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A consistent approach to definitions and symbols in fisheries acoustics

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Long-standing problems with acoustical terminology in fisheries applications such as echo-integration indicate the need for a more consistent approach. Based where possible on existing terms, a scheme of explicitly named quantities is proposed, backed by clearly stated definitions and preferred symbols. The emphasis is on scattering phenomena because the terminology in this area presents the main source of difficulty. Starting with the scattering equations for a small target, the volume, area, and line coefficients relevant to multiple, distributed targets are defined, leading to practical formulas for the important application of remote biomass estimation from echo-integration. The aim is to incorporate, as far as possible, common practice in fisheries-acoustics terminology and related fields. The developed scheme has been commended by the ICES Fisheries Acoustics Science and Technology Working Group as a constructive approach to better communication standards in fisheries-acoustics publications.

Keywords: acoustics, definitions, fisheries, ICES, symbols, sonar, units, WGFAST.

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Introduction

In any scientific field it is essential to be clear about the definition of physical quantities and naming conventions. In the case of fisheries acoustics there has been a long-standing problem mainly due to confusing descriptions of the various scattering measures that are central to biological observations using sonars and echo-integrators. With the growing importance of acoustic methods in remote biomass estimation, many practitioners agree that a more consistent approach to acoustical terminology must be adopted in fisheries applications.

Existing guidance on these matters is limited and somewhat contradictory. General texts on acoustical terminology (ANSI, 1994; Urick, 1983) do not define adequately processes like area scattering which are seldom mentioned outside fisheries' applications. At the more specialised level, Hall (1995) considers that solid angle measures should be included in the definition of target strength and related parameters. However, this idea is not supported by Medwin and Clay (1998) in their more complete treatment of the ground rules that apply to acoustical oceanography. For historical and other reasons different practices appear in the fisheries literature (Craig, 1981; MacLennan and Simmonds, 1992; Foote and Knudsen, 1994). Our primary concern is to address the lack of consistency arising in the latter field.

A common pitfall, for example, is the distinction between the quantities s_a and s_A. Although these terms have been described (e.g. Foote and Knudsen, 1994), there is no common name for the quantity s_A, notwithstanding that this is the primary output from the most common scientific echosounder, the Simrad EK500. More disturbingly, although these terms differ by a factor of $4\pi(1852)^2$ (Foote and Knudsen, 1994), such that $s_a = s_A/4\pi(1852)^2$, the Simrad EK500 instruction manual notes that ''. . . the S_a(mean) to be used for fish density calculations is $S_a(\text{mean}) = S_A/4\pi$'' (note also the incorrect use of capitalisation: S_A is used instead of s_A). The definitions depend critically on the relationships between fish density, s_a, s_A, and fish target strength but no single document exists which encompasses and defines all these terms in a complete and consistent manner.

Here, we propose a complete scheme of definitions and terminology which, hopefully, will encourage more uniform use of terms to describe measurements in fisheries-acoustics publications. The emphasis is on scattering phenomena because these are the main source of difficulty.

Primary measurements

Acoustical quantities such as the target strength are not measured directly. They are determined by numerical evaluation of a defining equation $X = f(Q_p)$ where Q_p is a set of primary quantities which can be measured directly. The equations show *inter alia* the dimensions and the units of the derived quantity in terms of primary measurements. Different Q_p might be selected for this purpose, however, to focus on scattering phenomena we start with the set listed below.

r	Distance of the measurement position from a small target. In this context, ''small'' means a target whose characteristic size is less than the radius of the first Fresnel zone, namely $\sqrt{(r\lambda/2)}$ where λ is the wavelength.
θ,φ	Spherical polar angle coordinates of the measurement position. The target is at the origin and the transmitted wave propagates in the direction (0,0).
x,y,z	Cartesian coordinates. The transmitted wave propagates towards the target in the +z direction.
I_{inc}	Intensity of the transmitted or incident wave at the target.
$I_{scat}(r,\theta,\varphi)$	Intensity of the scattered wave at the measurement position.
$I_{bs}(r)$	Intensity of the backscattered wave, equal to $I_{scat}(r, -\pi\ 0)$.
I(z)	Intensity of a plane wave as a function of distance along the propagation path.
V	Volume occupied by a scattering medium or multiple discrete targets.
A	Area of a school echo-trace observed on an echogram.

Naming conventions

The first requirement is to adopt a set of names which are unique for each quantity having a specific physical definition. Furthermore, quantities which are scaled by factors other than powers of 10 should have different names, like degrees and radians in the case of angles. Given a non-confusing and widely accepted set of names, the symbols are less of a problem, or at least those which have dimensions. In that case, SI units are the norm, with 10^n scaling factors as needed. On the other hand, it is not necessary to cover every quantity which might be expressed with non-decadal scaling. The need is to include those which are often used in fisheries acoustics in order to eliminate any risk of confusion.

Table 1 shows a list of derived quantities relevant to scattering by one or more insonified targets. We start with the intensity scattered by a small target which is normally direction-dependent. This leads to various cross-sections that describe the acoustical size in terms of the ratio of the scattered and incident intensities. Medwin and Clay (1998) prefer to start with the complex scattering length, $L(\theta,\varphi)$ which expresses phase as well as amplitude information. It is usual to consider cross-sections and scattering lengths as frequency dependent functions. Alternative models, based on time dependent functions, may be simpler and more robust. The latter could well become important as and when sonars have much wider bandwidths than current instruments.

We concur with Medwin and Clay (1998) that the name ''differential scattering cross-section'' be used to describe the scattering over all directions, measured bistatically. However, we believe the related symbol should have a functional form such as $\sigma(\theta,\varphi)$ or $\sigma(r)$, as opposed to $\Delta\sigma(\theta,\varphi)$. We prefer not to use the Δ qualifier in this context because it normally indicates a small but finite increment, whereas $\sigma(\theta,\varphi)$ is a continuous function.

It follows that other cross-sections relating to specific directions, or with no directional dependence, should have different and less general names. Their symbols should be written as σ followed by subscripts which describe the context. In the case of the ''backscattering cross-section'' (σ_{bs}), this is in line with current practice. In the case of the isotropic cross-section ($4\pi\sigma_{bs}$, which assumes no directional dependence), rather general names have been used in the past; it is often symbolised by σ with no subscripts. We feel something more specific is needed. The term ''spherical scattering cross-section'' (symbol σ_{sp}) is suggested as being appropriate to the isotropic assumption in the definition of this quantity.

In the case of multiple distributed targets volume-scattering measures are straightforward. The ''volume-backscattering coefficient'' is well understood as $s_v = \Sigma\sigma_{bs}/V$ where the sum is taken over all the discrete

Table 1. Preferred names, definitions and symbols for scattering quantities in fisheries acoustics.

Symbol	Name	Defining equation	Dimensions	Units
α	Acoustic absorption coefficient	$\alpha = 10 \log_{10} [I(z)/I(z+\Delta z)]/\Delta z$ (I measured in the absence of biological scatterers)	L^{-1}	$dB\ m^{-1}$
$\sigma(\theta,\varphi)$	Differential scattering cross-section	$\sigma(\theta,\varphi) = [r^2\ I_{scat}(r,\theta,\varphi)\ 10^{\alpha r/10}/I_{inc}]$	L^2	m^2
σ_{bs}	Backscattering cross-section	$\sigma_{bs} = [r^2\ I_{bs}(r)\ 10^{\alpha r/10}/I_{inc}]$	L^2	m^2
σ_{sp}	Spherical scattering cross-section	$\sigma_{sp} = [4\pi\ r^2\ I_{bs}(r)\ 10^{\alpha r/10}/I_{inc}]$	L^2	m^2
σ_s	Total scattering cross-section	$\sigma_s = \int_0^{2\pi} [\int_0^{\pi} \sigma(\theta,\varphi) \sin\theta\ d\theta]\ d\varphi$	L^2	m^2
σ_e	Extinction cross-section	$\sigma_e = [\Delta I(z)/\Delta z - \alpha \ln(10)/10]/[n\ I(z)]$ (I measured in the presence of biological scatterers)	L^2	m^2
σ_a	Absorption cross-section	$\sigma_a = \sigma_e - \sigma_s$	L^2	m^2
TS	Target strength	$TS = 10 \log_{10} (\sigma_{bs})$	—	dB re 1 m^2
s_v	Volume backscattering coefficient	$s_v = \Sigma\sigma_{bs}/V$	L^{-1}	m^{-1}
s_a	Area backscattering coefficient	$s_a = \int_{z1}^{z2} s_v\ dz$	—	$(m^2\ m^{-2})$
s_A	Nautical area scattering coefficient (NASC)	$s_A = 4\pi\ (1852)^2\ s_a$	—	$(m^2\ nmi^{-2})$
s_L	Line backscattering coefficient	$s_L = \int\int_A s_v\ dx\ dz$	L	m
S_v	(Mean) Volume backscattering strength (MVBS when s_v is averaged over a finite volume)	$S_v = 10 \log_{10} (s_v)$	—	dB re 1 m^{-1}
S_a	Area backscattering strength	$S_a = 10 \log_{10} (s_a)$	—	dB re $1(m^2\ m^{-2})$
S_A	Nautical area scattering strength	$S_A = 10 \log_{10} (s_A)$	—	dB re $1(m^2\ nmi^{-2})$
S_L	Line backscattering strength	$S_L = 10 \log_{10} (s_L)$	—	dB re 1 m

targets in the volume V, or $s_v = \Delta\sigma_{bs}/\Delta V$ in the case of a continuous scattering medium. The SI unit (m^{-1}) is the norm for s_v and 4π scaling is seldom if ever used. In this case, Δ is used in its correct mathematical context (cf. above).

Area scattering is more of a problem. Being dimensionless, the units of area-scattering coefficients are more difficult to express clearly when different scaling factors are applied. A naming convention is essential to distinguish the various scaled versions. By analogy with the volume case the unscaled quantity is the "area-backscattering coefficient" (s_a) which is defined as the integral of s_v over a range interval. The most commonly used scaled coefficient is denoted by the symbol s_A as implemented in the Simrad EK500 echosounder. The relevant scaling factor is $4\pi(1852)^2$; for historical reasons, the nautical mile enters the calculation (1 nmi = 1852 m). In the absence of a better idea, we have called this scaled quantity the "nautical area-scattering coefficient". That is a rather long expression, but in practice it could be contracted to the acronym NASC.

There has been much work recently on the echo statistics of fish schools (Reid, 2000). Various measures are needed for echo-trace classification purposes, in particular, a measure of the total-echo strength. Consider an echosounder on a ship running a line transect. The echogram shows a 2D section of a school as a composite over several pings. The required measure is the integral of s_v over A, the area of the section. This quantity has the dimensions of length. By analogy with the volume and area cases, we call it the "line-backscattering coefficient" for which s_L is an appropriate symbol. A is the mean echo-trace height multiplied by the length determined from the ship speed and the transit time.

All the above mentioned quantities have equivalent logarithmic versions. Many are in regular use, especially the target strength $TS = 10 \log_{10} (\sigma_{bs})$ which remains unaltered in our consistent scheme. In the case of volume, area and line scattering, the log name is simply the linear name with "strength" substituted for "coefficient". Note that expressions like "mean target strength" imply the logarithm of the averaged linear quantity, not the average of the logarithms. An important example is the "mean volume-backscattering strength" or MVBS, which is well known as 10 $\log_{10}$ [mean (s_v)].

Symbols

We suggest that the following conventions should be adopted. To a large extent they correspond to current practice.

(1) Linear measures have symbols beginning with (a) brush script "$\mathcal{L}$" for scattering lengths; (b) Greek "σ" for cross-sections; and (c) lower case Roman "s" for volume, area, and line coefficients.
(2) Logarithmic measures have symbols beginning with a capital Roman letter.
(3) The final subscript letters, the case is immaterial, indicate the context, e.g. bs for backscattering. They are not normally relevant to the particular quantity or the units of measurement.
(4) In the case of area scattering only the subscript case is significant. s_a and s_A refer to the area-backscattering coefficient and the NASC, respectively. This convention has been adopted to conform to current practice and to be consistent with the vast amount of archived historical data.

Biomass estimation

Perhaps the most important application of acoustics in fisheries research is the estimation of the density or abundance of biological targets. It is essential to be clear about the formulas used to convert the acoustical measurements to biological quantities. Consider the simple example of a layer between depths z_1 and z_2 below the transducer. ρ_a is the density of targets expressed as the number per unit surface area of the layer. ρ_a is proportional to s_a and inversely proportional to $\langle\sigma_{bs}\rangle$, the expected backscattering cross-section of one target. $\langle\sigma_{bs}\rangle$ is so written to denote an expected value rather than a mean, since it is determined indirectly from the size distribution of fished samples and empirical equations relating the target strength to fish length. Equivalent formulations may be written in terms of s_a or s_A, $\langle\sigma_{bs}\rangle$ or $\langle\sigma_{sp}\rangle$ with the appropriate scaling factor. Some examples are, with the units of ρ_a in square brackets:

$$\rho_a = s_a/\langle\sigma_{bs}\rangle \ [\mathrm{m}^{-2}]$$

$$\rho_a = 10^6\ s_a/\langle\sigma_{bs}\rangle \ [\mathrm{km}^{-2}]$$

$$\rho_a = s_A/\{4\pi\ \langle\sigma_{bs}\rangle\} = s_A/\langle\sigma_{sp}\rangle \ [\mathrm{nmi}^{-2}]$$

In practice, it is the last of these equations which is the most important as it includes the quantity (s_A) that is output from the principal instrument used in fisheries acoustics (the Simrad EK500), and the backscattering cross-section (σ_{bs}) which is derived from the well known target strength (TS).

Discussion and conclusions

The names proposed for key quantities relevant to fisheries acoustics, together with their definitions and suggested symbols are summarised in Table 1. The list in Table 1 is not intended to be exhaustive. The need is to include those which frequently appear in the literature pertaining to fisheries acoustics. We have incorporated common formulations from related fields as far as is practicable. Thus the absorption coefficient, α (dB m^{-1}), has been used in preference to β (nepers m^{-1}) so that our definitions correspond to those recognised by acoustical oceanographers (Medwin and Clay, 1998).

As is the normal practice in physical descriptions names should be chosen to avoid confusion between different quantities and, in each case, the quantity is defined by an equation which shows how it is determined from primary measurements. The units and dimensions follow from those of the quantities in the defining equation. SI units are normally adopted as is generally required in formal publications. It is necessary to allow for non-SI units in a few cases; in particular when a non-SI unit is needed to conform to current practice in the field.

While the scheme presented here is not the only one that might be considered, it has been commended by the Working Group on Fisheries Acoustics Science and Technology (WGFAST) of the International Council for the Exploration of the Sea (ICES), as a consistent approach to better communication standards in fisheries acoustics. As such it should help to prevent some of the common pitfalls which beleaguer fisheries scientists when negotiating the tricky waters of the largely "engineering science" of fisheries acoustics.

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