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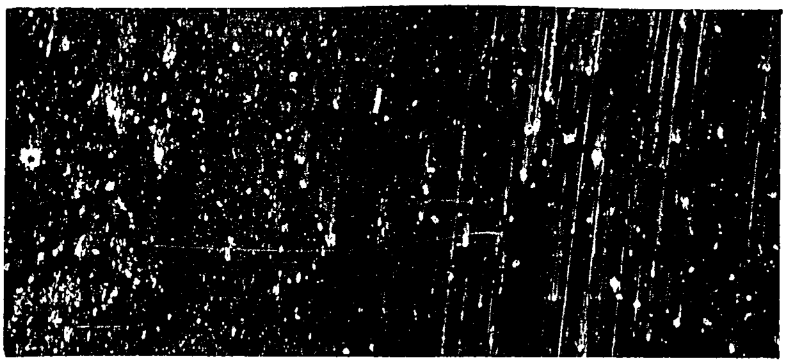

FISHERIES STOCK ASSESSMENT

TITLE XII

Collaborative Research Support Program

Fisheries Stock Assessment CRSP Management Office
International Programs, College of Agriculture
The University of Maryland, College Park, Maryland 20742

In cooperation with the United States Agency for International Development (Grant No. DAN-4146-G-SS-5071-00) the Fisheries Stock Assessment CRSP involves the following participating institutions:

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The University of Washington—Center for Quantitative Sciences
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"HYDROACOUSTIC ASSESSMENT OF FISH STOCKS IN THE GULF OF NICOYA, COSTA RICA

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The Fisheries Stock Assessement CRSP (sponsored in part by USAID Grant No. DAN-4146-G-SS-5071-00) is intended to support collaborative research between U.S. and developing countries' universities and institutions on fisheries stock assessment and management strategies.

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HYDROACOUSTIC ASSESSMENT OF FISH STOCKS IN THE GULF OF NICOYA, COSTA RICA

John B. Hedgepeth[1], Richard E. Thorne[2], and V. F. Gallucci[3]

ABSTRACT

The Gulf of Nicoya, Costa Rica is a relatively shallow, tidally-influenced estuary that supports a substantial artisanal fishery on various stocks, primarily corvinas. Little is known about the population size or productivity of these stocks. Hydroacoustic techniques have been successfully applied to fish population estimation in many circumstances. However, application to the Gulf of Nicoya stocks faces a double consideration: economic considerations force a relatively simple, cost effective approach, but the environment, including the species and size composition is complex.

We approached the problem of the complex biological composition with Clay's deconvolution technique. This approach allowed us to obtain substantial information about the acoustic size characteristics and density of the fishes with a relatively simple, single-beam echo sounder. We implemented the deconvolution analysis, along with standard echo integration techniques, using the BioSonics ESP acoustic signal processing system. This PC-based system combines portability with substantial processing power and storage capability. The deconvolution technique provides the necessary scaling factor for echo integration, so that absolute population estimates can be made.

INTRODUCTION

The Gulf of Nicoya covers about 1530 square kilometers and is the largest of the Pacific Ocean gulfs of Costa Rica. The inner or northern half of the Gulf is more shallow than the outer parts, with typical depths of 4 to 20 meters. About 50% of the production of fish and invertebrates in Costa Rica comes from the Gulf of Nicoya [1]. Artisanal fisheries contribute to the majority of landings. The dominant group of the 100 species of commercial fishes is the Sciaenidae, consisting of 31 species. About 30% of the Gulf's production is represented by three sciaenids, the corvina species, *Cynoscion albus* (corvina reina), *Cynoscion squamipinnis* (corvina aguada) and *Micropogonias altipinnis* (corvina agria).

Until now knowledge about the abundance of fishes in the Gulf of Nicoya came from fisheries landing statistics and some scientific trawl sampling. Using semi-balloon trawls, Leon [2] found that, in the inner Gulf, a non-commercial sciaenid dominated catches, followed by sea catfish, then engraulids and clupeids. From a later survey, Bartels et al. [3] published a similar finding except that engraulids and clupeids were less important.

During September 1987, we began a survey of the inner Gulf of Nicoya using hydroacoustic equipment consisting of a single-beam echo sounder. Groundtruthing by net sampling was limited, but a rapport with fishermen was established to sample catches aboard vessels and to work in proximity to their fishing gear. Early in 1988, we designed and built a midwater trawl in order that groundtruthing could proceed unhindered, and we conducted another survey in the inner Gulf, August and September 1988. We have begun to analyze this most recent data with deconvolution analysis [4,5], along with echo integration techniques. Preliminary results suggest that previous studies have undersampled smaller size fishes.

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METHODS

The basis for the mobile hydroacoustic sampling design was a stratified random sample of parallel transects. Tidal currents are swift in the inner Gulf of Nicoya, and so for ease of navigation, transects were run parallel to current direction, and consisted of about three nautical miles in length. In this paper, we apply the deconvolution technique to data from two of these transects.

Deconvolution of Fish Signals

A beam from an echosounder is like a flashlight which is strongest on the center axis and weaker at the edges. Simplistically, voltages received from the same size fish farther from the acoustic axis are, on average, smaller than from those on the axis. In order to compare all of the voltages, one needs to remove this beam pattern effect. Clay [4] presented an outline of a inverse technique, a deconvolution procedure, which removes the beam pattern effect from fish echo signals. Earlier, Clay and Medwin [6] showed that fish echoes were a convolution of the beam probability density function (PDF) and the on-axis voltages. Stanton and Clay [5] also described the deconvolution procedure and included a minimum density estimator when fish targets are too dense to use a deconvolution procedure successfully [7].

The inverse problem has been long recognized. In 1877, Lord Rayleigh suggested that it would be possible to determine the density distribution of a string from knowledge of its vibrations [8]. In 1966, Kac posed this problem again in a famous paper, "Can one hear the shape of a drum?" Robinson [8] and his proteges developed an inverse or deconvolution approach for seismic exploration, removing the effect of various strata overlying an oil field. Clay's deconvolution method gives the distribution of on-axis voltages, which can provide estimates of backscattering cross sections as well as density estimates.

To promote an understanding of the inversion process of deconvolution, the convolution of two signals follows. A simple example, given in Twomey's [9] text, is that of running means, taken three at a time. Samples from the signals are taken at discrete intervals; a similar process has been applied to the convolution and deconvolution of fish echo signals. There are two sets of data to consider in the running mean example. One set is the data to be smoothed, available at positive and negative integer intervals. The other set (responsible for the running mean procedure) is centered at the origin, with amplitude 1/3 at -1, 0 and 1, and 0 amplitude elsewhere. First, reflect the data set responsible for the smoothing procedure about the origin. Since it is centered on the origin, the reflection does not change this signal. Multiply one data set by the other at corresponding integer locations. The running mean at 0 is then the sum of the multiplications. Shifting the rectangular 1/3 amplitude signal (the data set responsible for the running mean procedure) one integer to the right or positive side of the other signal, multiplying and summing, gives the mean at 1. Shifting in the other direction gives the mean at -1. Shifting twice gives the mean at 2 and -2, and so on. Now the inverse problem could be the following in this example. Given the set of running means, and the process and signal (1/3 amplitude signal) which formed them, find the original data set. (If you didn't throw away the end data points, of the original set of data, this is possible by recursive division.)

Deconvolution has been performed by polynomial division of z-transforms of the fish echoes by the z-transforms of the beam PDF [4,5]. This result comes from discrete linear system theory [10], the approach used in the running mean example above. In order to follow the deconvolution procedure into its goals of density and backscattering cross section estimates, the theory will be presented.

If all fish were on-axis, after correcting for spreading and absorption losses they would create a voltage PDF, $f_S(s)$. However, the fish are not all on-axis, and so the collected data possess a PDF, $f_V(v)$ where V is measured in volts. If the beam pattern PDF is $f_B(b)$, then the cumulative density function, $f_V(v)$, was shown by Clay and Medwin [6] to be

$$F_V(v) = \int_0^1 f_B(b)\,db \int_0^{\frac{v}{b}} f_S(s)\,ds$$

The maximum value of b is 1 (on axis) and the maximum of S for any b is v/b. The derivative of $F_V(v)$ with respect to v is the PDF

$$f_V(v) = \int_0^1 \left(\frac{1}{b}\right) f_B(b) f_S\left(\frac{v}{b}\right) db$$

This becomes the convolution integral [11] after a change of variables

$$b = e^{-x}, \quad 0 < b < 1 \quad \text{and} \quad v = e_0 e^{-y}, \quad 0 < v < e_0$$

$$f_V(y) = \int_0^{\infty} f_B(x) f_X(y-x)\,dx$$

Both f_B and f_V need to be sampled at integer intervals, m and n, so that deconvolution can proceed by using z-transforms and discrete linear system theory.

$$m = \frac{x}{a}, \quad 0 \le m \qquad n = \frac{y}{a}, \quad 0 \le n \qquad a = \frac{\ln 10}{N}$$

where N is the number of steps per decade. Stanton and Clay [5] recommend N = 20 and no less than 10. The discrete form of the convolution integral is the convolution or superposition sum:

$$f_V(n) = \sum_{m=0}^{\infty} f_B(m) f_S(n-m)\,a$$

The PDF, $f_S(s)$, is desired, and for polynomial division to retrieve at least part of this PDF, the length of n and m should be equal. The length of n and m cannot realistically be infinity, or even large, because it is difficult to sample the echo returns close to the noise level due to the peak sampling procedure, noise and the accuracy of the data acquisition system.

(Stanton and Clay, as we do, restrict this method to positive n and m, but if $v = e^{-y}$ there would be negative n's and the method would still work.)

Density Estimation

The frequencies of the raw echo peaks can be expressed as

$$\mathrm{Number}(v) = N_f M_p Vol_g f_V(v)\delta v \quad \text{where}$$

N_f - fish density in numbers per m^3

v - center voltage of the voltage interval δv

M_p - number of pings over sampling interval

Vol_g - $2\pi(R_2^3 - R_1^3)/3$, gated volume from range R_1, R_2

The deconvolution (symbolized by "·/·") of the raw frequencies can be expressed as

$$\mathrm{Number}^*(n) \;\cdot/\cdot\; (a f_B(m)) = k f_S(n)$$

Then, $k f_S(n)$ is what results from deconvolution, and can be used to estimate fish density using

$$N_{f,n} = \frac{a e_0 e^{-na} k f_S(n)}{(\delta v M_p Vol_g)}$$

$$N_f = \sum_N N_{f,n}$$

* In our deconvolution implementation, *Number(n)* is interpolated using cubic splines from linearly binned data, not logarithmically binned as Clay suggests, and, when deconvolved, requires the above weighting to estimate density.

Expectation of S^2, On-axis Voltage Squared

The expected value of S^2, $[S^2]$, can be used to scale echo integration results, in order to estimate absolute densities. By definition

$$E[S^2] = \int_0^\infty s^2 f_S(s)\,ds$$

and will be approximated by

$$\approx \left(\frac{1}{N_f}\right)\sum_n e_0^2 e^{-2an} N_{f,n}$$

With system gain and receiving sensitivity, $E[S^2]$ can be used to estimate the average backscattering cross section $av(\sigma_{bs})$, or it can be used directly in the "integration equation" using the same data collected with a $40 \log R + 2\alpha R$ time varied gain.

$$N'_I = \frac{av(V^2_{R_1,R_2})B_c}{(av(B^2(0))T_0 c\pi E[S^2])}$$

N'_I = estimated density of fish using integration

$av(V^2_{R_1,R_2})$ = averaged integrated voltage squared from R_1 to R_2

B_c = time varied gain correction, $1/R^2$

$av(B^2(0))$ = expected value of the beam pattern

c = speed of sound

T_0 = pulse duration

With a calibrated system, integrated echo voltages can be used to estimate density in terms of biomass.

Beam Pattern PDF, Echo Frequencies and Deconvolution

Instead of using an approximate PDF, an analytic solution is obtained for the beam pattern. Ehrenberg et al. [12] presented a similar form of this PDF and used numerical techniques for its solution. We use commercial computer language library functions to evaluate an analytic solution of the beam PDF.

The deconvolution technique attempts to remove the beam pattern effect, assuming that fish are uniformly distributed in the water column, and that the beam pattern can be accurately described. Kinsler et al. [13] present an equation for the directional factor of the beam, $H(0)$, for a circular transducer, which when multiplied by the on-axis pressure gives the pressure radiation at angle 0 from axis.

$H(0) = |2J_1(U)/U|$ where U = ka sin (0)

k = angular frequency divided by the speed of sound

a = effective transducer radius

$J_1()$ = bessel function of the first kind order 1

$H(0)$ ranges from 1 to 0. $B(0)$ is equal to $H(0)^2$ and represents the two-way response assuming that reception and transmission beam pattern are the same. Stanton and Clay [5] follow Ehrenberg's [14] approximation for the PDF of $B(0)$. We used a derived PDF of B as a function of U. Ehrenberg (1972) gave the PDF of θ

$$f_0(0) = \sin(0), \quad 0 < 0 < \frac{\pi}{2}\,.$$

Using the transformation technique [11] the PDF of U is

$$f_U(u) = \left|\frac{dh^{-1}(u)}{du}\right| f_0(h^{-1}(u) I_D(u) \quad , \quad h^{-1}(u) = \sin^{-1}\left(\frac{u}{ka}\right)$$

$$= \frac{u}{\left[(ks^2)\sqrt{\left(1 - \frac{u}{(ka)^2}\right)}\right]} \quad , \qquad 0 < u < ka \quad ,$$

Following Ehrenberg et al. [13]

$$f_B(u) = \frac{f_U(u)}{\left|\frac{dB(u)}{du}\right|}$$

Taking the derivative,

$$f_B(u) = \frac{u^3}{\left[8(ka)^2 J_1(u) J_2(u)\sqrt{1 - \left(\frac{u}{ka}\right)^2}\,)\right]}$$

where $J_2() =$ bessel function of the first kind order 2.

Microsoft Quick-C programming language routines were written to accomplish deconvolution, and the language has library functions with the bessel functions. Given integer m and thus b_1 and the equality $b(u) = h(u)^2$, the directivity function is iterated to get u, and $f_B(u)$ is evaluated.

To be safe, Ehrenberg et al. [12] suggest comparison of the actual beam pattern density with the theoretical approximation. First, a value was determined for ka by iterating

$$\left[\frac{2J_1(ka\sin(0_{-3dB}))}{(ka\sin(0_{-3dB}))}\right]^2 = 0.5$$

The beam pattern was digitized from a polar plot and a PDF was constructed using the equation given by Ehrenberg et al.

$$f_B(b) = \frac{\sin(0)}{\left|\frac{dB(0)}{d0}\right|}$$

This derivative was approximated from the digitized pattern using a difference formula and points digitized surrounding the b and 0 of interest. Figure 1 compares the analytical solution against the digitized solution and shows close agreement between the two PDFs.

The sensitivity of the deconvolution procedure to parameters ρ_0, ka, n, and m was investigated by convolving a simulated distribution of on-axis fish echoes, then deconvolving the beam pattern while varying one of the parameters. Two Rayleigh PDFs were used, with equal weighting and parameters of .1 and 1.0 respectfully. Figure 2 shows the sensitivity to ka. If ka is misspecified, resulting fish densities will be in error. However, despite small errors in ka, the procedure should still provide good backscattering cross section estimates. When ρ_0 was chosen to be obviously below a more suitable maximum value, densities were overestimated at or slightly below ρ_0, but the procedure recovered the smaller voltage densities. The length of n will control lower sampling threshold for voltage, while the length of m will affect the beam threshold. Both should be the same integer length. Thus, sampling of the beam signal and of the voltage signal are interrelated; choosing the lower limit of $B(0)$ affects the lower voltage limit and vice versa. When the length of n and m is lessened, information is lost from the voltages smaller than $\rho_0 e^{-\alpha n(max)}$ but deconvolution remains accurate above that level.

Fish echo voltages were collected from field measurements in the inner Gulf of Nicoya at the receiver output of a Simrad EYM echosounder and recorded in digital format on magnetic tape. Data was collected at 40 log(Range) time-varied gain, and a ping-pong ball target gave a return of about .28 volts on axis. The tapes were replayed into a BioSonics ESP signal processor and the BioSonics program DB.EXE was used to extract echo peak voltages. Peaks were accepted if -6 dB levels were located, in windows that extended 75% of the .34 ms pulse width, on either side of the peak. From the ESP generated files, voltages were gathered into .02 volt bins. Frequency values for each integer n were derived by cubic spline interpolation [15]. A deconvolution program from Robinson [8] was adapted to a C language program. This program also generated values for the PDF of the beam pattern, optionally smoothed the binned raw data using a three-point running mean, used a cubic spline interpolation for sampling the binned data, and computed density estimates.

The same tape data was replayed into the BioSonics ESP and analyzed using the echo integration program, EI.EXE, with the threshold level set at 80 mv. An integration program was written to read the ESP files, correct for TVG and estimate density.

RESULTS

Data from two transects in the inner Gulf of Nicoya were analyzed using the deconvolution filter. The two transects were run on 7 September 1988, 0156 hour and 10 September 1988, 2100 hour. Gillnet and trawl samples were also collected. Estimates of $E[S^2]$ from the deblurred distributions were used in echo integration.

Figure 3 shows echograms typical of the two transects; 7 September indicates a dense layer between 2 and 6 m, while 10 September appears more homogeneous. Depths on 7 September ranged to 11 meters, and on 10 September to 6 meters. Voltage data that were interpolated from the binned and smoothed, digitized echo data appear in Figure 4. Both datasets result from about 30 minutes of real time echosounding. Depth intervals used in the analysis for 7 September were contiguous and those for 10 September overlapping. Voltage data after deconvolution (Figure 5) give estimates of density. From the appearance of both the echograms and sampled echoes, using Stanton's criteria [7], the 4 to 10 m depth interval, 7 September, contains overlapping targets. Therefore, density and voltage estimates from this interval are erroneous. For purposes of integration, we chose an estimate for $E[S^2]$ intermediate to the depth intervals above and below this layer. Table 1 summarizes our results.

Table 1. Summary of deconvolution and integration results. Critical density was computed using Stanton's [7] formula, above which overlapping targets occur.

Transect Date	Depth m	Deconvolved $fish/m^3$	Deconvolved $E[S^2]$	Critical Density $fish/m^2$[7]	Integrated $fish/m^3$
7 Sept.	1-2	1.93	0.32	1.85	1.76
	2-6	.175*	0.63*	.26	1.27
	6-10	.035	0.20	.065	.048
10 Sept.	1-3	.79	.027	1.04	.847
	2-4	.24	.029	.46	.199
	3-5	.13	.030	.26	.112

* These estimates are erroneous because they are taken from multiple targets. Estimated $E[S^2]$ for integration used was .025.

DISCUSSION

Net catches from the two September transects can be compared to the acoustic results using Love's [16] formula for target strength TS

$$TS = 19.1\log_{10}(\text{length, cm}) - .9\log_{10}(\text{frequency, kHz}) - 62$$

and the observation that a ping-pong ball with theoretical TS of -40.5 dB returned approximately .28 v on-axis (see Figure 6). The trawl data on 7 September produced an average TS of -46.13, intermediate to the deconvolution results from shallow and deep depth intervals. The trawl density estimate was .082 fish/m^3, slightly above the 6-10 m depth interval estimate. Since the trawl was towed with its headrope at a depth of 4 to 5 meters, the net and acoustic densities correspond well.

Gillnet and trawl data from 10 September were scaled to each other by setting the frequencies in overlapping length bins approximately equal. The net density estimate, .15 fish/m3, was intermediate between the 2-4 and 3-5 m acoustic estimates, and corresponds well, since the headrope was at a depth of 2 m. The average TS from net data was -43.6 dB, higher than the other estimates. Deconvolution results show the influence of larger fishes at all depths on 10 September, reflected in both high and homogeneous estimates of mean TS. On 7 September, in the upper and lower depth intervals deconvolution produced different shaped distributions, suggesting the presence of a greater fraction of larger fishes in the upper water column at that time.

The use deconvolved data looks promising in the initial analysis. However, reliability of the estimates is subject to error in time-varied gain particularly at short range, to artifacts of the peak sampling procedure especially at low voltage levels, to the smoothness or distribution of higher voltage data, and to the presence of overlapping targets. We hope that by analyzing more of the August and September 1988 data, as well as data from August 1987, we will better understand these limitations and more accurately portray the distribution of fishes in the inner Gulf of Nicoya, Costa Rica.

An interesting tentative conclusion based on the deconvolved data, as well as our trawl samples, is that previous studies have undersampled smaller size fishes, represented in this study mainly by engraulids and clupeids.

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FIGURE LEGENDS

Figure 1.	Comparison of theoretical and observed beam pattern PDF, using ka = 8.28.
Figure 2.	The deconvolved, on-axis voltage distributions show error when misspecifying ka. The true ka, 8.28, was used in the beam pattern PDF for convolution with the original fish signal and for regaining the signal through deconvolution.
Figure 3.	Nine-minute echogram samples from two transects in the Gulf of Nicoya. Samples A and B were made on 7 September 1988 and 10 September 1988, respectively. Horizontal lines appear every 2 m of depth.
Figure 4a.	Interpolated raw data from one transect on 7 September 1988 prior to deconvolution.
Figure 4b.	Interpolated raw data from one transect on 10 September 1988 prior to deconvolution.
Figure 5a.	Estimated on-axis distributions from one transect on 7 September 1988 after deconvolution.
Figure 5b.	Estimated on-axis distributions from one transect on 10 September 1988 after deconvolution.
Figure 6a.	Comparison between net and acoustic samples from one transect on 7 September 1988 in the Gulf of Nicoya.
Figure 6b.	Comparison between net and acoustic samples from one transect on 10 September 1988 in the Gulf of Nicoya.

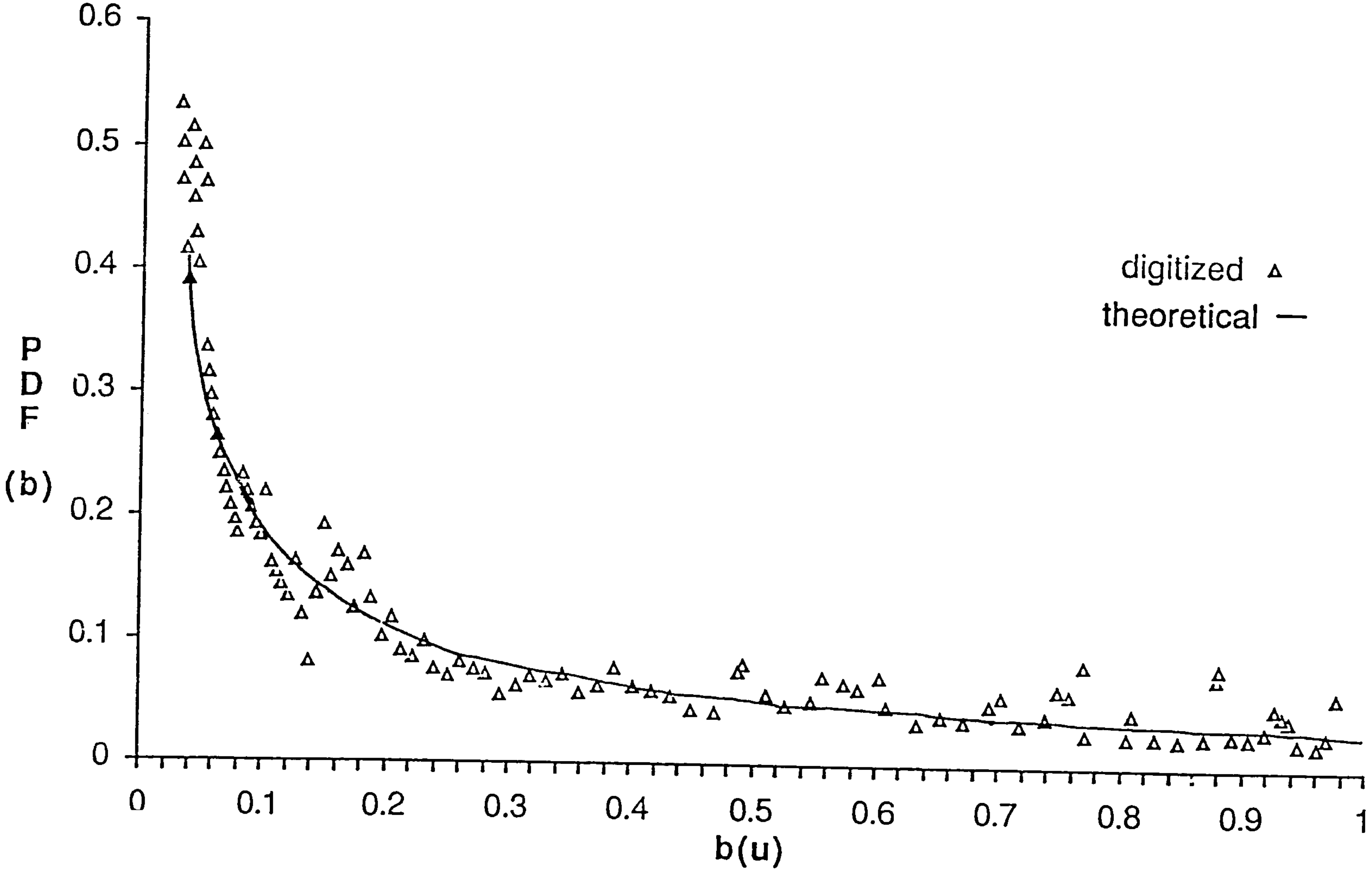

Figure 1. Comparison of theoretical and observed beam pattern PDF, using ka = 8.28.

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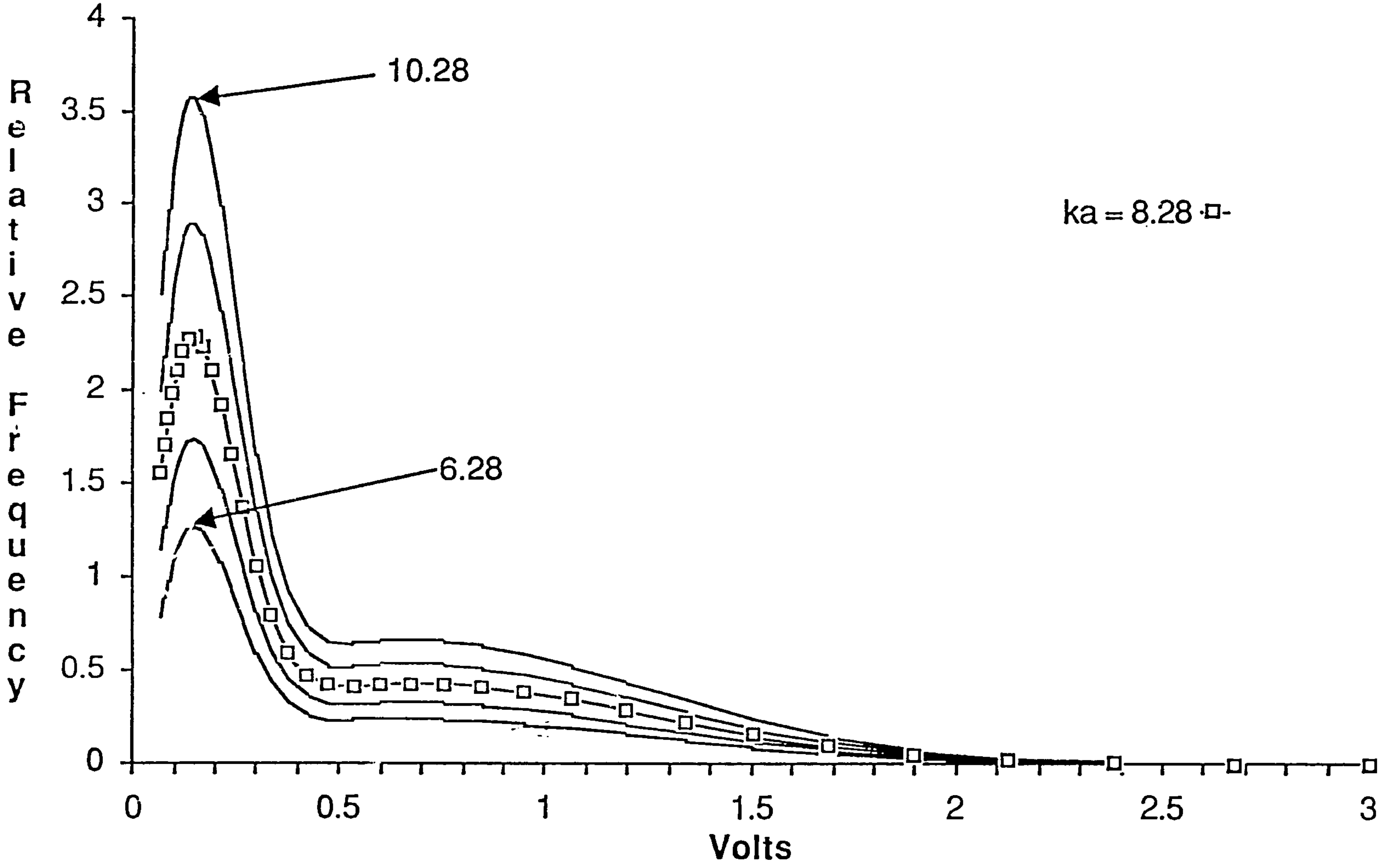

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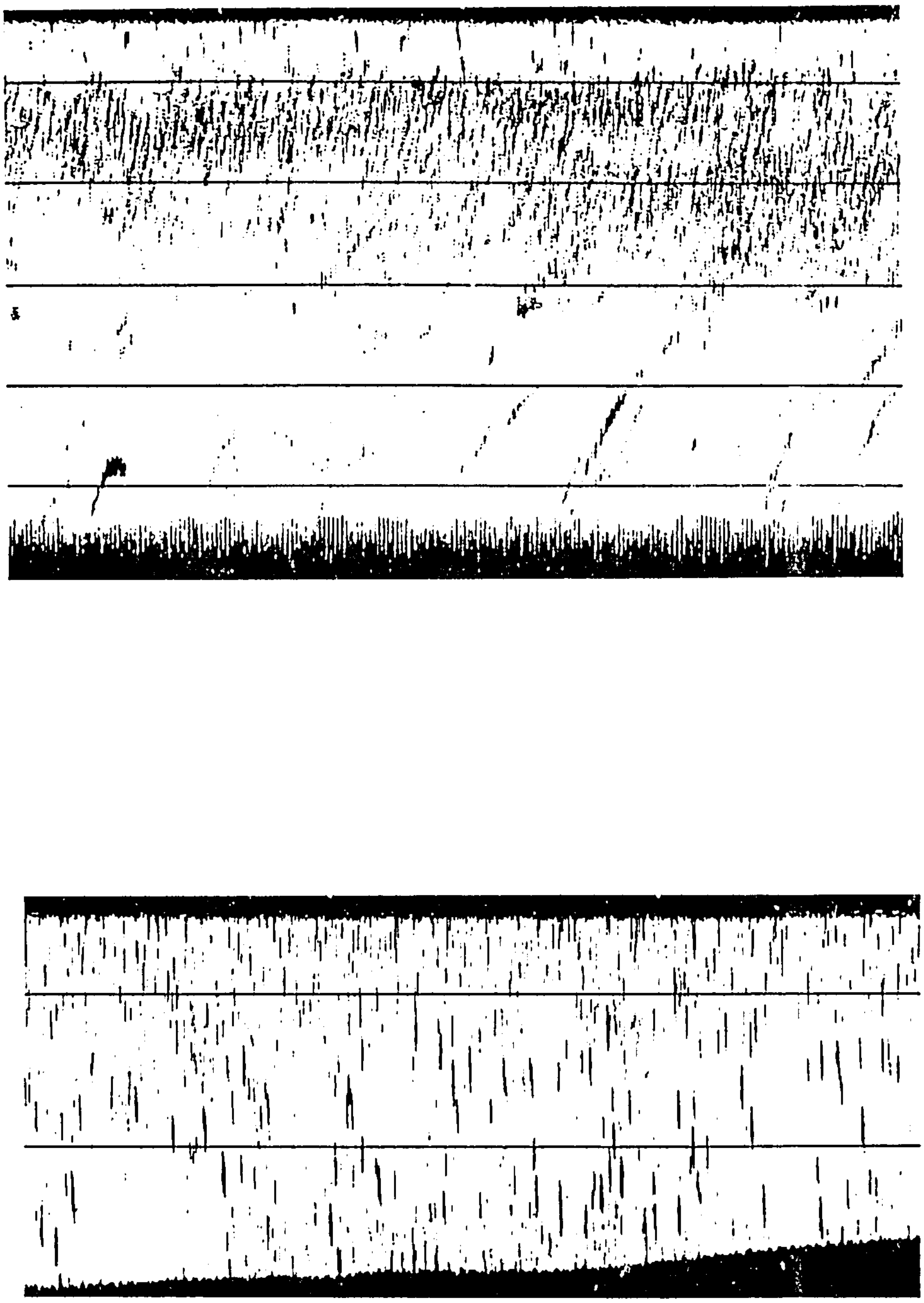

Figure 3. Nine-minute echogram samples from two transects in the Gulf of Nicoya. Samples A and B were made on 7 September 1988 and 10 September 1988, respectively. Horizontal lines appear every 2 m of depth.

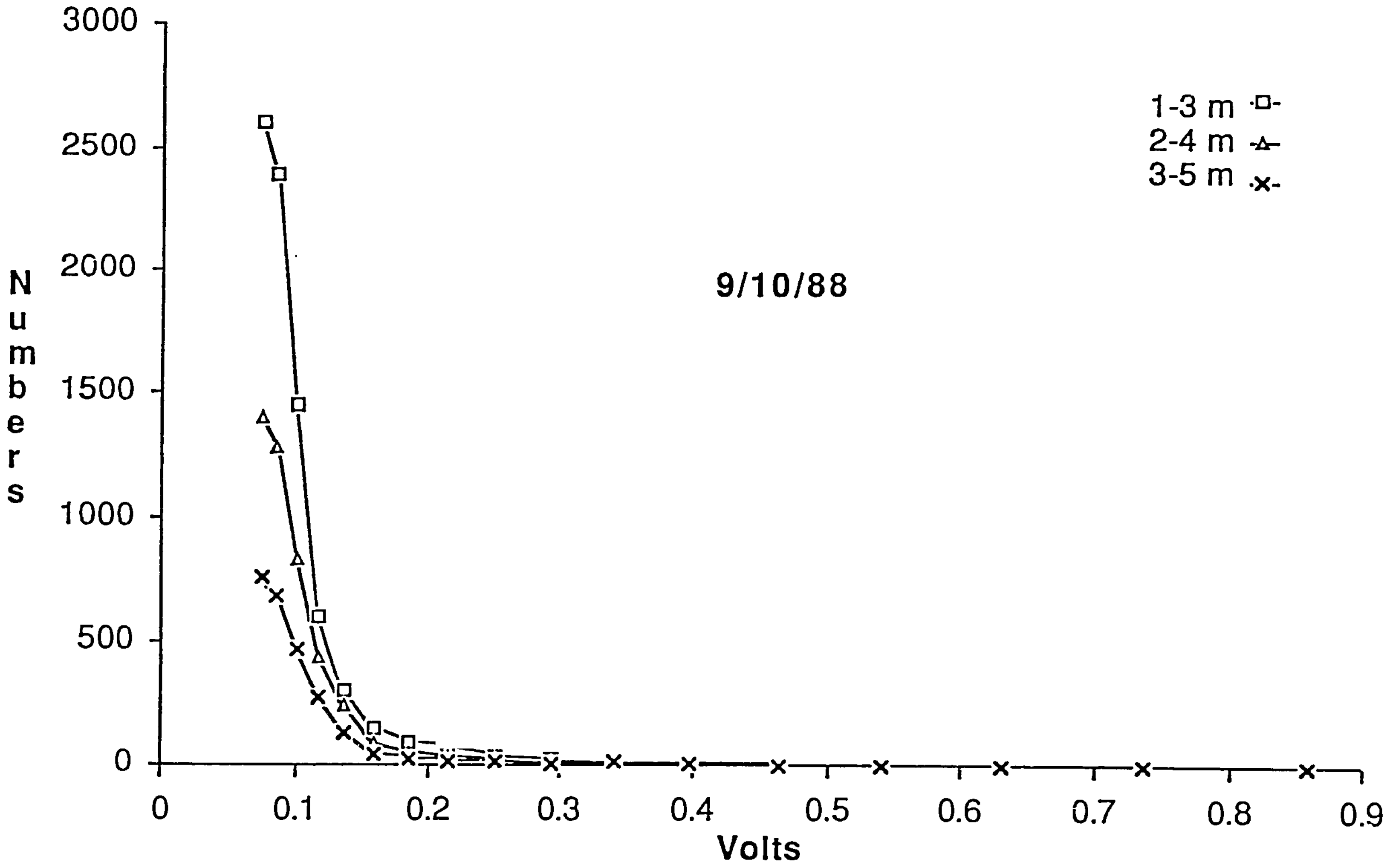

Figure 4b. Interpolated raw data from one transect on 10 September 1988 prior to deconvolution.

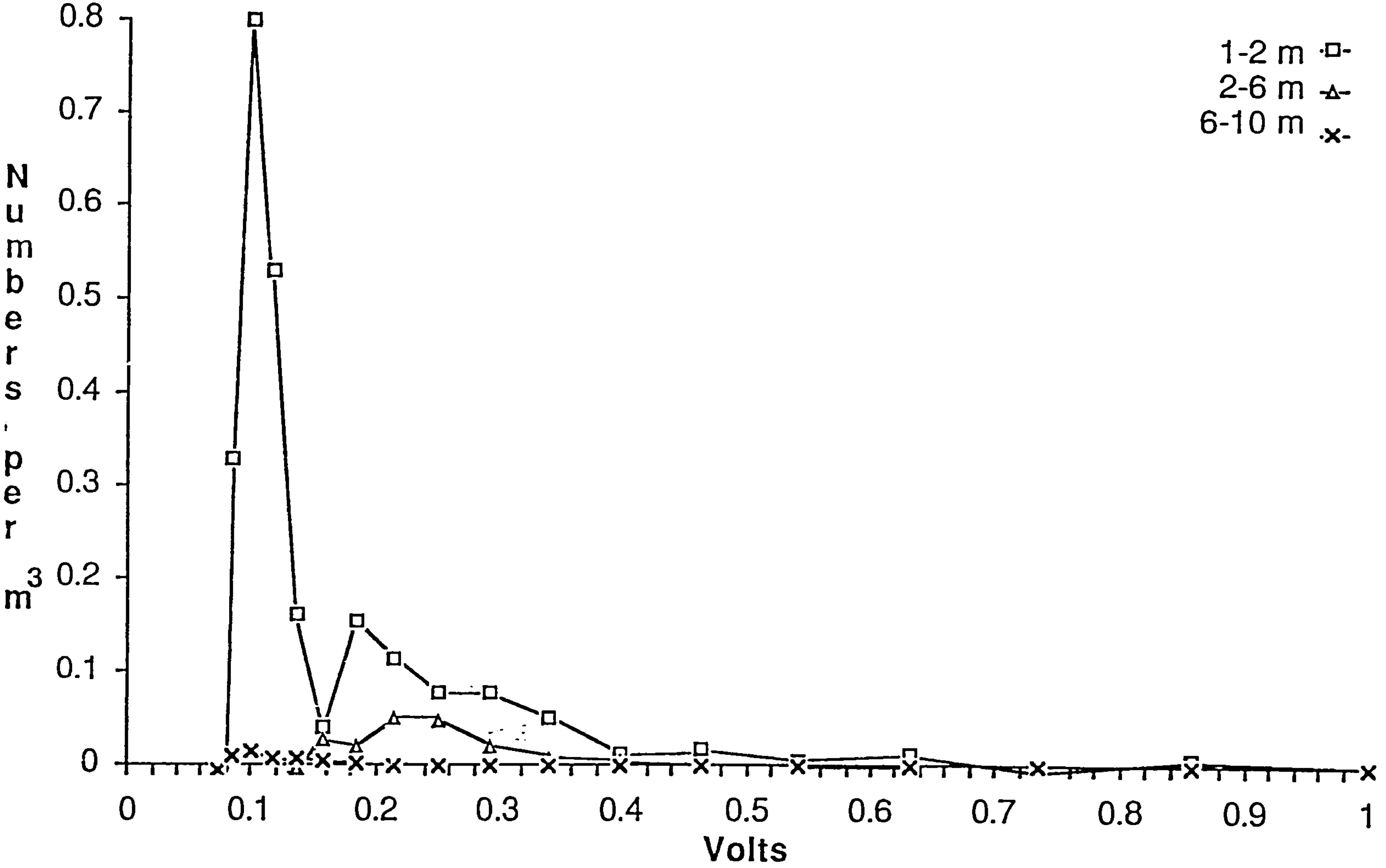

Figure 5a. Estimated on-axis distributions from one transect on 7 September 1988 after deconvolution.

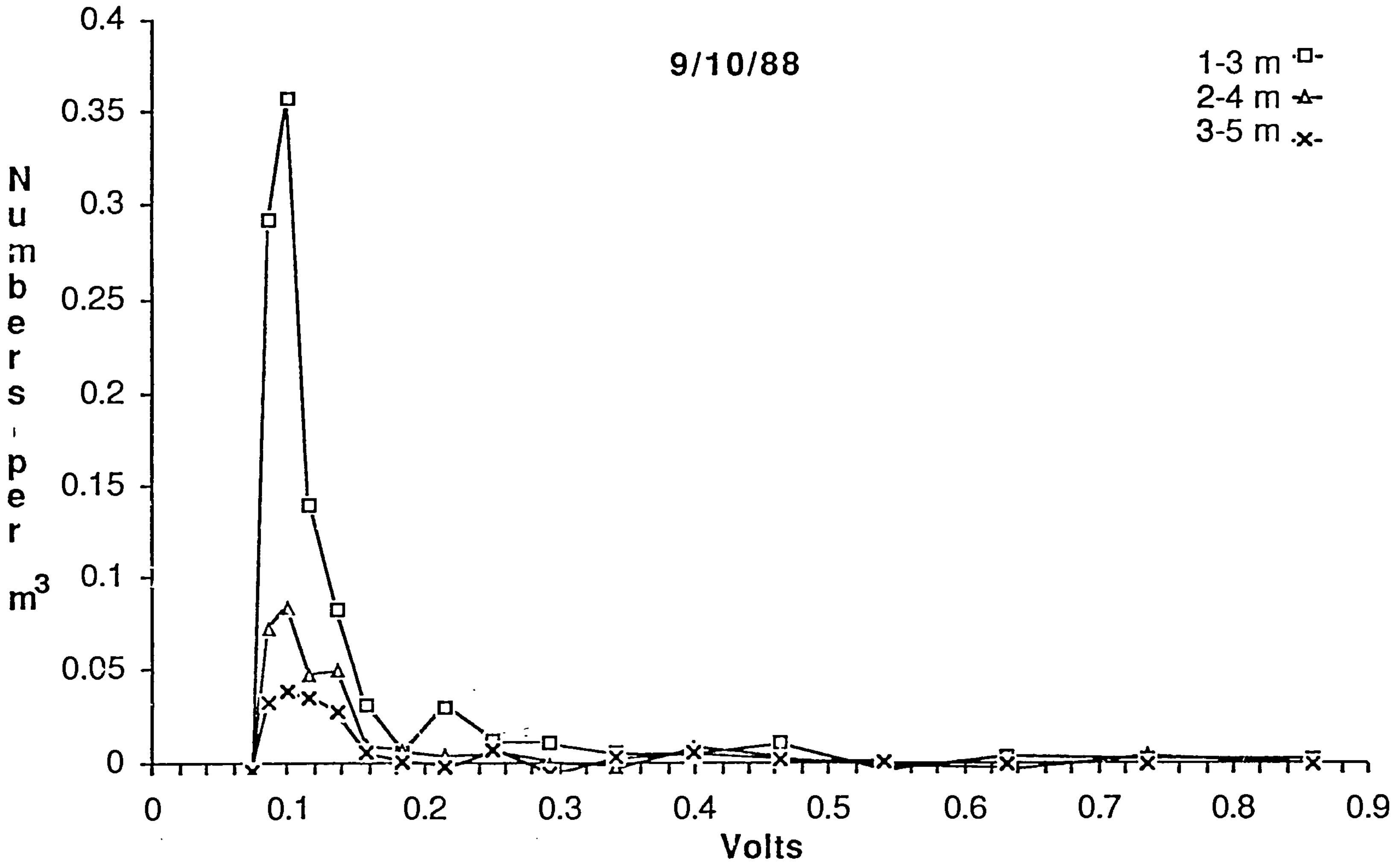

Figure 5b. Estimated on-axis distributions from one transect on 10 September 1988 after deconvolution.

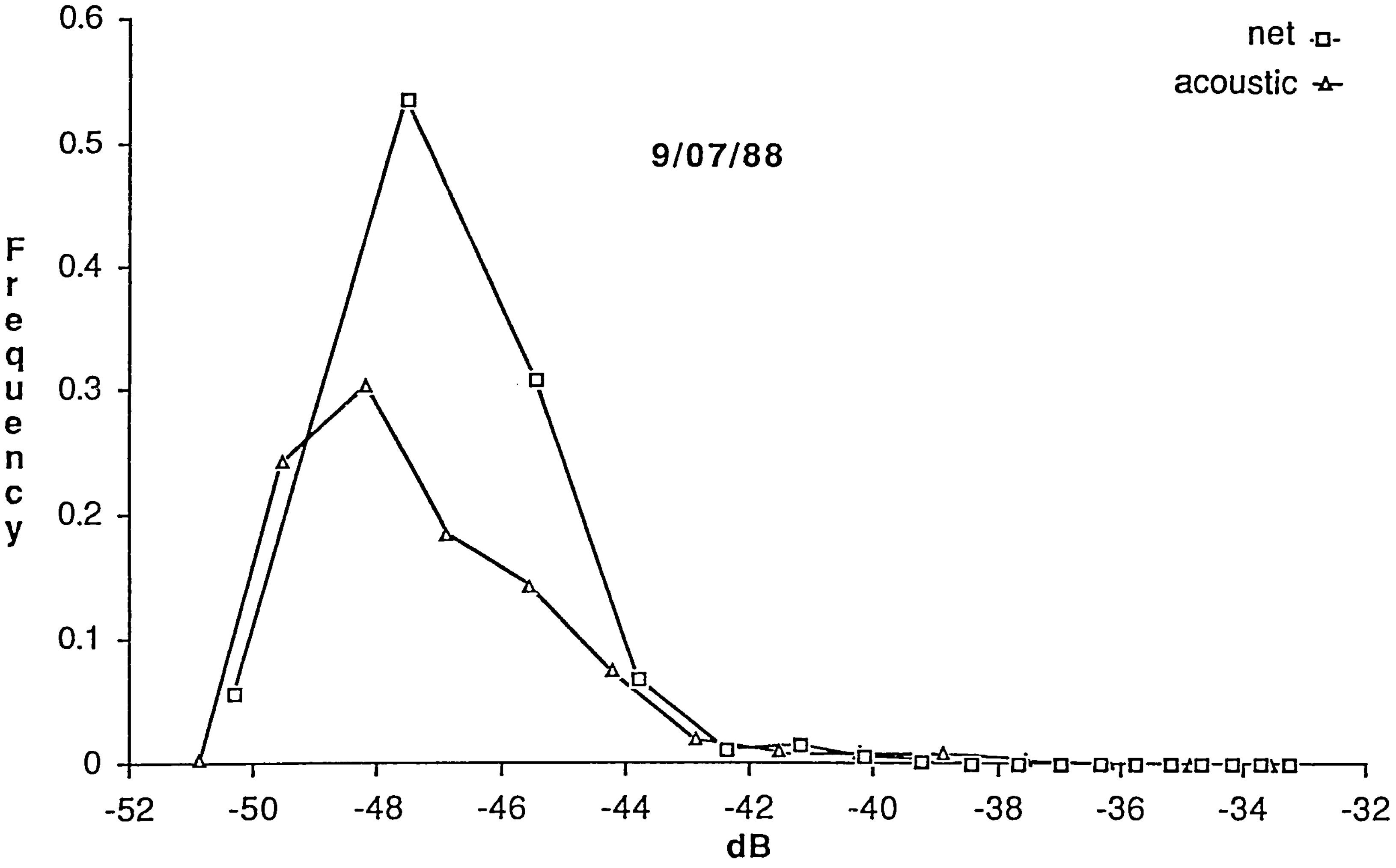

Figure 6a. Comparison between net and acoustic samples from one transect on 7 September 1988 in the Gulf of Nicoya.

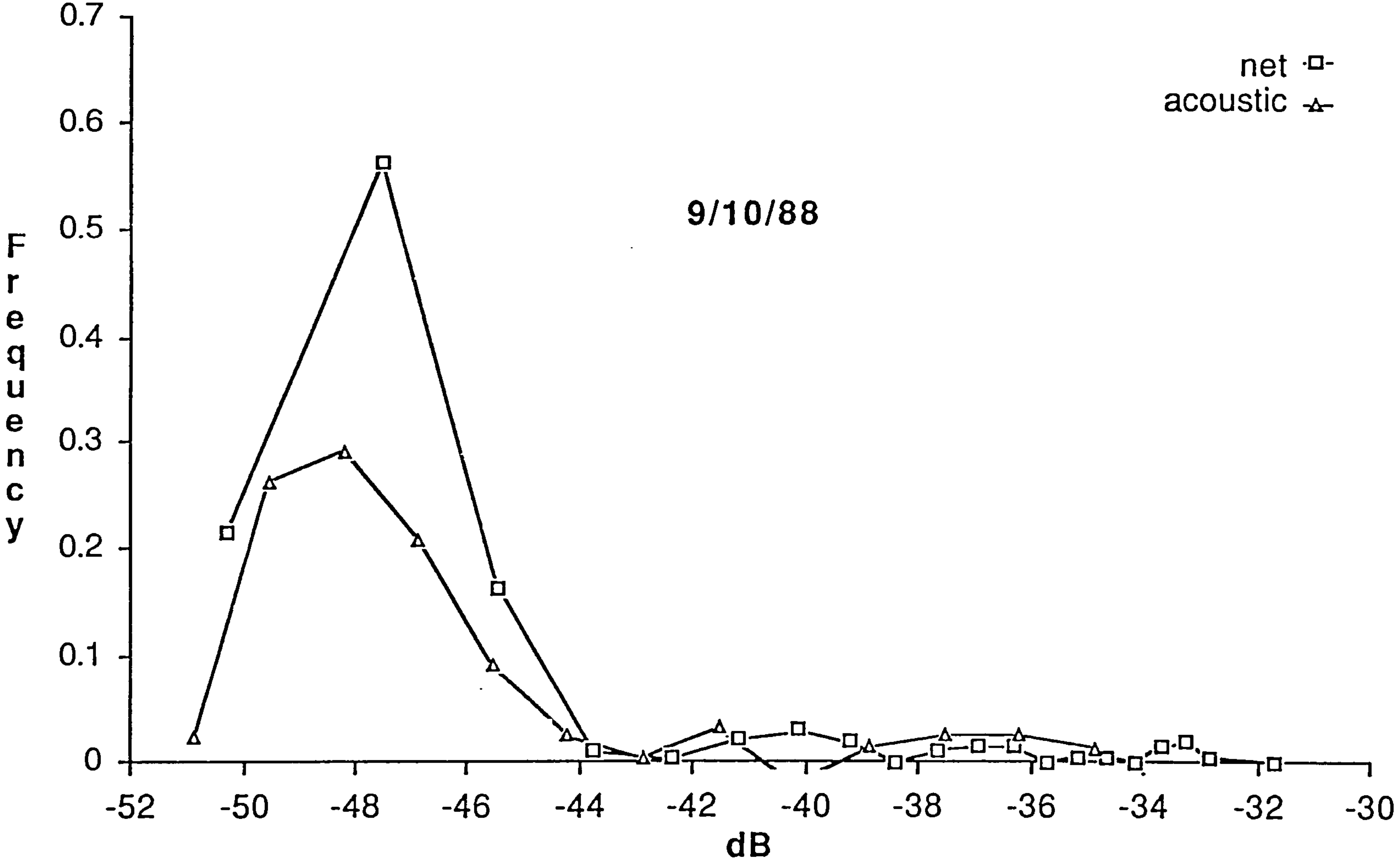

Figure 6b. Comparison between net and acoustic samples from one transect on 10 September 1988 in the Gulf of Nicoya.