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BIAS AND PRECISION IN ACOUSTIC BIOMASS ESTIMATION

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INTRODUCTION

The aim of an acoustic survey is to estimate biomass and its distribution. Accuracy in this estimation is one of the most important aspects. However, it remains insufficiently well studied. There is widespread opinion that a bias in calibrating or determining mean target strength leads to a corresponding bias in biomass estimate[1]. Confidence intervals are not always calculated and the methods of computing do not take into account all necessary factors. Specialists differ in opinion about methods of collecting and processing data on fish density along tracks. For this reason the problem of accuracy in biomass estimation relates to the most disputable matters. This paper is a contribution to this discussion.

ACCURACY OF DENSITY ESTIMATE

Let us assume that a survey is carried out with a calibrated echo-sounder and echo-integrator. If the echo-sounder TVG is 20 logR + 2αR surface density is calculated by integrator reading M:

$$\rho_s = CM \qquad (1)$$

where C is integrator scale factor[2].

$$C = \frac{3.43 \cdot W}{C_{ea}\ K_\alpha \cdot \frac{\nu}{4\pi} \cdot \psi} \qquad (2)$$

where W is mass of a single object (g);

- C_{ea} - electroacoustic constant of the equipment;
- ν - acoustic cross-section of the object;
- K_α - extra sound attenuation coefficient;
- ψ - equivalent beam angle.

The accuracy of estimating ρ_s is affected by many factors which can be divided into two groups: factors related to the equipment, and to the object and environment. The former include errors of the equipment and its calibration. Errors in determining ν, K_α and α in the formula of the TVG law belong to the second group of errors. This group also includes errors caused by changes in fish behaviour under the effect of ship noise. Errors are divided into systematic biases and random errors. Below it will be shown how systematic and random errors are summarized. But first let us consider their source and levels.

The equipment errors will be estimated in relation to the equipment including echo-sounder Sargan (20 and 136 kHz), precision TVG amplifier USOD and digital echo-integrator SIORS used in echometric surveys in the USSR[3]. Measuring shows that instability is random and does not exceed 3% (mse). The total SIORS error of integration is about 5%. The main contributions are detector non-linearity and the error of A/D conversion at low levels. The TVG error also relates to equipment errors. The USOD amplifier allows the operator to set the attenuation coefficient α in the TVG law 20 logR + $2\alpha R$. The value α depends on operating frequency, and the temperature and salinity of sea water. These values can change (even at one frequency) several times which causes a corresponding bias of 3-5 dB. If mean temperature and salinity in TVG range are known from hydrological data with an accuracy of up to 0.1° and 1 ppt, the error in determining the required TVG law is 0.1-0.2 dB (2-4%). The TVG law set by the operator works with an error not exceeding ±0.4 (10%) at any point (maximum value). It should be noted that both errors are of a systematic character and therefore can be reduced if the accuracy of determining α is raised and if corresponding biases are compensated for after the real TVG has been measured. In this case with the use of a computer it is possible to decrease the TVG error up to ±0.2 dB (4%).

The error of equipment calibration with a standard sphere is estimated as 0.5 dB[4] and is of a systematic character connected with sphere declination from the transducer axis. For narrow beam transducers the calibration error increases and exceeds 1 dB (26%). The value of the equivalent beam angle for standard transducers is usually given by the manufacturer. However, the measurements of the two standard transducers of the Sargan echo-sounder show a standard deviation from the mean value ψ for this series of 16% at 20 Hz, 18% with a wide diagram (4°) at 136 Hz and 28% with a narrow diagram (2°)[5].

Reference[6] shows that for a standard transducer installed in the hull ψ decreases up to 1.5 dB (41%). Therefore the most accurate method of determining ψ is to calculate it by a measured directivity diagram of a transducer installed in the hull. If the diagram is measured with the help of a sphere or a hydrophone with ±1° accuracy the random error of determining ψ is 14%. If it is impossible to measure the real diagram of an actual transducer, it is necessary to calculate ψ by typical diagram, or use the data of the manufacturer. However the possible random error in this case may reach 20% and more.

Errors related to the object and environment

Extra sound attenuation is caused by the aeration of the near-surface layer due to the wind, waves and ship movements. Coefficient K_α takes into account this attenuation which greatly depends on frequency as well as on the vessel type and the place of installation of the transducer. Experimental studies with special equipment allowed the dependence of K_α on wind speed at different frequencies to be determined[7]. These data are in accordance with the measurements from two vessels of different displacement made by Norwegian scientists[8]. The analysis of the data has shown that deviation of K_α for both vessels does not exceed 0.5 dB (±12%). This value is taken as the systematic error in estimating K_α.

The error of measuring target strength is made up of many components. By substituting value ψ in formula (1) we average it by a number of parameters: size and species, aspects of insonification, slope and physiological state. These factors may greatly vary therefore it is reasonable that target strength be measured *in situ*. Let us assume that such measurements are made by the most precise "direct" methods (dual-beam or split-beam methods). In this case the distribution obtained (histogram) allows the mean value and its dispersion to be determined. When measuring target strength the equipment is calibrated by a standard sphere. With an accuracy of measuring target strength in relation to the sphere equal to the accuracy of calibration (0.5 dB), the error of estimating mean target strength will be 1 dB.

Comparative measurements of the target strength of walleye pollack by dual-beam and split-beam methods in combination with fishing have shown difference in mean target strength to be 0.5-0.6 dB[7]. The target strength measurements of live gadoids gave results close to the above figures - deviation of mean target strength was about 0.6 dB. Thus, the bias of measuring the target strength of gadoids *in situ* can be taken as 0.6 dB although factors related to fish behaviour are disregarded in this case.

Underwater observations have shown that freely swimming unscared fish are characterized by the normal law of tilt distribution with mean deviation of 0° ÷ -4° and standard deviation of 5° ÷ 15°[7]. Another serious source of bias is fish avoiding the ship which causes a decrease in density and variation in tilt. The latter depends on fish schools, depth and the main engine power. Measurements show that the error of estimating target strength may vary from 0 to -5 dB as depth decreases from 100 to 20 m with a ship of 300 tons displacement and from -1.25 dB to -13 dB for the same depth with a ship of 1500 tons displacement[9].

The physiological state of fish considerably affects their target strength. Thus, the volume, shape and pressure in the swimbladder as well as fatness, state of gonads and stomach contents may cause changes in target strength from 2-5 dB[10]. Measurements *in situ* by "direct" methods during the survey ensure the least bias in mean target strength ~1 dB. Without measurements *in situ*, when target strength is calculated by known regression dependences for the given species, the error increases: for the well-studied gadoids it is up to 1.3 dB for other species up to 2 dB and more. With changes in behaviour and physiological state of fish and their avoiding the ship at shallow depths the bias reaches 5 dB and more. Along with biases there are random errors in target strength measuring. They are caused by changes in target strength of different fish depending on their length, physiological state, insonification aspect and so on. These errors can be estimated (unlike biases) by target strength distributions. It is an accepted fact that this distribution reflects size composition of measured fish. In reality target strength is also affected by other factors which widen the distribution. The effect of these factors can be taken into account through dispersion determined by measuring distribution of target strength when calculating density confidence intervals (see below). Table I shows the above factors causing errors in estimating density. Two variants of error values are considered: minimum (estimate from below) and a more real one. In both cases we assume that the effect of the behaviour and physiological state of fish is taken into account in the target strength measurements. Let us try to estimate the total error of estimating density with allowance for these factors.

Table I Components of error in estimating density

No.	Source of error	Value of systematic error %/dB		Value of random error %/dB	
		Variant I	Variant II	Variant I	Variant II
1	2	3	4	5	6
1.	Instability of emission and reception tracks			3/0.26	3/0.26
2.	Total error of integrator			5/0.4	5/0.4
3.	Inaccuracy in determining echo attenuation coefficient α	5/0.2	5/0.2		
4.	Errors in TVG	10/0.4	10/0.4		
5.	Calibration by sphere	12/0.5	26/1.0		
6.	Determination of equivalent beam angle ψ			14/0.57	20/0.8
7.	Determination of extra sound attenuation coefficient K_α	12/0.5	12/0.5		
8.	Estimation of mean target strength	26/1.0	41/1.5		
TOTAL ERROR		65/2.17	94/2.88	15.2/0.61	20.8/0.82

When estimating the total error, it is more correct to summarize separately systematic and random errors with allowance for their PDF. Unlike random errors, systematic errors do not decrease in multiple measuring of the same process. Detecting and estimating systematic errors require special studies. Let us accept the uniform PDF for systematic errors and the normal PDF for random ones. Though the nature of the law of systematic errors distribution is often unknown, the assumption of its uniformity is close to the physical picture of phenomena. Besides, the uniform PDF suggests the worse case of distribution, i.e. the estimate from above. The values of systematic errors cited in Table I correspond to maximum values and those of random values to mse. The summing up of systematic errors is made arithmetically. For random errors variances are added up. Proceeding from the total errors cited in Table I it is possible to calculate confidence intervals.

Assuming that systematic and random errors are statistically independent, it is possible to determine the variance of the total error as

$$\sigma_\Sigma^2 = \sigma_G^2 + \sigma_u^2 = \sigma_G^2 + \frac{1}{2b}\int_{-b}^{b} x^2 \cdot d_x = \sigma_G^2 + b^2/3$$

where σ_G^2, σ_u^2 are variances of normal (Gaussian) and uniform distribution;
$2b$ = range of uniform distribution.

The distribution of summary error is the convolution of the components. Therefore

$$W_\Sigma(y) = W_G{\cdot}W_u = \frac{1}{2b}\left[\Phi\left(\frac{b-y}{\sigma_G}\right) - \Phi\left(\frac{-b-y}{\sigma_u}\right)\right] \qquad (4)$$

where $W(y)$ is PDF of summary distribution;
Φ = probability integral.

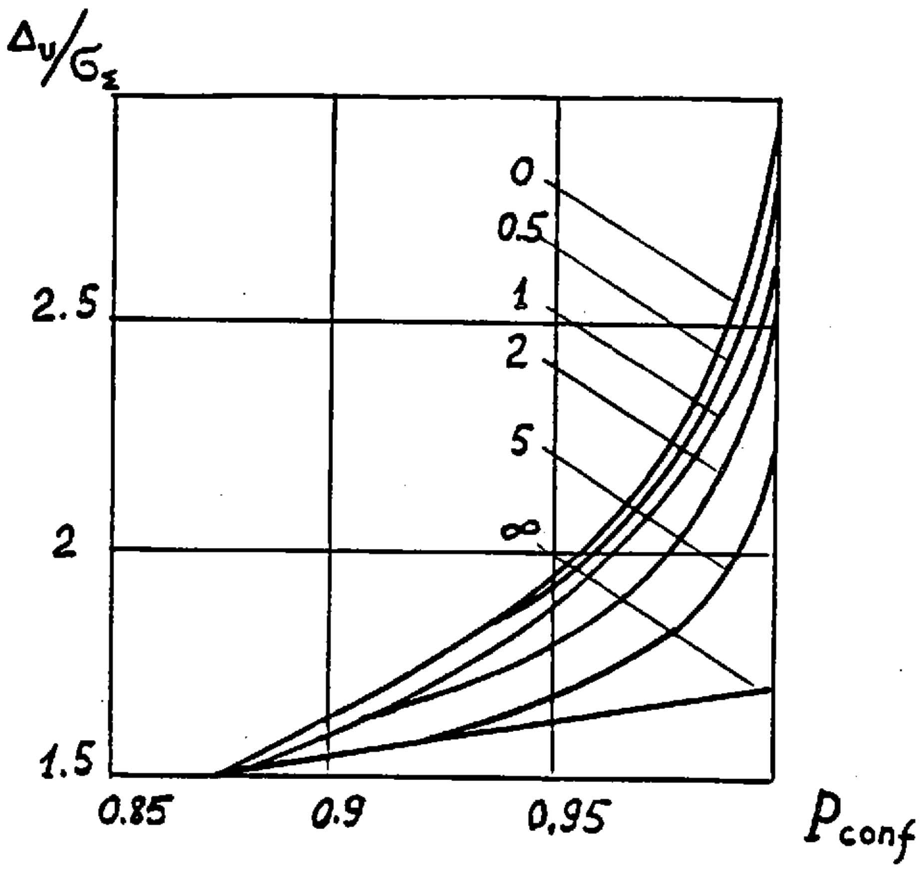

Figure 1 The limits of a confidence interval with summarized errors of normal and uniform distributions. Parameter $\beta = \frac{b}{\sqrt{3}\sigma_G}$.

Hence it is easy to calculate confidence intervals. Figure 1 shows the results of the calculations[11]. The parameter of the curves is value

$$\beta = \sigma_u/\sigma_G = \frac{b}{\sqrt{3}\,\sigma_G}.$$

With $\beta = 0$ the systematic error is absent and the ratio of a confidence interval to the standard deviation corresponds to the normal law (with $P_{conf.} = 0.95$ $\Delta_u/\sigma_\Sigma = 1.96$). With $\beta = \infty$ the random component is absent. In our case we obtain for both variants $\beta_I = 1.23$ and $\beta_{II} = 1.3$. Respectively, for a 95% probability the upper border of the interval is $\Delta_{upI} = 0.446$; $\Delta_{upII} = 0.61$. Thus, the effect of systematic and random errors tells on the widening of mean density confidence intervals. However, besides the considered errors, these confidence intervals are affected by variation in target strength. As known, integrator readings are proportional to back-scattering volume, i.e.

$$M = K\rho_v\nu = \frac{K}{\Delta R}\,\rho_s\nu = K_I\,\rho_s\nu \qquad (5)$$

where K_I, K are constants, ρ_v - volume density, ΔR - layer of integration. Assuming that ρ_s and ν are random values with variances σ_ρ^2 and σ_ν^2 we obtain the following expression for the variance of integrator readings:

$$\sigma_M^2 = K_1\left(\bar{\rho}_s^{\,2}\,\sigma_\nu^2 + \bar{\nu}^2\,\sigma_\rho^2 + 2\bar{\rho}_s\,\bar{\nu}\,\sigma_\rho\,\sigma_\nu\,\tau_{\rho\nu}\right) \qquad (6)$$

where $\tau_{\rho\nu}$ is correlation coefficient between density of fish and their cross-section. Value $\tau_{\rho\nu}$ can be estimated on the basis of data from[12]. For nine species of fish of 2.3 to 75.6 cm mean length the correlation coefficient proves equal to $\tau_{\rho\nu} = -0.345$. The negative value is evidence of decreasing density with increasing length and acoustic cross-section, which agrees with the common idea of fish distribution. However, in real surveys concentrations with a large range of size of different fish species rarely occur. Most often variations in density are mainly connected with behaviour, environment, fishing effect and other factors.

Evidently, value $\tau_{\rho\nu}$ is usually far less and in most cases the last term in formula (6) can be ignored. From formula (6) it follows that dispersion of integrator readings includes not only density variations, but also depends on mean target strength and its variance. Density measured by integrator readings is a random value. It can be characterized by mean value and dispersion. Density variance includes the above systematic and random measuring errors, and variations of density and target strength in concentrations. To differentiate the contribution of each factor to total variance is practically impossible. It is recommended to calculate confidence intervals of biomass estimation which is the ultimate aim of the survey. However, the present-day techniques of integrating signals for a series of soundings does not allow density variance to be correctly calculated. Besides, in calculating density, target strength variations are not taken into account, though this has been suggested before[13]. Integrator readings for a distance unit (ESDU) are a summary value by which it is possible to calculate mean density, but not its variance.

In our opinion it is time to give up integration for ESDU and come over to taking integrator readings for each sounding and calculating distribution of these values (histograms). This distribution should be used in calculating mean integrator readings $\bar{M}$ and their variance σ_M^2. The <u>in situ</u> measured distribution of target strength makes it possible to determine mean target strength and its variance which allows mean density and its variance to be calculated. These values should be used for calculating biomass estimate and its confidence intervals.

Accuracy of biomass estimation

If the bias in biomass estimation due to incompletely surveying the area is absent, the precision of estimate depends on the volume of sampling, i.e. the number of transects. In this case the precision is determined by confidence intervals of biomass estimate. As a serial correlation of data underestimates the actual variance, different methods of taking it into account have been suggested, among which the method of cluster sampling gives the best results[14]. Besides, all the existing methods of data processing are based only on integrator readings of ESDU (from 1 up to 10 and more miles depending on the scale of survey) which are mean values for a large number of soundings. The variances of these values are not taken into account because of which the actual precision of biomass estimate is considerably distorted. To obtain reliable values of confidence intervals it is necessary to change the technique of collecting and processing data in echo survey.

Integration of echo-signals for an ESDU should be substituted by integration for one sounding. The value of integral M_1 should be memorized for subsequent processing. This consists of a histogram of values M_1 plotted for the required distance by which are calculated mean $\bar{M}_1$ and variance σ_M^2. Value $\bar{\rho}_s$ is calculated by the usual way - by formulas (1) and (2). By measured target strength $\bar{\nu}$ and σ_ν^2 are calculated. After that σ_ρ^2 is computed by formula (6). If the size distribution of fish in the surveyed concentration varies within a small range (1.5-2.0 times), correlation coefficient $\tau_{\rho\nu}$ in formula (6) can be assumed ≈ 0. With considerable differences in the size composition $\tau_{\rho\nu}$ should be taken equal to $-(0.2 \div 0.3)$.

Autocorrelation of integrator readings may considerably alter variance σ_M^2. Therefore to exclude acoustic beam overlaps the integrator readings should be taken regularly for several soundings (depending on speed, frequency and integration layer depth). The degree of data correlation should be estimated by calculating the autocorrelation function of memorized values M_1. If correlation is great the computing of σ_M^2 should be carried out with the use of the method of cluster sampling. After that σ_ρ is calculated by corrected value σ_M^2.

σ_ρ is used to calculate confidence intervals of mean density estimate. It should be emphasized that calculated confidence intervals may be asymmetric. The upper interval $\Delta_{up} = \gamma_{up}\,(P_{conf})$, the lower $\Delta_\ell = \gamma_\ell\, P_{(conf)}$ where γ_{up} and γ_ℓ are coefficients determined by PDF.

For normal distribution

$$\gamma_G(P_{conf}) = \gamma_{upG} = \gamma_{\ell G} = \Phi^{-1}\left(1 - \frac{\varepsilon}{2}\right) \tag{7}$$

where Φ^{-1} is inverse function of probability integral. Asymmetric distributions can be described by coefficients of skewness K_{sc} and curtosis K_{cu}. If K_{sc} is different from 0, the length of the confidence interval hardly changes but the interval shifts[11].

$$\gamma_{sc_{up}} = \gamma_G(P_{conf}) + C_{sc}[\gamma_G(P_{conf})]K_{sc} \qquad (8)$$

where dependence $C_{sc}(\gamma_G)$ is shown in Figure 2.

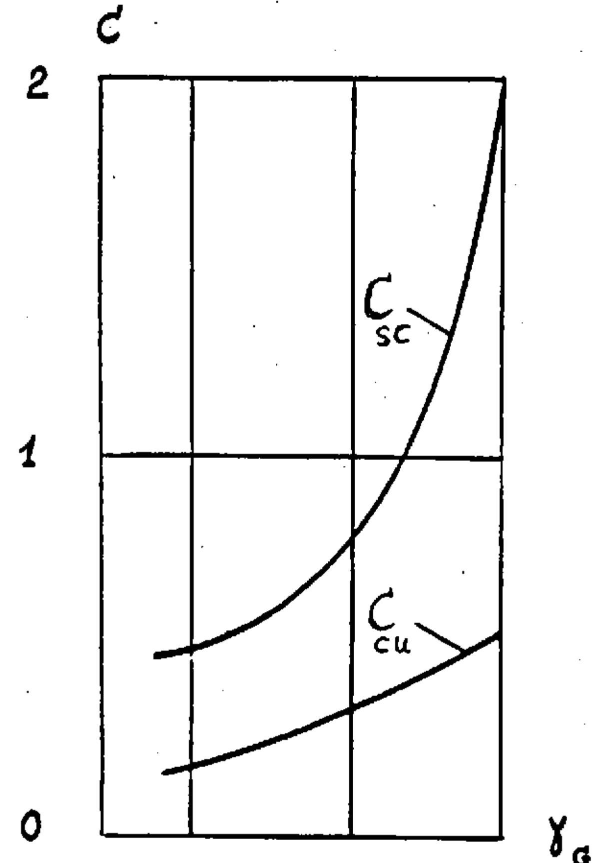

Figure 2 Proportion coefficients in confidence intervals for distributions different from normal distributions.

If $K_{cu} > 0$, the confidence interval is widened as compared with normal distribution. If $K_{cu} < 0$, it becomes narrow:

$$\gamma_{cuup} = \gamma_G(P_{conf}) + C_{cu}[\gamma_G(P_{conf})]K_{cu}$$

where dependence $C_{cu}(\gamma)$ is shown in Figure 2.

Thus, after computing K_{sc} and K_{cu} we can plot real confidence intervals of mean density estimate and then calculate confidence intervals of biomass estimate B:

$$\Delta_{Bup} = \gamma_{up}\, \sigma_{\rho s}\, (\bar{\rho}_s A); \quad \Delta_{\beta \ell} = \gamma_{\ell} \sigma_{\rho s} (\bar{\rho}_s A) \qquad (9)$$

where A is the area where mean density $\bar{\rho}_s$ is calculated. The choice of this area is determined by several factors. As a rule by the results of survey it is necessary to determine the biomass and strength of size groups of the concentration. Therefore the choice of the area is connected with changes in size distribution of fish which can be determined by catches or by measuring target strength *in situ*. Another factor is natural and artificial borders (for instance, economic zones) of the surveyed concentration, as well as statistical regions of fisheries. And, finally, distance between transects. In the most simple case of regular parallel transects the width of the area is equal to distance between transects and the length is equal to the length of these transects. It should be noted that here we do not consider questions pertinent to the survey design and precision of biomass estimation depending on distance between transects (see, for instance, [15]).

After calculating biomass with confidence intervals for each area, it is possible to calculate summary biomass for each size group. Confidence intervals of total biomass are calculated by summing up standard deviations separately for upper and lower intervals. It should be noted that mapping of biomass distribution can be made by the usual methods through mean values $\bar{M}_1$.

CONCLUSION

1. The difference in nature of random and systematic errors with their PDF when summed up decrease precision of mean density which can be estimated by confidence intervals. The main contribution is made by errors of calibration and target strength measurements.

2. The standard method of integrator reading for a distance unit does not take into account variance of density which alters confidence intervals. Readings should be taken and memorized for one sounding (but not for each). After that it is necessary to plot their distribution and compute mean value, variance and other statistical parameters. Calculations of variance should be made with allowance for auto-correlation of data along a transect.

3. When calculating confidence intervals of mean density, variance of target strength distribution should be taken into account. Therefore during a survey target strength *in situ* should be measured more often.

4. Asymmetry of integrator readings distribution is the cause of changes in confidence intervals. They can be calculated with the help of skewness and curtosis coefficients.

5. The suggested changes in data collecting and processing techniques complicate this process but provide real precision of biomass estimate.

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