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SIMULATING ECHOGRAMS

by

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ABSTRACT

Simulation of echo data can be useful for verifying echo integrators realized in computer software. A model is presented which associates distinct stochastic processes with each of the following: bottom depth; number, depth, and orientation of fish in the beam; and background noise. A measure of realism is preserved, perhaps, by (1) simulating echo registration with an ideal circular transducer of 8-deg beamwidth, moving forward at 10-knots speed; (2) allowing individual fish to be tracked through the beam; and (3) using measurements on fish to describe the target strength. Attendees may form their own opinion of the success of the simulation from examples to be shown - in colour.

RESUME: SIMULATION D'ECHOGRAMMES

La simulation d'échos peut être utile pour vérifier les intégrateurs d'echos réalisés en software. On présente un modèle qui associe des processus stochastiques distincts avec les variables suivantes: profondeur; numéro, profondeur et orientation des poissons dans le faisceau; bruit de fond. Du réalisme est peut être conservé en simulant l'enregistrement des échos par un transducteur circulaire idéel avec une largeur du faisceau de 8 degrés, se déplacant en avant à une vitesse de 10 noeuds; en permettant que les poissons soient détectés individuellement dans le faisceau; en utilisant des mesures sur poisson pour décrire l'index de réflexion. Les participants pourront juger le succès d'une telle simulation par les exemples qui seront montrés - en couleur.

INTRODUCTION

Fish echo data have been simulated by, among others, Griffiths and Smith (1978), Borud et al. (1984), and Guo and Griffiths (1989). Borud et al. (1984) generated data for use in a simulator.

During development of the new Bergen Echo Integrator (BEI) (Knudsen 1989a and b), another kind of echo data was required. Because of the design of the BEI as a post-processing system for data preprocessed by the new SIMRAD EK500 scientific echo sounder (Bodholt et al. 1988, 1989), data are expected in the form of absolute values of the mean volume backscattering strength (Urick 1983). In particular, for each ping for each transducer, an array of 650 numbers is transferred from the EK500 to the BEI. The first 500 data represent successive values of the mean volume backscattering strength spanning the operator-defined depth interval in equal steps. The final 150 data represent values from 10 m over the detected bottom to 5 m under the same, with 0.1-m resolution. The potential dynamic range of these data is that of the EK500, roughly 160 dB.

It was to provide precisely known data in the required form that the present study was undertaken. Further, anticipated uses of the data could be, for instance, in systematic studies of echo integration and echogram interpretation, and in testing automatic algorithms to extract single-fish target strengths, perform echo-trace analysis, and classify echograms on the basis of features.

In the following, a model for simulating echo data is described and illustrated through computed echograms. Improvements to and uses of the model are discussed.

METHOD

The fundamental physics of sound scattering by fish drives the present model, hence is described first. The model is then outlined, parameter values are given, and the generation of random numbers used in a simulation program is briefly described.

Physics

The backscattered pressure wave, p(t), from an ensemble of fish may be expressed by the following summation:

$$p(t) = \sum_i \frac{e^{-2\beta r_i}}{r_i^4} b(\hat{r}_i) \, \sigma_i^{\frac{1}{2}}(\hat{r}_i, \theta_i, \phi_i) \, s_i(t - r_i/c) + n(t) \quad , \qquad (1)$$

where β is the coefficient of absorption at the center frequency of the transmitted signal, assumed to be narrowband; $\underline{r}_i$ is the vector position of the i-th fish, r_i is the corresponding range, and $\hat{r}_i$ is the unit vector in the direction of the fish, $\underline{r}_i = r_i \hat{r}_i$; b_i is the product of transmit and receive directivity patterns in the amplitude domain in the direction $\hat{r}_i$; σ_i is the backscattering cross section of the i-th fish, the arguments θ_i and ϕ_i describe the tilt and azimuthal angles, respectively; s_i describes the form of the echo signal from the i-th fish at the retarded time $t - r_i/c$, where c is the speed of sound and $\int s^2(t)\,dt = 1$; and n(t) is the background noise. Since the echo data are to be expressed in terms of the mean volume backscattering strength, the echo energy is computed from equation (1):

$$\varepsilon = \Sigma \, g_i b_i^2 \sigma_i + \varepsilon_o \quad , \qquad (2)$$

where g is a gain factor containing both purely geometric and scaling factors, b^2 is the product of transmit and receive beam patterns in the usual intensity domain, σ is the backscattering cross section, each for the i-th fish, with suppression of the arguments shown in equation (1), and ε_o is the corresponding value of echo energy due to noise.

Equation (2) can also be expressed in terms of the mean volume backscattering coefficient s_V. For a transducer with product beam patterns b^2 and equivalent beam angle $\psi = \int b^2 \, d\Omega$, the mean volume backscattering coefficient due to the scatterers in a spherical shell of radius r and thickness $\Delta r \ll r$ is

$$s_V = \frac{1}{\psi} \sum_j \frac{b_j^2 \sigma_j}{4\pi r^2 \Delta r} + s_{V_o} \quad , \qquad (3)$$

where the summation is performed over all scatterers in the shell. In exact analogy with equation (2), s_{V_o} is the noise contribution.

Model

Equation (2), or equation (3), underlies the model. This has, however, more elements than may be immediately apparent. These are now described in their order of computation in simulating a matrix of values of mean volume backscattering strength, the logarithmic measure of the defined coefficient s_V. This has 650 rows representing depth and as many columns as are necessary to cover a predefined sailed distance. The vertical resolution is assumed, for definiteness, to be 1 m, thus the first 500 rows of the matrix span a depth range of 500 m.

Noise At the outset, the matrix is filled, or 'initialized' in computer cant, by either a predefined constant threshold value or noise value, whichever is greater. The noise value is computed at each point according to the summation

$$s_{V_o} = s_{V_n} \left| \sum_{j=1}^{10} \cos(2\pi u_j) \right|^2 \quad ,$$

where u_j is a uniform random variate defined on (0,1).

Surface This is assumed to be horizontal. A Euclidean coordinate system is established with origin in the horizontal, x-y plane, with z-axis pointing downwards. The plane is thus described by the equation z=0. The x-axis is aligned in the direction of motion of the transducer, which is assumed to move with constant velocity.

Bottom The bottom depth is generally described as a stochastic process defined by two independent Gaussian distributions, with predefined horizontal and vertical scale sizes. The horizontal, x-scale size is described by the mean and standard deviation of the corresponding number of pings. The vertical, z-scale size is similarly described by a mean and standard deviation, but in absolute units of distance. Between two successive distances x_1 and x_2, determined by the first distribution, a mean gradient $\Delta=(z_2-z_1)/(x_2-x_1)$ is computed. The precise depth at distance x_j, where $x_1 \leq x_{j-1} < x_j \leq x_2$, is determined by the prescription

$$z_j = z_{j-1} + p_j\Delta \quad ,$$

where, somewhat arbitrarily, p_j is a stochastic variable equal to unity 80% of the time and negative unity 20% of the time, determined ping by ping from a uniform distribution. The bottom is indicated by adding the quantity 5/12 to the pair of matrix elements at or immediately below the bottom depth.

Bottom fish layer limits The upper limit for the entry of new fish into the beam follows the bottom, differing in depth by some constant offset, a predefined depth-difference parameter. The lower limit is that of the bottom itself.

Bottom fish layer This part of the matrix of mean volume backscattering strengths is filled in the following way. For each ping, the number of new fish entering the beam is determined by sampling a Poisson distribution of predefined mean specified for the bottom fish. The depth of each of these is determined according to a parabolic distribution, i.e., one which is based on a constant volume density of scatterers. The permissible depth range is that defined by the bottom fish layer limits for the particular ping. The x-coordinate of each new fish position is determined to within the distance sailed by the transducer-bearing vessel between successive pings. At 10 knots and a ping rate of 1/s, this is 5.1 m. The precise distance is assigned according to a uniform distribtion, which, for the example, spans [0,5.1] m. The y-coordinate is determined from a uniform distribution defined exactly over the width of the beam at the predefined maximum detection angle. In filling the matrix, each fish is tracked from its first detection to exit from the beam-sampled volume. The position of each fish is assumed to remain constant during passage of the beam, hence the x-coordinate changes by constant distance from ping to ping. The fish position is examined with respect to the sampling volume of the beam, as defined by a cone of circular cross section and vertex angle corresponding to the predefined maximum angle of detection. If it is outside of the cone, the contribution to the scattering strength is assumed negligible, and the next position is examined. At each position within the conical sampling volume the product beam pattern is computed, assuming identical transmit and receive beams arising from the same ideal circular piston with 8-deg beamwidth at the -3-dB level. The fish orientation is described by a pair of stochastic variables, with tilt angle that is distributed according to a normal distribution with predefined mean and standard deviation, and azimuth that is uniform over 360 deg. The effective tilt angle, as observed from the transducer, is computed in the usual way (Foote 1980). This in turn is used in extracting a value of target strength from tabulated reference data, where the target strength function of tilt angle has already been selected, according to a uniform distribution, for the subject fish. Although the fish is assumed to remain fixed in position from ping to ping, it is allowed to change its orientation within the confines of the two distributions. The contribution to the mean volume backscattering coefficient from each fish in each position in the beam is computed and added to the corresponding matrix element.

Expanded bottom channel This layer, which extends from 10 m over the bottom to 5 m under the same, but with 0.1-m resolution, is filled by those bottom fish echoes lying within 10 m of the bottom. The 150 values occupy row numbers 501-650 in the s_v-matrix. The corresponding bottom-fish backscattering cross section is assumed, however, to be modulated by this ad hoc function:

$$\left\{\cos\left[\frac{\pi(j-j_{peak})}{15}\right]\right\}^{1/4} \mathrm{rect}\left(\frac{j-j_{peak}}{15}\right) \quad ,$$

where j is the row number within the range [493,657], and j_{peak} is the row number corresponding to the determined fish range. The bottom itself is represented by adding 5/12 to each matrix element from row 600 to row 620 inclusive.

Pelagic fish layer limits Like the bottom depth, the upper and lower depths of new pelagic fish entering the beam at a predefined maximum detection angle are each determined by a pair of independent Gaussian distributions. The upper limit is defined analogously to that of the bottom depth, but with independent distribution parameters and the imposed conditions that the upper limit be confined to the zone between the surface and upper bottom-fish layer depth. This is done by hard-limiting for computed excursions exceeding the bounds. The lower depth of new pelagic fish entering the beam is defined similarly to that of the upper pelagic fish layer depth, but with the condition that this lower depth lie between the corresponding upper depth and bottom, again enforced by hard-limiting.

Pelagic fish layer This is filled analogously to that of the bottom fish layer, except that a normal distribution is used to determine the number of fish in the layer. Possible negative values are used by taking the magnitude or absolute value.

Multiple pelagic fish layers Each pelagic fish layer is defined and filled independently of other pelagic fish layers.

Mean volume backscattering strength The logarithmic measure is preferred to the computed coefficient. This is moreover desired in a base-two system, with resolution of 3 dB/256. Integer expression is also desired, hence the following conversion is performed:

$$s_v \rightarrow [(256/\log_{10}2)\log_{10} s_v] \quad , \tag{4}$$

where the brackets here indicate taking the integer part.

Parameter values

Several values of model parameters have already been mentioned. These are the basic depth range [0,500] m, with vertical resolution 1 m; expanded bottom channel observed from 10 m over to 5 m under the detected bottom, with 0.1-m resolution; registration of the bottom by the s_v-value 5/12; distance sailed at 10-knots speed between successive pings at 1/s pulse repetition rate, namely 5.1 m; and transducer beamwidth of 8 deg, measured across the transmit or receive beam at -3-dB level.

Some additional values of model parameters assumed in a computer simulation program are the following. The threshold amplitude is $10^{-17.2}$ and the noise amplitude s_v is 10^{-10}. The maximum detection angle is assumed to be 40 deg, as measured from the beam axis. For the mentioned transducer beamwidth, the equivalent beam angle is 0.0108 sr. Tilt angles of fish are assumed to follow the normal distribution N(0,5) deg, for which observational evidence is offered by Foote and Ona (1987). Reference target strength data are the functions of tilt angle measured by Nakken and Olsen (1977) and tabulated by Foote and Nakken (1978).

Random numbers

A number of different random variates are used in the simulation. Each of these depends on the uniform random variate defined over (0,1). This is generated by a variant of the following purely multiplicative version of the linear congruential method:

$$R_{n+1} = \alpha R_n \pmod{m} \quad ,$$

where the choices $\alpha=2^{16}+3$ and $R_o=2^{31}-3$ have been based on Moshman (1967). The modulus m is 2^{32}, as the simulation model was realized on Norsk Data 500-series digital computers, with 32-bit word size. The homemade part of the algorithm was designed to avoid negative numbers.

The other distributions were defined in terms of the uniform variate. The normal distribution N(0,1) is computed by summing 12 uniform variates, and subtracting six (Zelen and Severo 1965). The parabolic or quadratic random variate is derived directly from the uniform variate by simple transformation (Wilks 1962). The Poisson variate is derived by apportioning the uniform variate according to the cumulative distribution function of the Poisson distribution.

RESULTS

Two simulated echograms, in harsh black and white, are presented here. The log markings at the top of the echogram, beginning with '530.2', are spurious, as the five vertical divisions cover almost exactly 5 km, not the implied 5 nautical miles. Other numbers shown on the echogram, including apparent two-colour spectrum to the right, are explained by Knudsen (1989b).

The bottom depth contour is the same in both echograms. It is characterized by horizontal and vertical scale sizes which follow the respective distributions N(100,25) pings and N(0,25) m, where the mean depth is 425 m.

In Fig. 1, two fish layers are shown. Both apply to cod (Gadus morhua) at 38 kHz, whose data base consists of 68 functions spanning the length range 6.7-96 cm. The mean density of fish in the 15-m-thick bottom layer is one new fish per ping. The density of fish in the pelagic layer is

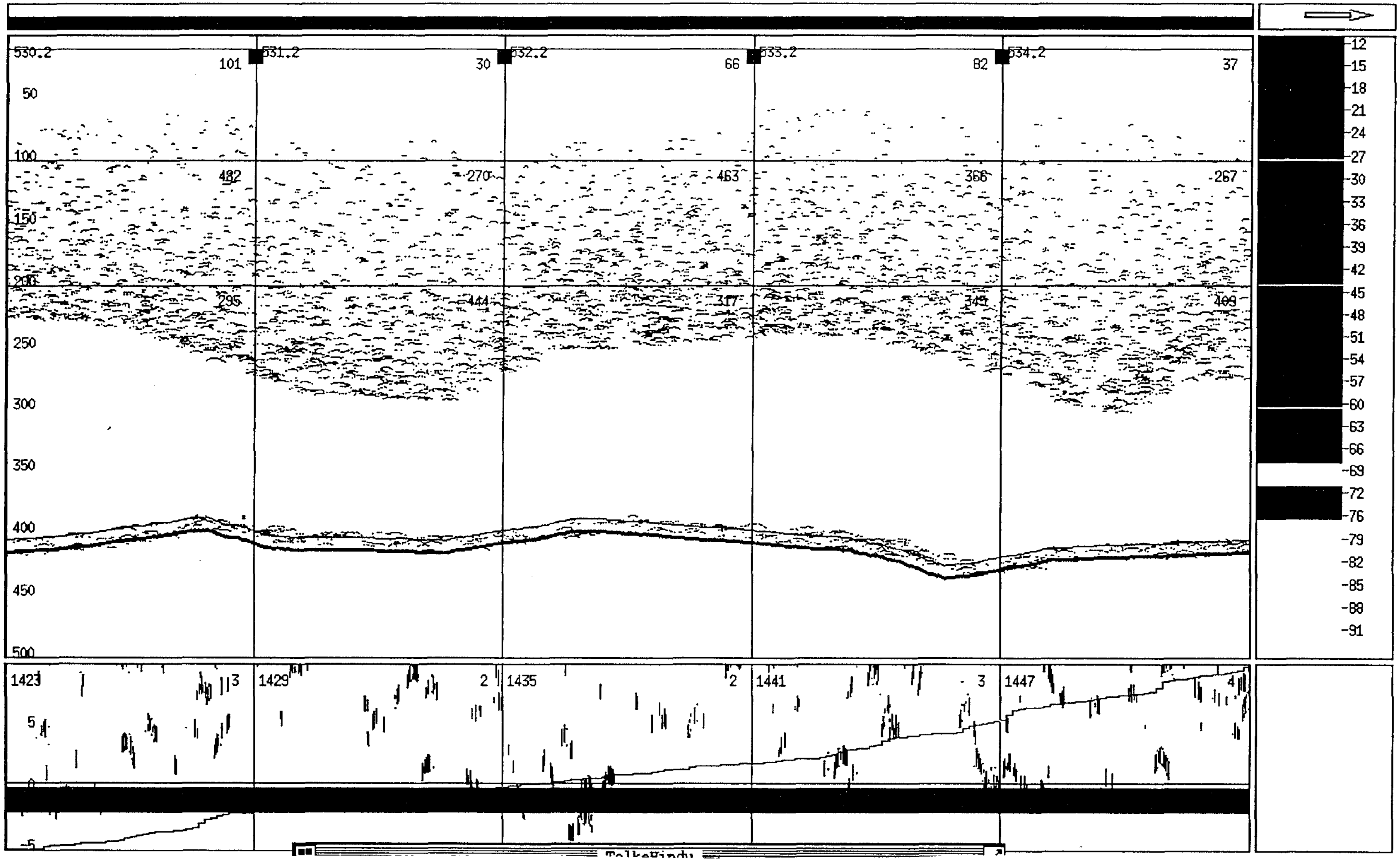

Fig. 1. Simulated echogram with bottom and single pelagic fish layers filled with cod echoes.

described by the normal distribution N(30,6), which represents the number of new fish entering the beam. The geometric parameters of the pelagic fish layer are shown in Table 1.

Table 1. Parameters characterizing the boundaries of the pelagic fish layer shown in Fig. 1. X- and z-scale units are pings and meters, respectively.

Layer limit	x-scale		z-scale		
	Mean	S.D.	Initial value	Mean	S.D.
Upper	50	15	80	0	20
Lower	75	25	225	0	35

Four fish layers are shown in Fig. 2. The source target strengths are the 171 functions representing 68 cod, 59 saithe (Pollachius virens), and 44 pollack (Pollachius pollachius). The density of fish in the 15-m-thick bottom layer is one new fish per ping. The densities and geometric parameters governing the three pelagic fish layers are shown in Table 2.

Table 2. Parameters characterizing distributions of density and boundaries of three simulated pelagic fish layers in Fig. 2. X- and z-scale units are pings and meters, respectively.

Pelagic fish layer	Density		Layer limit	x-scale		z-scale		
	Mean	S.D.		Mean	S.D.	Initial value	Mean	S.D.
1	40	8	Upper	50	15	80	0	20
			Lower	75	25	345	0	35
2	15	3	Upper	50	20	140	0	5
			Lower	75	25	170	0	10
3	25	10	Upper	50	20	290	0	20
			Lower	75	25	360	0	10

DISCUSSION

The two figures are not the most aesthetically pleasing. They also suffer from lack of dynamic range. This is inevitable with the use of a "two-colour printer". The resolution is, however, excellent. Many single-fish traces can be discerned or imagined.

Use of a 500-m vertical range means that the resolution, 1 m, hence one pixel, is rather coarse with respect to echo-trace identification, although still sufficient for this. Use of a 250-m vertical scale would double the height or amplitude of the characteristic inverted-V's. The effect of finer resolution on appearance is suggested by the echo traces in the expanded bottom channel, where the resolution is the maximal 0.1 m applicable at 38 kHz.

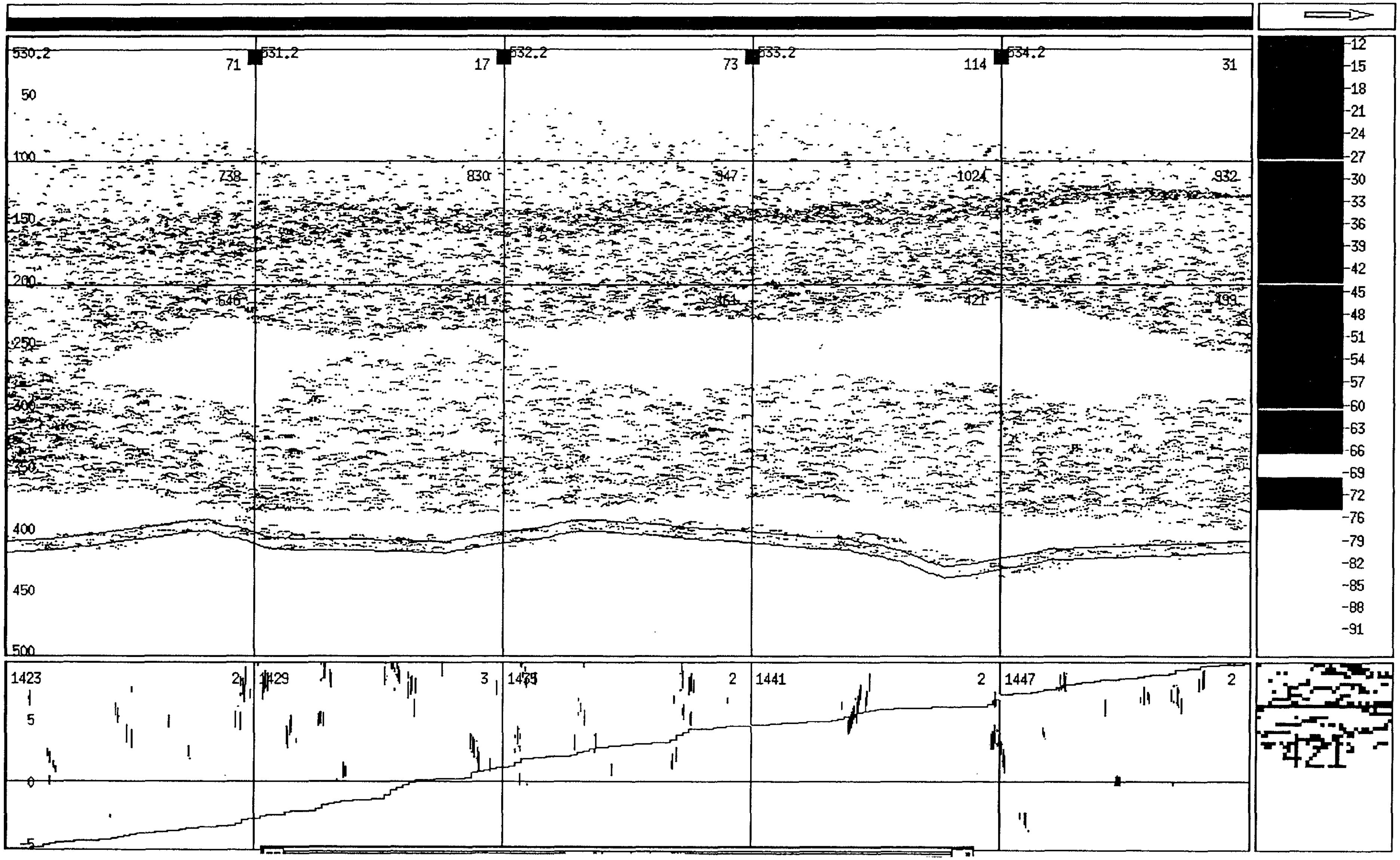

Fig. 2. Simulated echogram with bottom and three pelagic fish layers filled with gadoid echoes.

The aesthetics or appearance of the echograms can also be improved by making them more realistic. Notwithstanding the substantial losses incurred by using the particular printing medium, some features could be improved. These include the upper and lower edges of the several bottom and pelagic fish layers. In practice, these are more diffuse. The density and density distribution could also be changed to advantage. A particular way would be to let the distribution parameters vary with distance, which in fact describes a principal characteristic of contagious distributions. These are undoubtedly more interesting than the stationary, purely stochastic Poisson and Gaussian distributions used in the present model computations.

Noise, which is not noticed in the two simulated echograms because of the limited dynamic range of the printer, could be simulated in more sophisticated fashion than is done in this model. Several alternative noise models are described by Libicki et al. (1989).

The model did achieve its primary aim of providing timely echo-like data for use in testing the prototype of the Bergen Echo Integrator. The model may have additional, future applications in testing the integrator, for example, in adapting or developing automatic algorithms or functions to extract single-fish target strengths, perform echo-trace analysis, and classify echogram features, as by discriminant analysis.

Since the model simulates stochastic processes, but realizes these in software, the model is deterministic for each set of initial or starting parameter values. The number of these is so large that the range of potential echograms is essentially unlimited. Thus a variety of echogram types can be generated. Study of these, while knowing the parameter values, may contribute fundamentally to understanding the connection between the appearance of an echogram and the underlying physical reality of a three-dimensional fish distribution. By attempting to match artificial echograms to field-derived examples, much might be learned about the aggregation properties of fish. Discrimination of bottom and fish might be addressed in the same way. These are, in any case, some hopes.

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