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INDIRECT FISH TARGET STRENGTH ESTIMATION USING ADAPTIVE KERNEL

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The typical approach to the problem of indirect fish target strength estimation from data collected using single-beam system is based on inversion of probability density function (PDF) of measured fish echo level. Due to ill-conditioning of most inversion algorithms, small errors in input data, and inaccuracies in the assumed form of the kernel, may result in large errors at the output. Therefore, all modern inversion algorithms use sophisticated techniques to achieve satisfying results, assuming fixed kernel in the inversion procedure. The paper presents different approach, which uses adaptive construction of the kernel, under assumption of non-negative constraints in the obtained estimate of fish target strength PDF. As a result, the more reliable beam pattern PDF is obtained which leads to unbiased and more accurate estimate of fish target strength PDF, than in the conventional (fixed kernel) methods.

INTRODUCTION

Indirect fish target strength estimation when using single-beam echosounder data leads to the inverse problem in which the probability density function (PDF) of target strength is estimated from fish echoes. Mathematically the problem is described by so-called single-beam integral equation , as a convolution-like integral of the following form [1]:

$$p_E(E)=\int_{B_{min}}^{0} p_B(B)p_{TS}(E-B)dB \qquad (1)$$

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

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), often presented as a linear operator equation:

$$y=K\,x+n \qquad (2)$$

where observation y is represented by echo level peak values PDF $p_E(E)$, linear operator K (kernel) is constructed from logarithmic beam pattern PDF $p_B(B)$ and x is unknown function representing fish target strength PDF $p_{TS}(TS)$. The noise n is an error in echo level PDF and can represent acoustic noise in the water and electrical noise of the echosounder receiver. Statistical linear inverse problems are typically ill-conditioned and can be solved using direct inverse techniques based on regularization (i.e. Windowed Singular Value Decomposition - WSVD) [4] or iterative ones in which additional constraints are specified (i.e. Expectation, Maximization, Smoothing - EMS) [3]. The ill-conditioning originates from the kernel of SLIP, which in this case is determined by beam pattern probability density function. In majority of high signal to noise ratio cases the observed data are restricted to a certain echo amplitude range limited by the first side-lobe level, which allows omitting the problem of ambiguity of beam pattern function [5].

1. METHODS

A number of references to the earlier work on indirect target strength can be found in [2]. In [3] and [5] the authors investigated some of the earlier methods and introduced some novel inverse techniques. Generally, two kinds of inverse methods direct and indirect (iterative), described below, are used.

Direct inverse techniques using regularization are based on pseudo-inversion in which Moore-Penrose matrix $K^{\#}$ derived from the kernel K of Eq.(2) is used. This matrix provides the minimum-norm least squares solution to the problem of finding the unknown vector x, that simultaneously minimizes the squared equation error $\|Kx-y\|_2$. This pseudo-inverse matrix can be effectively computed using SVD techniques and some other modification applied by introducing weighting factors w_j to singular values γ_j, what leads to solutions in the form [5]:

$$\hat{x}_{WSVD} = \sum\nolimits_j w_j \gamma_j^{-1} [\, y, h_j \,] e_j \tag{3}$$

where γ_j^2 and e_j are, respectively, the eigenvectors and eigenfunctions of K^*K, normalized image is defined by $h=K/\|K\|$, and $[.,.]$ is the standard inner product in L_2 space.

The EMS technique is an example of indirect inverse technique. In addition the method constrains estimates to be positive and reduces the time needed to converge by smoothing groups of estimates per iteration. Every iteration procedure performed during solution consists of three steps called respectively: expectation, maximization and smoothing. First step estimates the statistics of y as a conditional expectation $y^{(n)}=E(y|\sum_i y_{ij}, x^{(n)})$ where $^{(n)}$ denotes n-th iteration. Second step takes the estimated data to calculate maximum likelihood estimates as a solution of the following equation: $E(y_{ij}|x)=y^{(n)}$. The last step in every iteration smoothes solution x using Gaussian kernel with locally weighted end points. The smoothing process centers the kernel at each data point: $x^{(n)'}=\sum_j S_{ij}\, x^{(n)}$, where S is smoothing matrix. Finally, assuming that observation y results from a Poisson process we received equation describing first two EM steps in a form [5]:

$$\hat{x}^{(n)}_{EMS} = \frac{x^{(n-1)}}{\sum_i K_{ij}} \left(\frac{y^t}{x^{(n-1)}\mathbf{K}^T} \mathbf{K} \right) \tag{4}$$

As stated before, SVD technique gives the solution with minimum squared error, which is typically used as a natural measure of global goodness-of-fit test for an estimate. However, due to sine-like nature of eigenfunctions e_j of linear operator Eq.(3), SVD often leads to the artifacts when interpreting obtained estimate as a probability density function (Fig. 1). The EMS estimate represents more smooth class of functions than those obtained by SVD and can be treated as a good estimate for a class of probability density functions, although resulting mean square error is much larger.

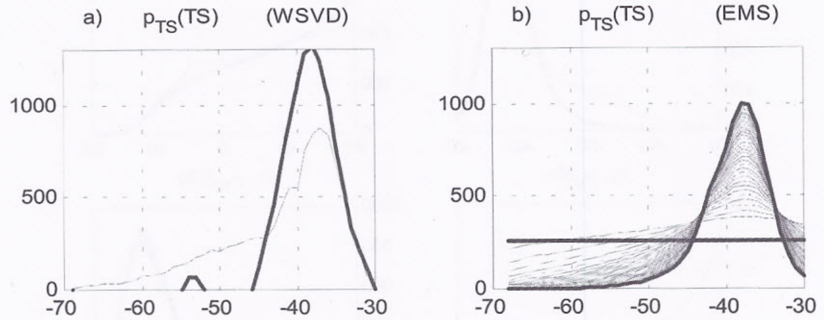

Fig. 1. a) Target strength PDF estimate using direct WSVD algorithm (thin line represents the dual beam estimate) b) TS PDF estimate using iterative EMS algorithm (all 32 iterations from initial uniform distribution).

The idea, which will be verified in the paper states that the square error for EMS can be minimized and the smoothness of solution will be preserved by the changes introduced in the kernel K of integral equation Eq.(1). This is particularly relevant for the case of fish target strength estimation as the construction of the kernel is based on heuristic assumption made on angular distribution of fish in calculation of beam pattern PDF. Thus, the estimation algorithm may adaptively change kernel K by solving another inverse problem in which the beam pattern PDF p_B is reconstructed from echo level PDF p_E and target strength PDF p_{TS} estimated just before. New estimate of p_B PDF allows calculating new kernel matrix K, which is used in the next step of such adaptive algorithm. The process can be terminated comparing the difference between two successive estimates.

2. RESULTS

To verify the idea of adaptive EMS technique the data provided by Parkinson from Coeur d'Alene Lake, Idaho survey [4] were used. Over 10000 echoes were acquired by a dual-beam system operating on 420kHz and post-processed by the sounder software. Narrow beam data were used for indirect estimation. Data from both beams were used to construct the estimate only for comparison purposes. Fig.2a. shows p_{TS} estimate obtained after first adaptive EMS step, its verification in the form of actual p_E and p_E obtained by convolution of p_{TS} estimate with assumed p_B estimate is presented in Fig 2b. Fig 2c shows reconstruction of beam pattern PDF p_B from the actual p_E and p_{TS} estimated just before. Fig. 2d presents next two estimates of p_{TS} obtained in successive adaptive steps. Table 1 reports the value of root-mean-square error for WSVD and three first adaptive EMS steps.

Tab.1. Root-mean-square error of WSVD estimate and successive adaptive EMS (AEMS) estimates.

	WSVD	EMS	AEMS (n=1)	AEMS (n=2)	AEMS (n=3)
RMS error	0.0231	0.1288	0.0477	0.0426	0.0419

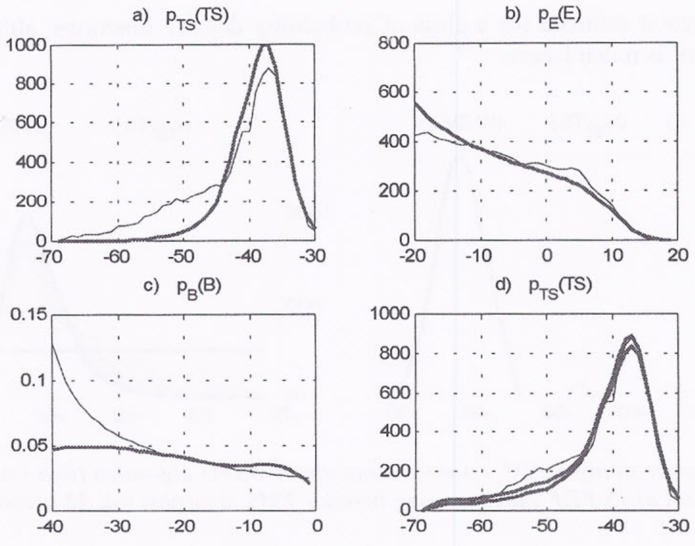

Fig.2. a) First EMS reconstruction of the target strength PDF compared with estimate obtained from dual-beam data (thin line), b) verification of first EMS reconstruction with actual echo PDF (thin line) , c) reconstruction of beam pattern PDF compared with assumed one (thin line) d) two successive adaptive EMS estimates (thin line – dual-beam estimate).

3. CONCLUSION

It was shown that adaptive EMS (AEMS) inversion technique proposed by the author, which uses modified kernel, gives better results than so far used inversion methods with fixed kernel. Application of AEMS results in smaller rms error as compared with those obtained when using SVD techniques and simultaneously represents good estimate for class of probability density functions. Additionally, as a result of kernel modifications, more adequate beam pattern PDF is obtained which leads to more reliable estimate of fish target strength PDF, than in conventional methods based on heuristic approach.

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