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Using single-beam side-lobe observations of fish echoes for fish target strength and abundance estimation in shallow water

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Abstract − Acoustic surveys for determining fish abundance in shallow water present many challenges. One constraint to down-looking (or vertical) surveys is that the sampling volume is limited due to the short range and typically narrow beams of acoustic transducers. By utilizing more of the acoustic beam, into the side-lobes for example, the sampling volume may be increased. Although the echo energy contribution from the side-lobes is usually small, these echoes may influence target strength estimation and echo counting, and by extension affect abundance estimation either directly or indirectly. With the advent of wide dynamic range echosounders, it is possible to assess both small and large acoustic-size targets. In this case, it is possible to collect signals from large targets in the beam side-lobes, and therefore an algorithm to use side-lobe data is proposed. The smoothed Expectation Maximization method (EMS) is used to estimate densities and target strength of fish from only main-lobe and main-lobe with side-lobe observations in simulation, and suggestions are made for real data from surveys. © 2000 Ifremer/CNRS/INRA/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

fisheries acoustics / indirect estimation / target strength / fish echoes / abundance estimation / maximization and smoothing

Résumé − Utilisation des lobes latéraux d'un sonar monofaisceau, pour l'observation des échos de poissons et l'estimation de l'indice de réflexion et de l'abondance en petits fonds. Des campagnes acoustiques pour déterminer l'abondance des poissons en petits fonds présentent un certain nombre de défis. Une contrainte des campagnes d'observation vers le bas (verticale) est que le volume échantillonné est limité en raison de la portée réduite et de l'angle d'ouverture étroit des transducteurs acoustiques employés. En tirant avantage de l'existence des lobes latéraux, le volume échantillonné peut être augmenté. Bien que la contribution de l'énergie de l'écho provenant des lobes latéraux soit habituellement faible, elle peut influencer l'estimation de l'indice de réflexion et le comptage des cibles, et affecter l'estimation d'abondance soit directement soit indirectement. Avec l'arrivée d'échosondeurs à larges bandes, il est possible d'estimer à la fois des cibles de petite et grande taille acoustique. Il s'agit alors de collecter des signaux à partir de grandes cibles dans les lobes latéraux du faisceau, puis d'appliquer un algorithme spécifique à ces données. La méthode de lissage des estimations des moyennes par maximisation est utilisée pour estimer des densités et des indices de réflexion des poissons à partir des observations du lobe principal seul ou du lobe principal et du lobe latéral en simulation, et des suggestions d'application sur des données réelles de campagnes acoustiques sont faites. © 2000 Ifremer/CNRS/INRA/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

acoustique appliquée à la pêche / estimation indirecte / indice de réflexion / échos de poissons / estimation d'abondance / maximisation et lissage

1. INTRODUCTION

With the advent of wide dynamic range echosounder systems, it is possible to collect relatively good signal-to-noise measurements (as compared to poor dynamic range systems) from larger acoustical-size targets in the side-lobes of the transducer beam, especially when the assessment goal is to determine smaller acoustic-size targets. For example, this can be a significant problem in shallow water estuaries that are the nursery ground for small pelagic fish. From acoustic surveys whose initial objective was to assess large size sciaenid fish in the Gulf of Nicoya, Costa Rica it was shown that the largest fraction of fish is indeed small pelagics that are easily assessed using single-beam, single-target techniques (Hedgepeth, 1994; Hedgepeth

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et al., 2001). Because of the short range for vertical echosounding, the signal-to-noise ratio is quite high and it is possible to collect small signals from large fish in the transducer side-lobes.

Target-strength estimation when using single-beam echosounder systems leads to an inverse problem in which the probability-density function (PDF) of the target strength (*TS*) is estimated from fish echoes. Due to the hydroacoustic system characteristics the reconstruction is based on incomplete data. This kind of problem is an example of a statistical linear inverse problem (SLIP), which is typically ill-conditioned and can be solved using direct inverse techniques based on regularization (i.e. Singular Value Decomposition, SVD) or iterative ones in which additional constraints are specified (i.e. Expectation, Maximization, Smoothing-EMS) (Hedgepeth, 1994; Hedgepeth et al., 1999; Stepnowski, 1998). The ill-conditioning originates from the kernel of SLIP, which in this case is determined by beam pattern probability-density function. In many high signal-to-noise cases the observed data is restricted to a certain acoustic intensity range limited by the first side-lobe level. This approach allows omitting the problem of ambiguity of the beam-pattern function (Moszynski, 1998). Nowadays, when the dynamic range of digital echosounders has increased, it is possible that echoes from side-lobes are included in the data set (*figure 1*).

2. METHODS

A number of references to the earlier work on indirect target strength can be found in Ehrenberg (1989). Stepnowski (1998) and Hedgepeth (1994) included some of these earlier methods in simulation comparisons with those discussed below.

The statistical linear inverse problems (SLIP) are often presented as a linear operator equation:

$$y(x) = Kf(x) + n(x) \tag{1}$$

where: f = unknown function, y = observation, K = linear operator, and n = noise. In case of a fish target-strength estimation, observation y is represented as a echo level peak-values PDF $p_E(E)$, the linear operator K is constructed from the logarithmic beam-pattern PDF $p_B(B)$, and the unknown function f represents the fish target strength PDF $p_{TS}(TS)$. The noise n is an error in echo level and can represent noise in the water, noise added by the transducer, or pre-amplifier noise. Equation (1) represents the discretized version of a single-beam integral equation (Hedgepeth, 1994), a convolution-like integral of the following form:

$$p_E(E) = \int_{B_{\min}}^{0} p_B(B)\, p_{TS}(E - B - G)\, dB \tag{2}$$

where G represents the system gain ($E = TS + B + G$) and $B_{\min}$ is the lower threshold of the logarithmic beam-pattern function included in calculations.

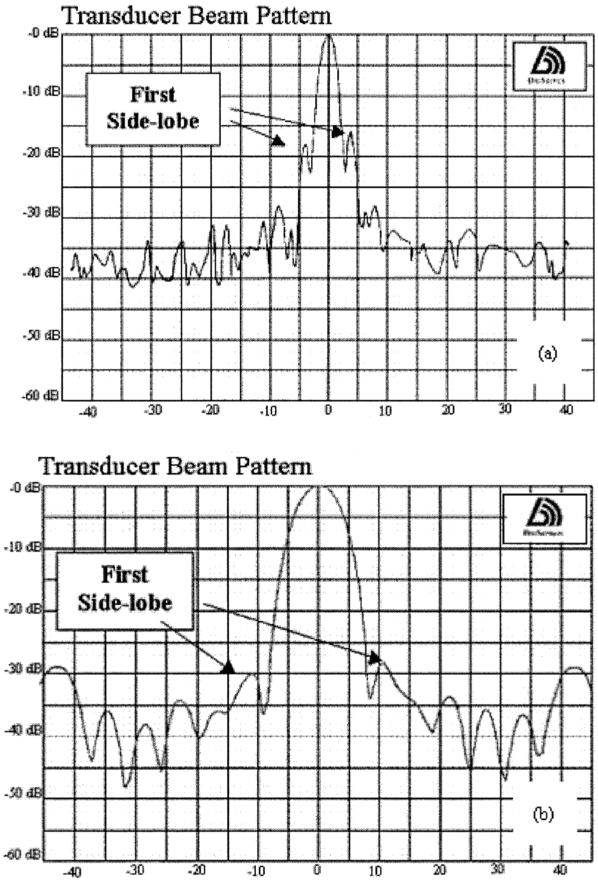

Figure 1. Two different 420-kHz wide dynamic range digital transducers demonstrate relatively high side-lobe transducer directivities (a), and relatively low side-lobe transducer directivities (b). Note: these are one-way directivities. The actual log directivity is decreased by a factor 2.

In practice the PDF $p_E(E)$ is a collection of echo levels and therefore the target-strength distribution that is indirectly estimated is a scaled PDF. The integral of the scaled target-strength distribution can be interpreted as the density of targets by dividing by volume sampled (Hedgepeth et al., 1999) and in this way the method can be used as a fish counter when fish density is much less than one fish per pulse volume.

For the PDF calculation, consider the ideal circular piston in an infinite baffle. Its one-way beam-pattern function b is:

$$b(\theta) = \frac{2J_1(x)}{x} \tag{3}$$

where is x defined by $x = x(\theta) = ka \sin\theta$ (k = wave number, a = transducer radius, θ = angle from beam axis to target) and $J_n(x)$ = Bessel function of first kind order n. *Figure 2* presents the logarithmic version of the two-way pattern which is derived by transform $B(\theta) = 10 \log b(\theta)^2 = 20 \log b(\theta)$.

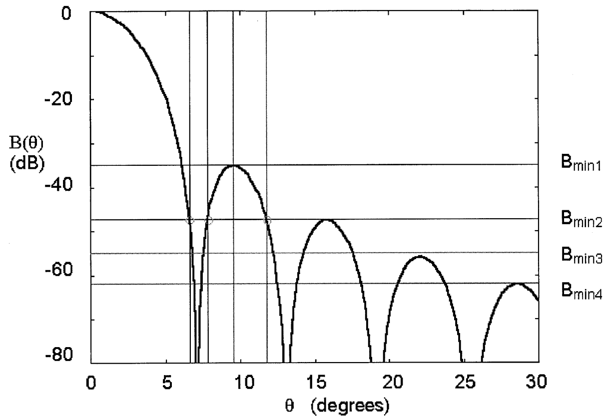

Figure 2. Two-way beam-pattern function for an ideal circular piston in an infinite baffle, showing four side-lobes. The main-lobe has a minimum directivity of $B_{\min1}$ where each B is assumed to have a single θ (degrees off-axis). From $B_{\min1}$ to $B_{\min2}$ the directivity takes he same level at three values of θ. Each side-lobe adds an additional two values of θ.

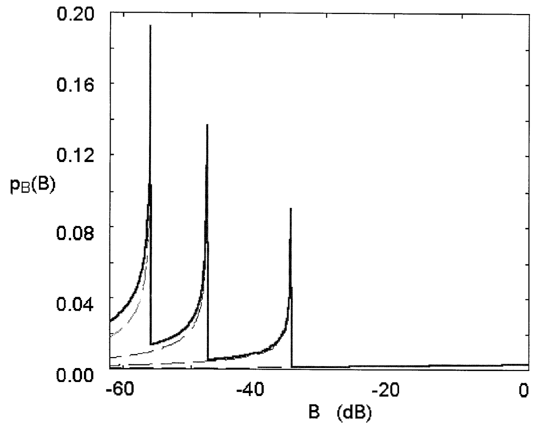

Figure 3. Theoretical beam-pattern probability density function $p_B(B)$ as a function of beam directivity B for an ideal circular piston when three side-lobes are included.

The kernel function of the inverse problem, $p_B(B)$, for a two-way system is obtained from its absolute version $p_b(b)$, which may be expressed as a parametric function $p_b(b) = (b^2(\theta), (p_b(\theta))$ with angle θ as a parameter:

$$p_b(b) = \left(\left(\frac{2J_1(x)}{x} \right)^2, \frac{p_\theta(\theta)\tan\theta}{\left| \frac{8J_1(x)\,J_2(x)}{x} \right|} \right) \quad (4)$$

where $p_\theta(\theta)$ is a probability-density function of random angular position of fish. Then using the logarithmic transform of variables $B(b) = 20\log b$ its PDF relation may be written as:

$$p_B(B) = \frac{\ln 10}{20}\,|10^{\frac{B}{20}}|\,p_b(10^{\frac{B}{20}}) \quad (5)$$

Calculation of the PDF of fish position p_θ is based on the assumption of a uniform fish distribution in the water column (Cartesian coordinates), which gives a *sine*-like distribution of the angular position θ (Hedgepeth, 1994):

$$p_\theta(\theta) = \frac{1}{1 - \cos\theta_{\max}}\sin\theta \quad (6)$$

where $\theta_{\max}$ is the maximum angle of the beam pattern involved in the calculation, and for $\pi/2$, or a hemispherical volume, results in: $p_\theta(\theta) = \sin\theta$.

When only the main-lobe of the beam pattern is used, the inverse of the beam-pattern function needed for $p_b(b)$ computation is single-valued. Note, however, that when side-lobes are involved the inverse function is non single-valued (*figure 2*) and then its PDF calculation must be made for all angles θ having the same value B. This makes equation (3) still valid but the inverse function $\theta(b)$ needs to be computed to find all occurrences of θ for every b. This is followed by the summation of PDF values for those angles. The inverse of beam-pattern function, $\theta(b)$, may be calculated iteratively using Newton iteration $x_{n+1} = x_n - f(x_n)/f'(x_n)$, which for a theoretical beam pattern leads to the following rule for frequency-space x determination:

$$x_{n+1} = x_n + \frac{J_1(x_n) + \frac{bx_n}{2}}{J_2(x_n)} \quad (7)$$

followed by angle determination θ from variable x:

$$\theta = arc\sin\frac{x}{ka} \quad (8)$$

The final result of this approach is presented in *figure 3*, which shows the theoretical beam-pattern PDF $p_B(B)$. with inclusion of three side-lobes. The components from each of the side-lobes are presented as dotted lines. Note the theoretical left-sided infinities in the PDF where side-lobes reach local maxima.

To construct the kernel of the inverse problem described by equation (1), the beam-pattern PDF needs to be discretized. In most cases this leads to a simple sampling of a theoretical PDF. In the case containing side-lobes, due to infinities and the discretation of the observed echo-level PDF $p_E(E)$, reconstruction must be done carefully. To check the behavior of the discretized version of the beam PDF another method is suggested. The distribution described by equation (6) can be generated using an inverse of the cumulative distribution-function (CDF) method. The inverse of a *sine*-like distribution is a *cosine*-like function. Hence, the angular-position distribution may be generated by

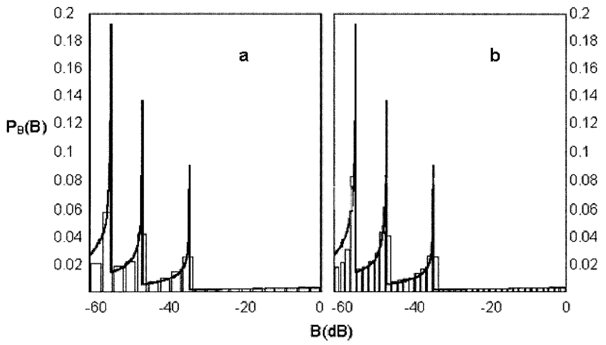

Figure 4. Randomly generated beam-pattern probability density function for ideal circular piston, (a) 20 bins (b) 40 bins.

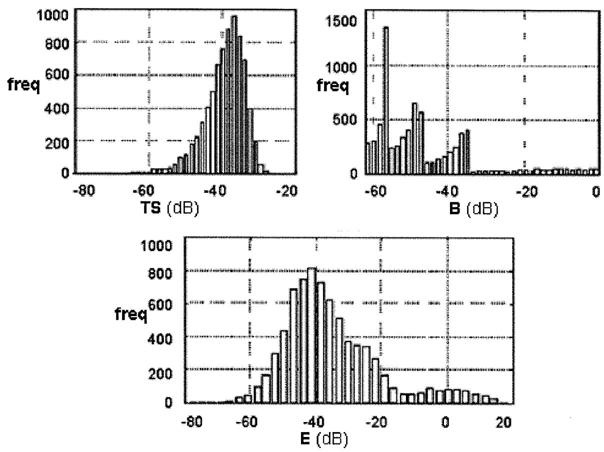

Figure 5. Simulated (sampled) probability density functions (PDFs). (a) Target strength PDF, (b) beam-pattern PDF, and (c) echo-level PDF. The simulated PDFs are actually represented by frequencies in decibel intervals of the target strength *TS*, observations *E* and beam-pattern directivity *B*.

transforming a uniform distribution by the *arccos* function. To obtain the distribution of the beam pattern, equation (3) is applied to the angular-position distribution followed by a logarithmic transformation. The results of this approach are presented in *figure 4* in form of a histogram chart with the theoretical PDF as a solid curve for comparison purposes. The histogram in *figure 4a* was generated using 10 000 realizations divided into 20 bins. The histogram in *figure 4b* used a 100 000 realizations divided into 40 bins. Note that the discrete approximation depends not only on bin width but also on bin position, especially when the bin contains a theoretical infinity and low values together. Additionally, the values in border bins may be inaccurate.

3. RESULTS

Being aware that care should be exercised in determining the discretized beam-pattern PDF function with side-lobes, the next step is to use it as the kernel of an inverse method for target-strength PDF estimation. Expectation, Maximization, and Smoothing (EMS), a robust iterative statistical technique, was adapted to this problem because its performance has been thoroughly tested (Hedgepeth, 1994; Stepnowski, 1998). To check performance in the case of side-lobe data, simulation data was generated. The fish backscattering cross-section σ_{BS} distribution was assumed to have a Laplace distribution, which, when transformed to the target-strength domain, represents a logarithmic Raleigh-distribution function. Note that the Raleigh distribution has often modeled the square root of σ_{BS} (e.g. Clay 1983). The histogram of simulated *TS* values is presented in *figure 5a*. The results of the simulation of the beam-pattern distribution (*figure 5b*) described in the previous section were used for the random values of beam pattern *B*. The –3 dB value of the beam pattern was set at 3° giving 6° of beam width and 23° was used as effective angular range, giving 62 dB of logarithmic dynamic range. The system constant *G* was set to 50 dB. The resulting echo-level PDF is shown in *figure 5c*.

Figure 6 shows splined probability density function estimates. Note, that if one wants to reconstruct the 40-dB range of *TS* data (from –70 dB to –30 dB) the rule of thumb in inverting the incomplete data says to select the 40-dB range of the observation and also the 40-dB range of kernel data. Otherwise, one runs a risk of using observations without complete representation. As an example, in *figure 6c*, the result of a direct convolution of bold parts of curves from *figures 6a* and *6b*, both having a 40-dB range, are presented. Only the half of it matches the simulated echo-level PDF, so only the 40-dB range from –20 dB to 20 dB is valuable to reconstruction purposes.

Figure 7 shows inverse reconstruction performances. To make the simulation more realistic, random observation noise was added to observation data (*figure 7a*). This does not consider system noise but it does consider processing and sampling errors. *Figure 7b* shows the naive reconstruction using the Singular Value Decomposition technique and *figure 7c* shows the EMS output compared to the original target-strength PDF $p_{TS}(TS)$. Both outputs were used as a data source, and after running through the direct process again, compared with a part of observation used in inverse process.

4. DISCUSSION

This paper presents the addition of side-lobe observations in the inverse process of reconstructing fish target-strength densities from single-beam data. It is especially valuable for new digital echosounders with increased dynamic range properties. A theoretical approach to the construction of the probability-density function of the beam pattern with side-lobes is presented. The shape of this function, which has local

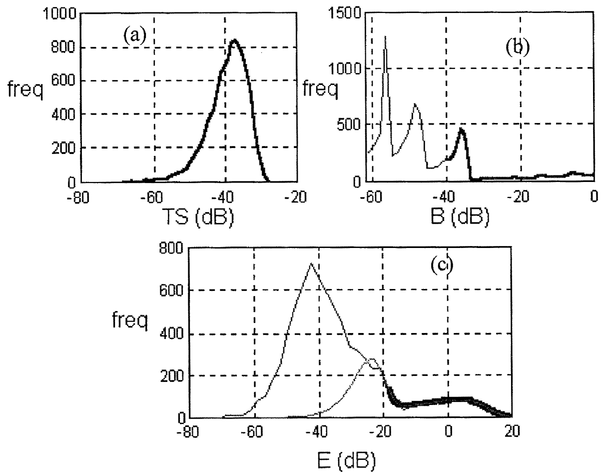

Figure 6. Splined versions of histogram data. The bold part of the curves represents data used in inverse process. (a) Sampled target-strength PDF, (b) sampled beam-pattern PDF, and (c) sampled echo-level PDF.

infinities, needs careful treatment and a robust inverse method. The smoothed Expectation and Maximization method was used as an iterative inverse method and its usefulness was confirmed by tests run on simulated data.

In shallow water fisheries applications, with the wide dynamic range available in modern echosounders, side-lobe data will be useful because range does not limit the signal to noise ratio as in deep water. Realistically, the first two side-lobes would need to be included for the up to 55-dB range of echo collection (*figure 1a*). The two-way directivity of an ideal piston transducer at the third side-lobe is 55.9 dB down from the maximum sensitivity. Current echosounder dynamic ranges can exceed the 120 dB, but noise often limits data to less than a 60-dB range. It should also be pointed out that low side-lobe transducers approach this range without side-lobe intrusion (*figure 1b*). However, with many transducers and applications it may be possible to partition probabilities in a single inversion with large and small acoustic-size fractions.

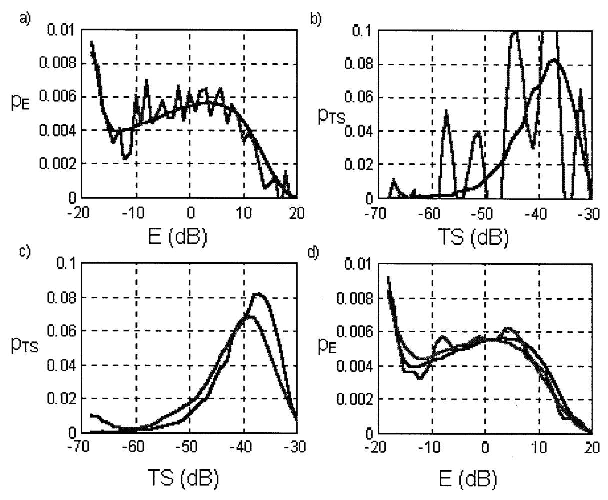

Figure 7. Reconstruction of: (a) source data with random noise, (b) naive reconstruction, (c) Expectation, Maximization and Smoothing (EMS) reconstruction, and (d) verification.

There are some other issues that can occur at short ranges. Users need to assure that the range to the fish is greater than the far-field for the transducer (approximately the transducer diameter squared divided by the wavelength). Also at close ranges, the fish may present a nearfield directivity or may be over-resolved by the transducer and therefore the target strength will differ from that measured when the fish is at a greater range.

We considered only the unimodal distribution for the sake of simplicity. The simulation should be extended to include multi-modal target-strength distributions (e.g. Parkinson et al., 1994) as a function of signal-to-noise ratios from 20 dB to 60 dB (mean on-axis to mean noise intensity). This kind of simulation of real-life conditions has been shown quite useful before embarking on the next phase of field data collection.

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