ANALYSIS AND IMPLEMENTATION OF HYDROACOUSTIC METHODS
FOR ESTIMATION OF HIGH DENSITIES OF FISH IN SEA PENS

A. STEPNOWSKI

Technical University of Gdańsk, Department of Electronics
(80-952 Gdańsk)

The paper presents the feasibility study of different acoustic methods with reference to system design, capable of estimating high density of fish, e.g. in aquaculture facilities. The velocity, attenuation and backscattering measurement methods are critically examined. The new, recursive echo integration method is introduced, which accounts for attenuation loss by dense collections of fish. The proposed implementation of this estimation technique employs the modified design of a dual-beam sonar-system ECOLOG II. The system provides the real-time absolute estimates of fish density in sea pens.

1. Introduction

The dynamically developing fish farming industry in recent years is in real need of new methods and techniques to estimate the number or biomass of fish in sea pens. In addition, the monitoring of these encaged fish spatial distribution patterns and their behaviour is also required. The newly introduced estimation techniques should provide quick and reliable data with high acuracy [1], [2]. Therefore the main objective of this paper is twofold. The first is to investigate the feasibility of hydroacoustic methods for quantitative estimation of dense fish populations in the sea pens. The second, is to develop a hydroacoustic system, capable of producing rapid and reliable estimates of the number density of the encaged fish concentrations. The proposed system design would have to materialize the results of the feasibility study and utilize the recent advances in new VLSI technology and digital signal processing techniques of the modern fisheries research sonar systems [3], [4].

The current methods of hydroacoustic fisheries assessment assume no acoustic inter-actions between insonified fish, i.e. first-order single scattering (FOSS) approximation is assumed. This implies that the received echo signal is directly proportional to the number (and size) of fish insonified at a corresponding depth, and independent of the number of fish in the sound beam at intermediate depth [5]. This can be a reasonable assumption when the collection of fish is neither dense nor of a large extent in the direction of sonar transmission. The most common acoustic technique which has been successfully used to quantify fish stocks in oceans and lakes is, at present, the echo integration technique (EIT). It is based on a single scattering approximation and a linear relationship between

the integrated echo intensity and the density of fish N_v in a volume sampled by the sonar transmit pulse. The echo integration technique depends only upon the backscattering characteristics of fish targets, determined in terms of their backscattering cross section σ_{bs} or, more generally, of their volume backscattering strength $S_v = 10 \log \sigma_{bs} + 10 \log N_v$ [5], [6].

In those situations where high-density aggregations of fish are encountered (e.g., sea pens or dense schools), the FOSS approximation is no longer valid; excessive sound attenuation, and possibly multiple scattering also, may significantly reduce the backscattering from the deeper parts of the fish collection. Consequently, due to such "shadowing effects", the density estimates obtained from an echo integration may be remarkably biased — usually underestimated [7], [8][1].

Therefore the development of the hydroacoustic assessment technique, adequate for estimating the high density of fish in sea pens, must be preceded by the introduction of a more complete model of scattering and associated effects. Additionally, alternative approaches based on the measurement of acoustical magnitudes different from backscatter which could provide data for the calculation of fish density estimates, should also be examined.

2. Analysis of acoustical methods for fish density estimation

Basically there are three methods allowing at least potentially to obtain acoustical estimates of the high density of fish in sea pens. These methods utilize the measurement of sound velocity, sound attenuation and sound backscattering.

2.1. Sound velocity measurement for fish density estimation

The sound velocity can be a very important and useful signature of the medium characteristics. Its measurements are used concurrently with other acoustical magnitudes in various applications of which acoustical tomography is probably most spectacular. Although this measurement does not seem very promising for the considered application, it will be shortly examined in order to be sure that any potentially possible method has not been neglected.

When a sound wave travels through water and strikes "bubble-like" targets (e.g. swimbladder of fish) of markedly different density and compressibility than seawater, the resonance response may occur. The resonating target may be viewed as intercepting a portion of the exciting sound wave characterized by the extinction cross section, and reradiating it as scattered sound in all directions as well as absorbing by converting it into heat. In addition, "bubble-like" targets change the compressibility of the water and cause the phase speed of sound to be a function of frequency. In the vicinity of resonance the sound velocity may be altered remarkably if the bubble concentration is high enough. When the bubbles are much smaller or much larger than the resonant size, the effect is not so profound.

---

[1] It should be noted, however, that under certain conditions high extinction cross section and a low absorption cross section of scatterers, the multiple, or more precisely second-order scattering, may increase the backscattered echo energy an appreciable amount above that expected by the FOSS theory alone [9].

The equation of an acoustic plane wave propagating through a bubbly medium can be written as

$$p(t, r) = P_i \exp[j(\omega t - kr)] =$$
$$= P_i \exp(-k_{im}r) \exp[j(\omega t - k_{re}r)] \tag{1}$$

where: P_i — amplitude of the sound pressure, $k = \frac{\omega}{c} = k_{re} - jk_{im}$ the complex propagation constant.

The imaginary part k_{im} of the complex propagation constant represents the excess attenuation of the wave through the bubbly region, while the real part k_{re} is the wave number for the propagation of constant phase surfaces. The ratio ω/k_{re} is the phase velocity of the sound wave in a bubbly medium. It is a function of frequency and the medium is said to be dispersive [9]:

$$c = \omega/k_{re} = c_0 \left[1 - \frac{2\pi a N c_0^2}{\omega^2} \frac{(\omega_r/\omega)^2 - 1}{[(\omega_r/\omega)^2 - 1]^2 + \delta^2]} \right] \tag{2}$$

where c_0 speed of sound through the bubble-free water, N — number of bubbles per unit volume (numbers density), a — equivalent average radius of a bubble, ω_r resonance frequency, δ — damping constant.
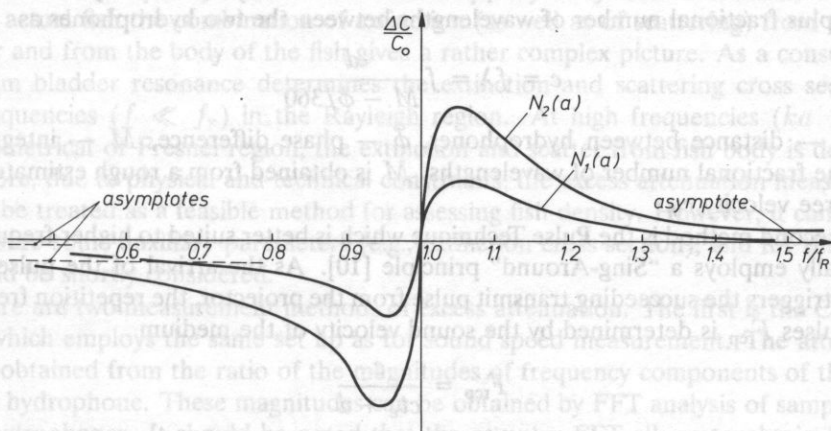

FIG. 1. Fractional change in sound velocity for two different bubble densities $N_2 > N_1$.

The fractional change in phase velocity $\Delta c/c_0$ derived from Eq. (2), for bubbles of uniform size and two different densities N is shown in Fig. 1. As it is seen from dispersion curves, the change in velocity is proportional to N. The velocity passes through the c_0 value at the resonance frequency. The high frequency asymptote is zero and the low frequency asymptote is proportional to the fraction of gas in bubble form $V = 4/3\pi a^3 N$. Any significant changes of sound velocity occur only in the resonant region, while well beyond the resonance (which is most likely the range of feasible measurement) the relative changes of velocity are too small for accurate measurement.

The resonance frequency of our "bubble of interest" (fish swim bladder) f_r can be obtained from a simplified formula [9]:

$$f_r = \frac{1}{2\pi a'} \left(\frac{3\gamma P^{1/2}}{\rho} \right) = \tag{3}$$

where: γ — ratio of specific heats of bladder gas ($\gamma = 1.4$ for air), P ambient pressure, $P = 105(1 + 0.1z)$, where z is depth [m], ρ density of sea water ($\rho = 1035\text{kg}/\text{m}^3$), a' — equivalent radius of a swim bladder, $a' = (3 \text{ bladder volume } /4\pi)^{1/3}$.

For fish size of commercial interest (20–100 cm), the bladder representing about 5% of the animal volume has its equivalent radius ranging from 0.3 to 3 cm. It gives a range of resonance frequencies from 0.1 to 1 kHz. Unfortunately, it is rather difficult to provide the efficient transmission of underwater sound at such low frequencies. Thus, as a consequence, there are two different kinds of constraints: poor sensitivity or accuracy for high frequency measurement and technical limitations for low frequency measurement. Despite this rather not optimistic conclusion, there are two existing methods of sound speed measurement which should be reported as feasible but have rather limited applicability for the extraction of fish density data.

The first method is the CW Phase Measurement Technique which is best suited for lower frequencies [9]. It requires only a sound projector and two hydrophones separated by a fixed and known distance. The speed of sound is easily obtained by measuring the integral plus fractional number of wavelengths between the two hydrophones as

$$c = f\lambda = f\frac{d}{M - \phi/360} \tag{4}$$

where d — distance between hydrophones, ϕ — phase difference, M — integral and $\phi/360$ the fractional number of wavelengths. M is obtained from a rough estimate of the bubble-free velocity c_0.

The second method is the Pulse Technique which is better suited to higher frequencies, and usually employs a "Sing-Around" principle [10]. As the arrival of the pulse at the receiver triggers the succeeding transmit pulse from the projector, the repetition frequency of the pulses F_{rep} is determined by the sound velocity of the medium

$$F_{rep} = \frac{c}{ct_e + d} \tag{5}$$

where d — distance between the projector and receiver hydrophone, t_e — sum of the electrical delay and time lost in the pulse front growing above the noise threshold.

The resulting pulse repetition frequency can be measured by the frequency counter connected to the "Sing-Around" loop, and t_e and d are obtained by direct calibration in a medium of known sound speed.

2.2. Sound attenuation measurement

The presence of bubble-like targets at sea, in addition to scattering, introduces also excess attenuation of acoustic waves[2] which, when properly measured and scalled, can also

---

[2] The term "excess" is used purposely to differentiate the effect introduced by the targets from „common" attenuation in the sea which is due to shear viscosity and molecular relaxation processes in the medium [10].

be used as a signature of the targets numbers density. Let us consider the aggregation of bubble-like targets (fish) of uniform size and assume that the targets are apart far enough to neglect interaction effects (multiple scattering)[3]. Then the excess attenuation per unit distance can be written as [10]:

$$\alpha_e = -\Delta SPL/x = 4.34\sigma_e N_v \tag{6}$$

where: σ_e — extinction cross section of the target, N_v — number of targets per unit volume, x distance traversed by the sound wave, $\Delta SPL = 20\log p(x)/p_1$ loss in sound pressure level over a distance x, p_i incident sound pressure.

If a population of targets has some size distribution function $n(a)$ and the number of targets per unit volume with sizes between a and $a + da$ is denoted by $n(a)da$, the effective extinction cross section

$$S_e = \int \sigma_e n(a)\, da \tag{7}$$

replaces the product $\sigma_e N_v$ in the formula (6) when attenuation due to a random mixture of bubble-like targets has to be obtained [10].

The estimates of bubble-like target density can be obtained from the excess attenuation measurement if the extinction cross section of bubbles is known or can be measured. Like the scattering and absorption cross sections, the extinction cross section has a maximum at the resonant frequency and falls off with frequency away from resonance. However, for the actual fish the combination of extinction (as well as of scattering) from the swim bladder and from the body of the fish gives a rather complex picture. As a consequence, the swim bladder resonance determines the extinction and scattering cross sections at low frequencies ($f \ll f_r$) in the Rayleigh region. At high frequencies ($ka > 1$), in the geometrical or Fresnel region, the extinction and scatter from fish body is dominant. Therefore, due to physical and technical constraints, the excess attenuation measurement cannot be treated as a feasible method for assessing fish density. However, it can be used to measure some auxiliary parameters (e.g., extinction cross section), and for this reason it should be shortly considered.

There are two measurement methods of excess attenuation. The first is the CW Technique which employs the same set up as for sound speed measurement. The attenuation can be obtained from the ratio of the magnitudes of frequency components of the signal at each hydrophone. These magnitudes can be obtained by FFT analysis of sampled data from hydrophones. It should be noted that the complex FFT allows to obtain from the same data the phase difference, what yields the sound velocity [9].

The second method is the Pulse Echo Technique which allows to obtain the excess attenuation introduced by an aggregation of fish, by measuring the variations of echo level, received from the special reference target, of known target strength (TS). If the sonar system used for measurement is calibrated acoustically (i.e., its source level (SL) and receiver sensitivity (SR) are known), then the echo level (EL) measurement allows, by the sonar equation, to obtain the entire two-way transmission loss ($2TL$)

$$EL = SL + SR + TS - 2TL \tag{8}$$

---

[3] Efectively this will be valid if the packing density of targets is so low that the separation is greater than the wavelength λ of the impinging sound wave, or alternatively greater than the square root of the extinction cross section σ_e of the target [10].

where $2TL$ includes two-way transmission loss of the medium combined with two-way excess attenuation of the fish aggregation:

$$2TL = 40\log(R_s/R_1) + 2\alpha(R_s - R_1) + 2\alpha_e(R_s - R_1) \qquad (9)$$

where R_s is the range of reference target, $R_1 = 1m$, and α is the attenuation coefficient of sound in the sea. As all other parameters but excess attenuation coefficient α_e are known, this can be easily extracted from Eqs. (8) and (9).

An alternative option in estimating α_e might be to make a similar measurement of the standard targer echo level twice: in the presence (EL_2) and in the absence (EL_1) of a fish aggregation. In such a case, the estimate of α_e can be easily derived from the increment $\Delta EL = EL_2 - EL_1$. This option does not require acoustic calibration of the sonar system.

2.3. Sound backscattering measurement — Echo Integration Technique

The sound backscattering measurement is the most common method of hydroacoustic assessment of fish density, especially when it is implemented as an echo integration technique (EIT). Skipping the details for incoherent addition of the individual fish echoes, the backscattered echo intensity due to the collection of randomly distributed fish scatterers, received from a shell volume at range R, can be written as [2]:

$$I_{(R)} = I_0 10^{-0.2\alpha R} \cdot R^{-2}(c\tau/2)\sigma_{bs}N_v b_{eq}^2 \qquad (10)$$

where: $I_0 = I_1 10^{0.1SL}$ — incident intensity, W/m^2, R — range to sonar transducer, m, $10^{-0.2\alpha R}R^{-2}$ antilog of two-way transmission loss $2TL$, σ_{bs} — mean backscattering cross section of fish, m^2, N_v — average number of fish per unit volume, m^{-3} $b_{eq}^2 = \int_{\Omega} b^2(\theta, \phi)\,d\Omega$ equivalent two-way beam width (mean squared beam pattern factor), $b(\theta, \phi)$ beam pattern of sonar transducer, $d\Omega = \sin\theta\,d\theta\,d\phi$ — elemental solid angle, srd; τ — pulse length, s; c — speed wave of sound wave in sea water, m/s; I_1 — reference intensity, W/m^2.

The corresponding echo envelope squared voltage, at the output of the sonar receiver, can then be written as

$$V_{(R)}^2 = I_{(R)}s_r^2 g_{TVG(R)}^2 \qquad (11)$$

where: $s_r = s_1 10^{0.1(SRT+G)}$ receiving sensitivity, V/Pa, G — constant gain of the receiver, dB, SRT — sensitivity of receiving transducer, dB, $g_{TVG} = 10^{0.1G_{TVG}(R)}$ time varied gain of the receiver, V/V, $G_{TVG}(R) = 10\log(R/R_1) + \alpha(R - R_1)$. dB. As this TVG function compensates for two-way transmission loss $2TL = 20\log R/R_1 + 2\alpha(R - R_1)$, the backscatter echo squared $V_{(R)}^2$ is proportional to the product of fish density and backscattering cross section

$$V_{(R)}^2 = C_s\sigma_{bs}N_v \qquad (12)$$

where the proportionality coefficient C_s is a sonar system constant

$$C_s = I_0(c\tau/2)s_r^2 b_{eq}^2 \qquad (13)$$

Thus, the measurement of the backscatter echo squared output voltage allows to obtain an estimate of fish density in insonified volume, assuming the system constant C_s and backscattering cross section of fish σ_{bs} are known.

To obtain the estimates of the average fish density, which are of practical interest, the backscatter echo squared output voltage $V_{(R)}^2$ must be averaged over some depth interval $\Delta R = R_2 - R_1$ and over some number p of pings. This is realized by the Echo Integration Technique (EIT). The first averaging is obtained by integrating the squared echo envelope (12) over the time interval $\Delta t = 2\Delta R/c$ for each ping

$$\int_t^{t+\Delta t} V^2(t)\,dt = C_s \int_R^{R+\Delta R} N_v(R)\sigma_{bs}(R)\,dR =$$

$$= C_s\sigma_{bs}(\Delta R)N_v(\Delta R) \tag{14}$$

where $\sigma_{bs}(\Delta R)$ average backscattering cross section of fish in layer ΔR, $N_v(\Delta R)$ average fish density in depth layer ΔR.

If the second averaging over the specified number of pings is done, the average fish density ρ_v in a layer ΔR can be estimated by

$$\rho_v(\Delta R) = (\text{const})^{-1}M \tag{15}$$

where $M = avg\{\int_{\Delta t} V^2(t)dt\}$ is the so-called "integrator output" [6] and the proportionality constant is the product of the constant C_s and the average σ_{bs} of fish surveyed in the layer ΔR. Thus, if the C_s has been measured and the σ_{bs} is known, or can be estimated, the mean integrator output yields the absolute estimate of average fish density.

Echo integration is implemented with a digital integrator which accomplishes an integration similar to Eq. (14), by using a "sum-of-squares" approach [12]. For each ping, the consecutive digital samples of the echo envelope within each depth layer are squared and summed. For the j-th layer on the k-th ping, the partial sum of m squared samples with the sampling interval i is given by

$$S_{jk} = \sum_{i-1}^m (V_i)_{jk}^2 \tag{16}$$

After acquiring the data for all pings in a specified sequence of p pings, the accumulated sum is calculated for each layer:

$$S_j = \sum_{k-1}^p S_{jk} = \sum_{k-1}^p \sum_{i-1}^m (V_i)_{jk}^2 \tag{17}$$

The accumulated sums are then averaged over the total number of pings p in the sequence and the number of samples m in the depth layer, giving the "integrator outputs" representing the relative estimate of fish density in the layers. Such a mean squared voltage of backscatter echo constituting the integrator output for the j-th layer is

$$V_{(\Delta R)j}^2 = M_j = \overline{m}^1\overline{p}^1 \sum_k^p \sum_i^m (V_i)_{jk}^2 \tag{18}$$

where: m — number of samples integrated within the j-th depth interval ΔR for a sampling increment of T_s seconds, $m = 2\Delta R/cT_s$; p — number of pings integrated within the ping sequence, i — current number of the voltage sample, k — current number of ping in the sequence, $(V_i)_{jk}^2$ — squared sampled voltage for the i-th increment in j-th depth interval and k-th ping.

Assuming the system parameters are constant within the averaging constraints, then the mean integrator output (18) can be finally converted to the absolute estimate $\hat{\rho}$ of the average density of fish in arbitrary depth layer:

$$\hat{\rho}_j = C^{-1} V_j^2 \tag{19}$$

where $C = C_s \hat{\sigma}_{bs}$ is the overall integrator scalling constant, and $\hat{\sigma}_{bs}$ is an estimate of the average backscattering cross section of the surveyed fish.

The echo integration data can be alternatively expressed in terms of the mean volume backscattering strength [6], [11]

$$MVBS = 10 \log \overline{V}^2 - (SL + SRT + G + 10 \log c\tau/2 + 10 \log b_{eq}^2) \tag{20}$$

where V^2 is determined by Eq. (19) and the expression in parenthesis is the system constant C in decibels, and MVBS is related to the average fish density as

$$MVBS = 10 \log \overline{N}_v + \overline{TS} \tag{21}$$

where $\overline{TS} = 10 \log \overline{\sigma}_{bs}/4\pi$ the average target strength of fish.

3. Development of the modified echo integration technique for estimation of high density of fish

3.1. Single scattering with attenuation approximation (SSA)

This approximation constitutes the extension of the single scattering solution, as additionally it assumes that the backscattered echoes from each scatterer are similarly diminished, as they are partly scattered or absorbed — extinguished in general — by other scatterers. This excess attenuation of the backscatter echo from fish at a given depth by other fish at intermediate depth violates the assumption on the integrated echo intensity dependence upon the backscattering characteristics of fish only. As a consequence, the application of the SSA requires knowledge of the mean backscattering cross section $\overline{\sigma}_{bs}$ as well as the average extinction cross section $\overline{\sigma}_e$ [5].

Let us consider an aggregation of randomly distributed scatterers with an average extinction cross section $\overline{\sigma}_e$ and assume that the volume number density of scatteres is in general a function of the range $N_v(R)$. If the acoustic wave of incident intensity $I(R)$ at the range R travels a distance dR, it encounters $N_v dR$. This is equivalent to the loss of the incident intensity dI over dR

$$dI(R)/dR = -\overline{\sigma}_e N_v(R) I(R) \tag{22}$$

which, after integration, gives

$$I(R) = I(R_0) \exp \left\{ - \int_{R_1}^{R} \overline{\sigma}_e N_v(R) \, dR \right\} \tag{23}$$

where R_0 is an initial range, and the exponent $\gamma(x) = \int_0^x \sigma_e N_v(x) dx$ is sometimes called the optical distance[4].

The echo intensity received from the range R for SSA approximation can be derived by using the attenuated intensity (23) in place of unattenuated incident intensity, viz.:

$$I_{a(R)} = I_{(R)} \exp \left\{ -2 \int_{R_1}^{R} \overline{\sigma}_e N_v(R') dR' \right\} \tag{24}$$

where $I_{(R)} = I_0^{-0.2\alpha R} R^{-2} (c\tau/2) b_{eq}^2 \sigma_{bs} N_v(R)$ is the received intensity in the absence of attenuation (see the formula (10)) and the factor 2 in the exponent is due to the two-way attenuation.

Proceeding in a similar way as for unattenuated echo intensity in Section 2.3 we can derive the echo squared voltage at the output of a sonar receiver as

$$V_{a(R)}^2 = C_s \sigma_{bs} N_v(R) \exp \left\{ -2 \int_{R_1}^{R} \overline{\sigma}_e N_v(R') dR' \right\} \tag{25}$$

The last equation shows that in contrary to FOSS approximation (12) the simple proportionality relation between the echo squared voltage and fish number density does not hold any more. Due to the presence of an excess attenuation, not only the average backscattering cross section but also the average extinction cross section of fish must be known. Consequently the echo integration technique algorithm must be modified to fulfill the new requirements introduced by SSA approximation on fish density estimates.

3.2. Modified echo integration algorithm for SSA model

Let us consider the integration of the squared echo signal (25) in the depth interval $\Delta R = R_2 - R_1$ carried out in thin depth increments of thickness δR. If one assumes the average values of the backscattering and extinction cross sections $\overline{\sigma}_{bs}$ and $\overline{\sigma}_e$ for all depth layers, then the echo integrator output for the j-th layer can be written as

$$M_j = C_s \overline{\sigma}_{bs} \rho_1(R) \exp \left\{ -2\overline{\sigma}_e \sum_{j-1}^{n} \rho_j \delta R_j \right\} \tag{26}$$

As it is seen from the last equation, and from the preceding integral form (25), the exponential attenuation factor comprising the fish density, affects all successive depth layers. For this reason the solution of Eq. (26) is recursive and, in order to extract the fish density in the j-th layer, the densities in preceding $j-1$ layers must be known [5]. In other words, the integrator output must be recursively updated by the data from the preceding layers.

The structure of the proposed density estimation technique is as follows. The squared echo voltages are integrated over the time intervals δt_j, associated with the successive

---

[4] The quantity $\gamma(x)$ indicates the extent to which the incident wave has encountered scatterers in the intervening volume and represents the merit of applicability of various approximations of scattering. If $\gamma \ll 1$ (low density case), the single scattering model is valid. If $\gamma \cong 1$ (medium and high densities) SSA approximation applies. If $\gamma \gg 1$ (very high densities), diffusion approximation is valid [5].

depth layers δR_j, and then multiplied by the gain factors $\exp\{\gamma(Rj)\}$ which compensate for the attenuation affecting each depth layer and which are computed from the density estimates of these preceding intervals. Thus the fish density estimate in the j-th layer is calculated from the estimates in previous $j-1$ layers as

$$\widehat{\rho}_j = C_s^{-1}\overline{\sigma}_{bs}^{-1}M_j \exp\left\{2\overline{\sigma}_e \sum_{r=1}^{j-1}\widehat{\rho}_r\delta R_r\right\} \tag{27}$$

By this means, we estimate the fish density in a given layer in such a way, as it is no attenuation in this particular layer, accounting the effect of attenuation in all preceding layers.

In order to employ the proposed density estimation technique, the two parameters must be known, viz.: the mean backscattering cross section $\overline{\sigma}_{bs}$ and the mean extinction cross section $\overline{\sigma}_e$. One method allowing for a direct "in situ" estimation of $\overline{\sigma}_{bs}$ is the Dual-Beam Method. This method has been implemented sucessfully in a newly developed ECOLOG II real-time computerized sonar system, [3], [12] and as an estimation technique it will be used in the considered application. The estimation of $\overline{\sigma}_e$ is a different matter and will be the subject of the next section.

3.3. Extinction cross section measurement

Unlike the well established measurement methods of the backscattering cross section, or target strength, the extinction cross section "in situ" measurements are not so well developed. One possible and feasible approach is an indirect method based on the excess attenuation measurement using a reference target see (Sect. 2.2). Thus performing a single measurement of the standard target echo level EL, and comparing Eq. (10) with Eq. (6), we obtain

$$\sigma_e = \frac{EL - [SL + SRT + TS - 40\log R_s/R_1 - 2\alpha(R_s - R_1)]}{2(R_s - R_1)4.34N_v} \tag{28}$$

For the case of double measurement of the standard target echo. i.e., in the presence $(EL2)$ and in the absence $(EL1)$ of the fish aggregation in the pen we have

$$\sigma_e = \frac{EL_2 - EL_1}{2(R_s - R_1)4.34N_v} \tag{29}$$

The only unknown which appears in Eqs. (28) and (29) is the mean numbers density of fish N_v. This must be known or must be obtained from some other experiment in order to extract the extinction cross sections estimate from one of these equations. Apparently the proposed approach seems to be contradictory as the extinction cross section is estimated in order to improve the unknown fish density estimate. Therefore the latter one cannot be used to obtain the first one. Fortunately it is not so since usually in aquaculture facilities some a priori information on fish density is available. These data can be used as a first approximation of the actual density of fish in pen for calculating a rough estimate of the extinction cross section. Alternatively this first approximation can be obtained from the echo integration when implemented in a conventional manner (see Eqs. (18) and (19)).

Substituting the approximate estimate of fish density in Eqs. (28) or (29) gives the rough estimate of σ_e which in turn will be used for calculating the fish density estimates in depth layers, according to the modified integration algorithm (27). Due to the recursive

structure of the proposed estimation algorithm, the density estimate for the first layer is assumed to be "accurate" as there is practically no excess attenuation for this layer. This density estimate can be used in calculating the corrected estimate of the extinction cross section which will then be used for calculating the final estimates of fish density according to the recursive algorithm (27).

4. Implementation of the estimation technique for high densities of fish

4.1. General system description

The recursive fish density technique proposed in Sect. 3.2 has been implemented in the modified design of the real time dual-beam signal processing sonar system ECOLOG II [3], [12], [13]. This system option has been labelled "Fish Counter" and its basic configuration consists of three major subassemblies:

Dual-Beam Transducer Unit

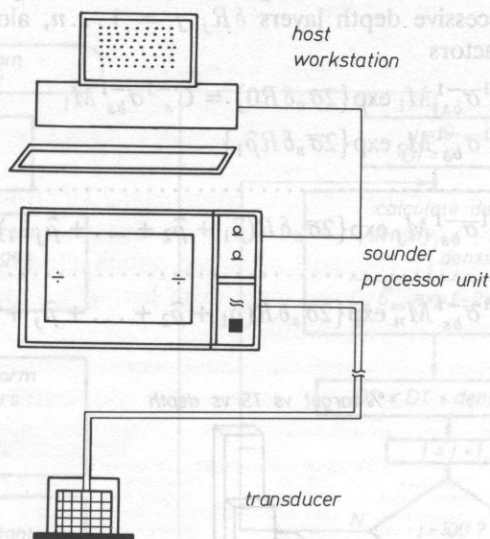Sounder-Processor Unit

Host Computer Workstation

FIG. 2. Major subassemblies of the FISH COUNTER system.

The transducer unit consists of a dual-beam transducer mounted inside a versatile housing, along with the matching/tuning network. The transducer can operate either as downward-looking, when floating on the surface above the pen, or as upward-looking when placed on the bottom below the pen.

The sounder/processor unit contains the compact, precision echo sounder and a powerful, high performance internal computer based on the Motorola M68010 16 bit microprocessor. The sounder parameters are fully programmable by the user from the host computer workstation. The high power electrical burst from the sounder transmitter is

routed to the transducer and radiated vertically in the water column on the narrow beam. The fish echoes received on both narrow and wide beams are subject to analog and digital processing in the two-channel receiver and digital signal processor (DSP). The DSP output data is processed immediately by the internal computer which performs in real-time the Echo Integration or Target Estimation mode of operation. The real-time computer output data is formated and sent by high speed data transfer to the host computer.

The host computer workstation is an IBM PC/XT/AT or any other compatible one. It is responsible for the whole user control and operation of the sounder/processor unit. It also provides post processing, data storage and graphics presentation of output data. The user friendly software is provided for system setup data entry and output.

Since the majority of the system hardware and software is the same as in the ECOLOG II system [3], [12], we will confine ourselves only to the discussion of the modified echo integration which is the specific operating mode of the proposed FISH COUNTER system design.

4.2. Modified recursive echo integration software

The proposed recursive estimation algorithm (27) can be expanded to show the density estimates in the successive depth layers $\delta R_j \; j = 1 \ldots n$, along with the exponential compensating gain factors

$$\widehat{\rho}_1 = C_s^{-1}\overline{\sigma}_{bs}^{-1} M_1 \exp\{2\overline{\sigma}_e \delta R0\} = C_s^{-1}\overline{\sigma}_{bs}^{-1} M_1$$

$$\widehat{\rho}_2 = C_s^{-1}\overline{\sigma}_{bs}^{-1} M_2 \exp\{2\overline{\sigma}_s \delta R\widehat{\rho}_1\}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$\widehat{\rho}_j = C_s^{-1}\overline{\sigma}_{bs}^{-1} M_j \exp\{2\overline{\sigma}_e \delta R(\widehat{\rho}_1 + \widehat{\rho}_2 + \ldots + \widehat{\rho}_{j-1})\} \quad (30)$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$\widehat{\rho}_0 = C_s^{-1}\overline{\sigma}_{bs}^{-1} M_n \exp\{2\overline{\sigma}_s \delta R(\widehat{\rho}_1 + \widehat{\rho}_2 + \ldots + \widehat{\rho}_j + \ldots + \widehat{\rho}_{n-1})\}$$
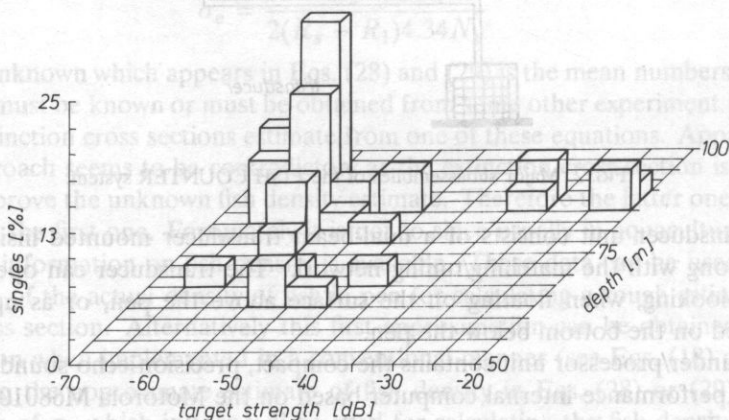

FIG. 3. Target strength versus depth 3 — D histogram.

The average backscattering cross section $\overline{\sigma}_{bs}$ can be obtained from the target strength data which are extracted from the single fish echoes by the dual-beam processing in the TS Estimation mode of the ECOLOG II system operation [3], [12]. The sample TS versus depth $3-D$ histogram provided by the ECOLOG II system is shown in Fig. 3. The average extinction cross section $\overline{\sigma}_e$ can be obtained according to the procedure described in Sect. 3.3.

The modified echo integration mode of system operation providing the recursive density estimates is implemented as follows. The wide beam data is processed only using the "sum-of-squares" approach (see Sect. 2.3). The internal computer maintains an array of data "table", $i = 0 \ldots 1023$, where i represents the depth and "table i" is the sum of squared echo voltages samples received at that depth. The data is accumulated over N_p pings and then transferred to the host computer. Once the host receives the array of the accumulated sums, it calculates the system constant C_s and the relative fish density array $\{M_j\}$, $j = 0 \ldots 99$. Finally this data is converted to the absolute fish density array "density"$_j$ employing the recursive procedure (30).

The flow chart of the recursive echo integration algorithms which are executed by the host computer is explained in Fig. 4.
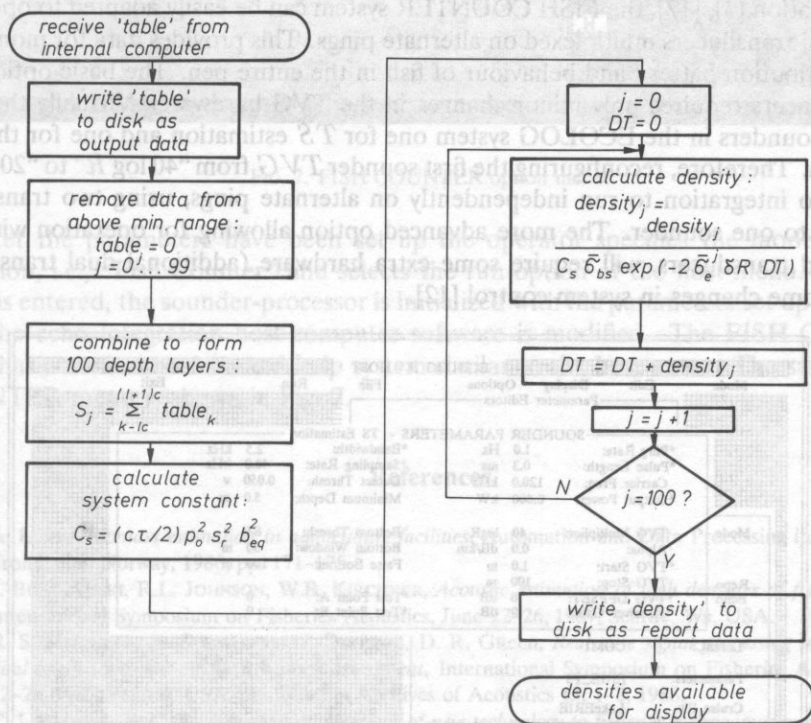

FIG. 4. The recursive fish density estimation flow chart - host computer modified echo integration software.
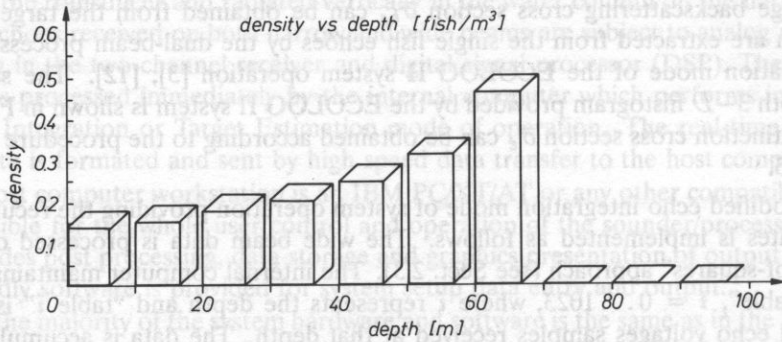
FIG. 5. Fish density versus depth distribution.

After each sequence of N_p pings the fish density data is copied to the display buffer for graphic presentation. A sample fish density profile in depth layers is shown in Fig. 5.

4.3. One system option with multiplexed transducers

Due to a unique feature of the ECOLOG II system, which is a simultaneous dual-mode operation [3], [12], the FISH COUNTER system can be easily adapted to operation with several transducers multiplexed on alternate pings. This provides data for monitoring of the distribution pattern and behaviour of fish in the entire pen. The basic option with two transducers requires only minor changes in the TVG hardware. Virtually there are two echo sounders in the ECOLOG system one for TS estimation and one for the echo integration. Therefore, reconfiguring the first sounder TVG from "40 log R" to "20 log R" allows echo integration to run independently on alternate pings, using two transducers connected to one sounder. The more advanced option allowing for operation with four multiplexed transducers, will require some extra hardware (additional dual transmitter) and also some changes in system control [12].
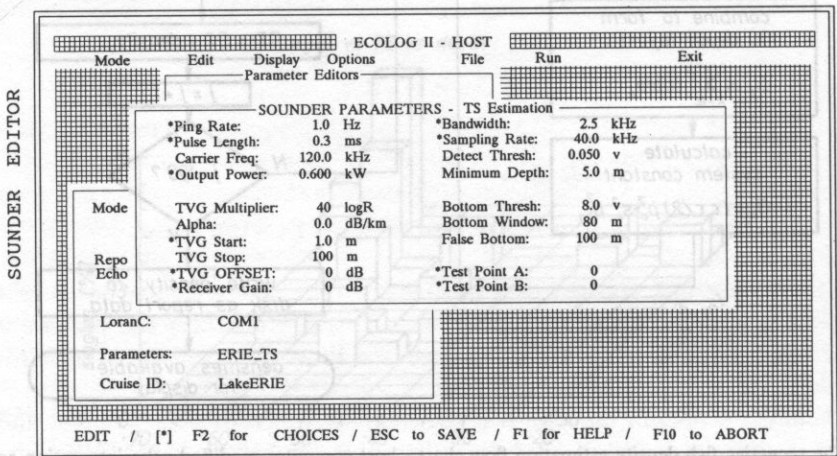

FIG. 6. ECOLOG II host menu and Sounder settings window.

4.4. System operation

The operation of the "Fish Counter" system is practically the same as the basic ECOLOG II system version. To run the system the operator enters the HOST command which loads, and runs the host computer programs. Once the host menu is displayed, the operator enters the desired parameters into the editing window or loads a parameter file. A sample ECOLOG II sounder settings editor of the host menu is shown in Fig. 6.
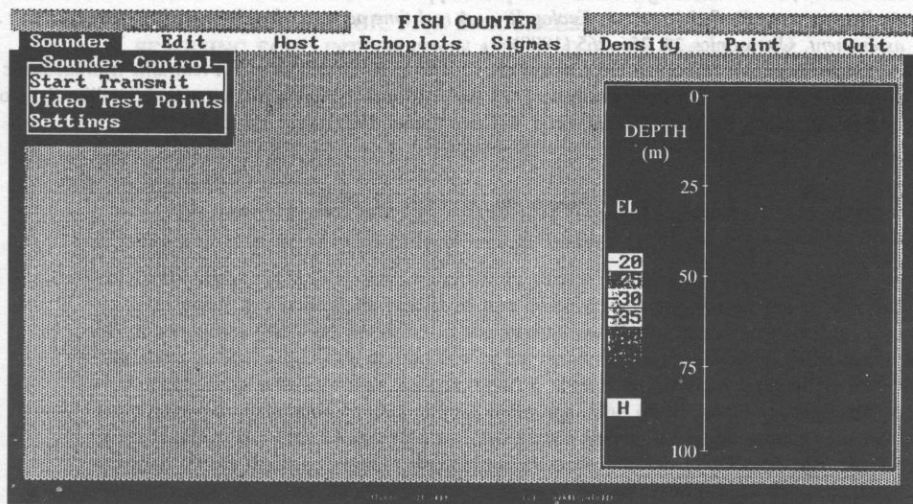

FIG. 7. FISH COUNTER option menu.

After the parameters have been set up the operator specifies the mode of system operation, i.e., "Fish Counter" and selects the run option of the host menu. When this mode is entered, the sounder-processor is initialized with the parameters set up previously. Also the echo integration host computer software is modified. The FISH COUNTER mode has a menu interface and help system similar to the host menu. The sample FISH COUNTER menu is shown in Fig. 7.

References

[1] A. LOVIK, *Biomass estimation in aquaculture facilities*, Automation and Data Processing in Aquaculture, Trondheim, Norway, 1986, pp. 171–175.

[2] J. BURCZYŃSKI, R.L. JOHNSON, W.B. KIRCHNER, *Acoustic estimation of high densities of fish in sea pens*, International Symposium on Fisheries Acoustics, June 22–26, 1987, Seattle, Wa, USA.

[3] R. S. MITCHELL, A. STEPNOWSKI, J. DROBNIK, D. R. GREEN, *Real time signal processing techniques in a dual beam sonar system for fish stock assessment*, International Symposium on Fisheries Acoustics, June 22–26, 1987, Seattle, USA, published in Archives of Acoustics **13**, 1–2, 1988.

[4] T. J. BROOKS, T. C. TORKELSON, *Applications of new technology to fisheries hydroacoustics data collection and analysis*, International Symposium on Fisheries Acoustics, June 22–26, 1987, Seattle, USA.

[5] D. W. LYTLE, D. R. MAXWELL, *Hydroacoustic assessment in high density fish schools*, ICES/FAO Symposium on Fisheries Acoustics June 21–24, 1982, Bergen, Norway, FAO Fish. Rep. 300, pp. 157–171.

[6] K. OLSEN, *Sound attenuation within scholls of herring*, Con. Meet. ICES 44, 1986.

[7]   K. G. FOOTE, *Linearity of fisheries acoustics with addition theorem*, J. Acoust. Soc. Am., **73**, 6, 1932–1940 (1983).

[8]   T. K. STANTON, *Effects of second-order scattering on high resolution sonars*, J. Acoust. Soc. Am., **76**, 3, 861–866 (1984).

[9]   C. C. CLAY, H. MEDWIN, *Acoustical oceanography*, J. Wiley and Sons Ins., 1977.

[10]   R. J. URICK, *Principles of underwater sound*, McGraw Hill, New York 1975.

[11]   A. STEPNOWSKI, J. BURCZYŃSKI, *The analysis of calibration constant in the hydroacoustic system of fish abundance estimation*, In: Meeting on Hydroacoustic Methods for the Estimation of Marine Fish Populations, June 25–29, 1979 Cambridge, USA, vol. 2 part A pp. 325–336.

[12]   A. STEPNOWSKI, R. S. MITCHELL, *Ecolog II — A real time acoustic signal processing system for fish stock assessment*, Ultrasonics **28**, 256–265 (1990).

[13]   A. STEPNOWSKI, R. MITCHELL, S. LAWRENCE, L. Kílian, R. GUDELEWICZ, *A real time hydroacoustic data processing system for fich stock assessment*, 13 International Congress on Acoustics, Satellite Symposium on Sea Acoustics, Dubrovnik Yugoslavia, 4–6 September 1989, vol. 5 pp. 213–216.