target strength. Two examples are given.

Preseining echo integration (I). If an aggregation of fish is sufficiently small, distinct, and catchable, it may be surveyed before capture, as by seining (Hagstrøm and Røttingen 1982). The quantity of surveyed fish may thus be known, and the mean echo energy ε or proportional quantity M may be determined. These quantities are, however, linearly related to the mean backscattering cross section $\bar{\sigma}$:

$$\bar{\varepsilon} = C_1 \bar{\sigma} \tag{3a}$$

or

$$\bar{M} = C_2 \bar{\sigma} \tag{3b}$$

The constants C_1 and C_2 may be determined by calibration with a standard target (Foote et al. 1987). Solution of either equation for $\bar{\sigma}$ follows.

Simultaneous echo integration and counting (II). If an aggregation is sufficiently dispersed, its area density may be determined in each of two ways. By counting the number N of resolved single-fish echo traces in a narrow layer on the echogram and relating this to the coverage area A, an estimate of the density,

$$\rho_1 = N/A \quad , \tag{4a}$$

is derived (Midttun and Nakken 1971). For a calibrated echo integrator, the density is also estimated as the ratio of echo integral M and $\bar{\sigma}$, i.e.,

$$\rho_2 = M/\bar{\sigma} \quad . \tag{4b}$$

Equating the two equations allows solution for $\bar{\sigma}$ (Ona and Hansen 1986).

Single beam (III-IX)

An ordinary, single-beam transducer is used in making measurements of the energy in resolved single-fish echoes. The data set $\{\varepsilon_j\}$ results. The gain factor g in Equation (1) is generally constant, i.e., $g_j=g$, when the "40 log r" type of time-varied gain is applied. The beam pattern b is also generally known, but the arguments of b, the angular coordinates (θ_j,ϕ_j) of the arbitrary target are unknown. To extract σ, therefore, the equation is solved numerically.

A variety of techniques for doing this have been developed since the pioneering work of Craig and Forbes (1969). Each begins by rewriting Equation (1) in terms of the probability density functions (pdf) of the several variables, expressed in the given intensity domain, the amplitude domain, or the logarithmic domain. Solutions of the rewritten equation are effected either nonparametrically, without assuming any particular form for the pdf of σ or TS (Methods III-VI), or parametrically, with assumption of a definite pdf type (Methods VII-IX).

The first of the nonparametric approaches, due to Craig and Forbes (1969), assumes that the measurements are noise-free (III). The integral equation with the logarithmic expression is discretized and reduced to a set of linear equations which are solved simultaneously. While the method can be successful (Lindem 1983), it is numerically unstable, and negative values in the pdf of target strength can result.

This problem is avoided by addition of the constraint that the TS pdf be non-negative (IV). This approach has been used by Degnbol et al. (1985).

Two other nonparametric approaches have been developed for use in the intensity domain. Ehrenberg (1972) has approximated the pdf of σ by an n-th degree polynomial (V). Robinson (1982) has sought to improve this by subdividing the range of σ and fitting low-order polynomials, in piecewise fashion, to each interval (VI).

Three parametric approaches are enumerated. The earliest, due to Peterson et al. (1976), assumes that the on-axis echo amplitude, proportional to $\sigma^{\frac{1}{2}}$, is Rayleigh-distributed (VII). The characteristic parameter of the distribution, $\bar{\sigma}$, is found by matching theoretical simulations of the echo amplitude distribution, with trial values or guesses for $\bar{\sigma}$, to the observed distribution. Ehrenberg et al. (1981) made use of the same assumption, but refined the computational procedure so that the observed echo amplitude distribution, after normalization, can yield an estimate for $\bar{\sigma}$ without the need for iterations (VIII). Another explication of this method is given by Ehrenberg (1983b). The parametric approaches are recognized to apply to uniform sizes.

Ehrenberg et al. (1981) also examined the Rayleigh distribution hypothesis. They found that this is most applicable for large fish sizes relative to the wavelength. They speculated on extending the method to smaller sizes and concluded that two parameters are required for the pdf.

This was the finding of Clay and Heist (1984), who applied Rice's pdf to the echo amplitude (IX). The two parameters of this are called the concentrated and distributed scattering components, σ_c and σ_d, respectively. Their relationship is conveniently expressed through the ratio $\sigma_c/\sigma_d=\gamma$. When this vanishes, the Rice pdf devolves to the Rayleigh pdf. When γ is large, the Rice pdf approximates the Gaussian. The two cases described, respectively, large and small fish. Fitting the Rice pdf to observations of echo amplitudes also shows that γ changes with the degree of swimming movement, i.e., γ is related to behaviour.

A generally tacit assumption of each of the single-beam methods is that the probability of obtaining a resolved single-fish echo in the main lobe is independent of ϕ and varies with θ as $\sin\theta$. That is, it is assumed that the occurrence of a fish in the volume defined by the beam and a narrow horizontal layer is equally likely with respect to the solid angle.

Dual beams (X)

The first of the two direct methods is that of dual beams. This was developed by Ehrenberg (1974) to provide an alternative means of determining σ or TS *in situ*, without having to make assumptions about the distribution of fish in the beam, hence to observe σ or TS directly.

The method works by using a circular transducer in each of two modes simultaneously. The entire circular array transmits in a narrow beam. In reception, the entire array forms a similarly narrow beam, and a small central circle of elements forms a wide beam. The echo energy for the same scatterer as received on each of the two beams is, in accordance with Equation (1),

$$\varepsilon_N = g_N b_N^2 \sigma \tag{5a}$$

and

$$\varepsilon_W = g_W b_N b_W \sigma \tag{5b}$$

The common assumption is made that the wide beam is essentially uniform wherever the narrow beam detects a target, hence $b_W=1$ in Equation (5b). Substituting this and solving for σ,

$$\sigma = \frac{g_N b_W^2}{g_W^2 b_N} \quad . \tag{6}$$

Given simultaneous measurements of ε_N and ε_W, the effective value of b_N can be sensed, thence applied in directly deriving a measure for σ or TS, without the need for numerical or statistical manipulation.

Split beams (XI)

The second direct method, that of split beams, was studied by Ehrenberg (1979), who judged it to be superior to the method of dual beams when the effect of noise is considered. SIMRAD introduced the first split-beam system for use in fisheries research (Foote et al. 1984).

It is based on division of the transducer into four quadrants. All act in concert during transmission, but each quadrant forms its own beam under reception. Summing of quadrant-beams to form half-beams and comparison of phases between fore-and-aft half-beams and between port-and-starboard half-beams determine the angular position of a detected target. Thus, in a constituent term of Equation (1), namely

$$\varepsilon_j = g_j \, b^2(\theta_j,\phi_j) \, \sigma_j \quad , \tag{7}$$

ε_j, θ_j, and ϕ_j are measured. Since g_j and b^2 are known by calibration, σ_j can be directly determined.

Tethered single fish (XII)

Measurement of tethered killed, stunned, or anesthetized fish in a fixed part of the echo-sounding beam represents a traditional and widely practiced form of *ex situ* measurement. Midttun (1984) gives 17 references on such measurements, and the number has grown since the 1982 Symposium on Fisheries Acoustics.

A significant aim of some tethered-fish measurement has been determination of the orientation dependence of target strength. This has been pursued by, for example, Midttun and Hoff (1962), Haslett (1977), and Nakken and Olsen (1977). The angle dependence has been used with distributions of fish orientation to determine the effective backscattering cross section or target strength of fish in the wild (Nakken and Olsen 1977). The validity of tethered-fish measurement and their use in model computations have been established (Foote 1983).

Caged fish (XIII)

Another popular form of *ex situ* measurement is that of caged fish. Live fish are confined in a cage which is suspended in the echo-sounding beam. Depending on circumstances, namely number and spatial distribution of fish in the cage, extent of the cage, and manner of calibration, Equation (1) or Equation (3a) can be applied directly in determining $\bar{\sigma}$, thence $\overline{TS}$.

An extensive series of caged-fish measurements is described by Edwards and Armstrong (1983). A number of variants on the basic idea are described in the caged-fish literature cited by Foote (1986).

Morphometry-based computation (XIV)

Scattering is a deterministic process. If the physical composition of a fish is known, it is in principle possible to compute σ or TS. Practical difficulties may be encountered, however, in both the morphometry and computation.

For physoclistous and physostomous fish, the swimbladder is the predominant scattering organ, suggesting a vastly simplified model based on these assumptions: that all of the scattering is due to the swimbladder and that this can be described as an ideal pressure-release surface. Swimbladder-based computations of TS for 32-44 cm pollack (*Pollachius*

pollachius) and saithe (Pollachius virens) (Foote 1985) and 35-42 cm walleye pollock (Theragra chalcogramma) (Foote and Traynor 1988) have agreed with direct measurement.

COMPARISONS

Results of many measurements with a given method are often expressed through the probability density function of target strength. For present purposes it is convenient to combine measurements on like fishes made with the same method by regressing the several mean target strengths $\overline{TS}$ on the respective mean fish lengths ℓ according to the equation

$$\overline{TS} = 20 \log \bar{\ell} + b \quad . \qquad (8)$$

The individual values of TS are determined in the intensity domain, through $\bar{\sigma}$, and expressed in the logarithmic domain by Equation (2). The intercept b and the standard error of regression, SE, are the two measures used here to characterize the measurement results. These are presented in Tables 1 and 2 for gadoids and clupeoids, respectively. The underlying data are compiled in Foote (1987).

DISCUSSION

Enormous progress has been made in the measurement of target strength since the 1982 Symposium on Fisheries Acoustics. This is evident from the number of new methods, the degree of refinement of established methods, and the general newness of measurement results.

Clearly, the work on target strength measurement shows both its importance and intrinsic difficulty. Each of the described methods has advantages and disadvantages, which are to be heeded in the particular application. Still, when different, if not disparate, methods are applied to like fishes, the results are quite similar, as is seen from Tables 1 and 2.

What ultimately matters is the accuracy of measurements of target strength. Performance of an absolute calibration, including beam-pattern mapping, defines or guarantees the level of potential accuracy. This may or may not be achieved depending on the circumstances of observation. It is the researcher's job to choose or find those conditions which permit good measurements of target strength and application of these in surveying.

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Table 1. Comparison of target strength measurements on gadoids. Method II: simultaneous integration and counting, X: dual beams, XI: split beams, XII: tethered single fish, XIV: morphometry-based computation. D/N denotes day/night for measurement.

Method	Year	D/N	$\bar{\ell}$(cm)	b(dB)	SE(dB)
II	1986	N	44	-67.7	2.0
X	1978-80	D&N	16-57	-67.3	3.0
X	1985	N	30-55	-65.9	0.9
XI	1984-86	N	15-82	-67.8	1.2
XI	1985	N	30-55	-65.4	0.9
XII	1971	D&N	7-96	-66.3	1.5
XII	1980	D&N	26-44	-67.3	1.0
XIV	1980	D&N	32-44	-66.9	1.7
XIV	1986	D&N	35-42	-66.7	1.2

Table 2. Comparison of target strength measurements on clupeoids. Method I: preseining echo integration, III: Craig and Forbes's single-beam solution, XI: split beams, XII: tethered single fish, XIII: caged fish.

Method	Year	D/N	$\bar{\ell}$(cm)	b(dB)	SE(dB)
I	1982	N	35	-73.5	1.5
I	1983	N	32	-73.5	1.5
III	1983-84	N	21	-74.0	1.7
III	1984	N	15	-70.7	3.0
XI	1984	N	28	-72.1	2.1
XII	1971	D	7-32	-68.5	2.5
XII	1971	N	7-32	-71.7	2.3
XII	1980	D	16-31	-69.1	1.2
XII	1980	N	16-31	-72.5	1.1
XIII	1978-81	D&N	24	-69.9	-
XIII	1981	D&N	9	-69.7	-

REFERENCES

Anon. 1987. Report of the Working Group on Fisheries Acoustic Science and Technology (F.A.S.T.). ICES C.M./B:34, 19 pp. [mimeo]

Clay, C. S., and Heist, B. G. 1984. Acoustic scattering by fish - Acoustic models and a two-parameter fit. J. acoust. Soc. Am., 75: 1077-1083.

Craig, R. E., and Forbes, S. T. 1969. Design of a sonar for fish counting. FiskDir. Skr. Ser. HavUnders., 15: 210-219.

Degnbol, P., Lassen, H., and Staehr, K.-J. 1985. *In situ* determination of target strength of herring and sprat at 38 and 120 kHz. Dana, 5: 45-54.

Edwards, J. I., and Armstrong, F. 1983. Measurement of the target strength of live herring and mackerel. FAO Fish. Rep., 300: 69-77.

Ehrenberg, J. E. 1972. A method for extracting the fish target strength distribution from acoustic echoes. Proc. IEEE Conf. Eng. Ocean Environ., 1: 61-64. IEEE, New York.

Ehrenberg, J. E. 1974. Two applications for a dual-beam transducer in hydroacoustic fish assessment systems. Proc. IEEE Cong. Eng. Ocean Environ., 1: 152-155.

Ehrenberg, J. E. 1979. A comparative analysis of *in situ* methods for directly measuring the acoustic target strength of individual fish. IEEE J. Ocean. Eng., OE-4: 141-152.

Ehrenberg, J. E. 1983a. A review of *in situ* target strength estimation techniques. FAO Fish. Rep., 300: 85-90.

Ehrenberg, J. E. 1983b. New methods for indirectly measuring the mean acoustic backscattering cross section of fish. FAO Fish. Rep., 300: 91-98.

Ehrenberg, J. E., Carlson, T. J., Traynor, J. J., and Williamson, N. J. 1981. Indirect measurement of the mean acoustic backscattering cross section of fish. J. acoust. Soc. Am., 69: 955-962.

Foote, K. G. 1983. Linearity of fisheries acoustics, with addition theorems. J. acoust. Soc. Am., 73: 1932-1940.

Foote, K. G. 1985. Rather-high-frequency sound scattering by swimbladdered fish. J. acoust. Soc. Am., 78: 688-700.

Foote, K. G. 1986. A critique of Goddard and Welsby's paper "The acoustic target strength of live fish". J. Cons. int. Explor. Mer, 42: 212-220.

Foote, K. G. 1987. Fish target strengths for use in echo integrator surveys. J. acoust. Soc. Am., 82: 981-987.

Foote, K. G, Kristensen, F. H., and Solli, H. 1984. Trial of a new, split-beam echo sounder. ICES C.M./B:21, 15 pp. [mimeo]

Foote, K. G., Knudsen, H. P., Vestnes, G., MacLennan, D. N., and Simmonds, E. J. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. ICES Cooperative Res. Rep. 144, 69 pp.

Foote, K. G, and Traynor, J. J. 1988. Comparison of walleye pollock target strength estimates determined from *in situ* measurements and calculations based on swimbladder form. J. acoust. Soc. Am., 83: 9-17.

Hagstrøm, O., and Røttingen, I. 1982. Measurements of the density coefficient and average target strength of herring using purse seine. ICES C.M./B:33, 13 pp. [mimeo]

Haslett, R. W. G. 1977. Automatic plotting of polar diagrams of target strength of fish in roll, pitch and yaw. Rapp. P.-v. Réun. Cons. int. Explor. Mer, 170: 74-81.

Lindem, T. 1983. Successes with conventional *in situ* determinations of fish target strength. FAO Fish. Rep., 300: 104-111.

Midttun, L. 1984. Fish and other organisms as acoustic targets. Rapp. P.-v. Réun. Cons. int. Explor. Mer, 184: 25-33.

Midttun, L., and Hoff, I. 1962. Measurements of the reflection of sound by fish. FiskDir. Skr. Ser. HavUnders., 13(3): 1-18.

Midttun, L., and Nakken, O. 1971. On acoustic identification, sizing and abundance estimation. FiskDir. Skr. Ser. HavUnders., 16: 36-48.

Nakken, O., and Olsen, K. 1977. Target strength measurements of fish. Rapp. P.-v. Réun. Cons. int. Explor. Mer, 170: 52-69.

Ona, E., and Hansen, K. 1986. In situ target strength observations on haddock. ICES C.M./B:39, 14 pp. [mimeo]

Peterson, M. L., Clay, C. S., and Brandt, S. B. 1976. Acoustic estimates of fish density and scattering functions. J. acoust. Soc. Am., 60: 618-622.

Robinson, B. J. 1982. An *in situ* technique to determine fish target strength with results for blue whiting (*Micromesistius poutassou* Risso). J. Cons. int. Explor. Mer, 40: 153-160.

Urick, R. J. 1975. Principles of underwater sound. Second edition, McGraw-Hill, New York. 384 pp.