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INVERSIONS OF STATISTICAL PARAMETERS OF AN ACOUSTIC SIGNAL IN RANGE-DEPENDENT ENVIRONMENTS WITH APPLICATIONS IN OCEAN ACOUSTIC TOMOGRAPHY

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1 INTRODUCTION

The statistical characterization of an underwater acoustic signal has been recently introduced in problems of ocean acoustic tomography and geoacoustic inversions, with encouraging results as regards the recovery of the environmental parameters using appropriate inversion procedures [1-3]. The test cases examined so far were based on range-independent environments. Simulated data either produced by the authors, or provided by third parties have been used to validate the signal characterization scheme and the associated inversion procedures [4]. Both noise-free and noisy data have been considered.

In this paper, the inversion procedure is applied in range-dependent environments. The aim of the study is to assess the applicability of the method for the recovery of range-dependent parameters in range-dependent environments. To this end we considered an environment with irregular bottom but range-independent sound speed profile and an environment with flat bottom with range-dependent sound speed profile representing a cold eddy. In the first environment, the recovery of the geometry of the water-bottom interface was studied, while in the second environment, the recovery of the structure of the eddy has been examined. The results obtained, confirm that the statistical characterization of a typical tomography signal can in principle be applied with acceptable efficiency in range-dependent environments for inversion purposes at least for the typical cases studied here.

2 INVERSIONS BASED ON THE STATISTICAL CHARACTERIZATION OF THE ACOUSTIC SIGNAL

2.1 Statistical Characterization

The details of the signal characterization based on the statistical analysis of the wavelet sub-band coefficients have been presented in previous works and will not be repeated in detail here. Instead an outline of the method will be presented. According to the method, an acoustic signal $S(t)$ is characterized by means of the statistical parameters of the coefficients resulting from the application of a 1-D Discrete Wavelet Transform (DWT) to the discrete signal $\langle S, \psi_{a,b} \rangle$, where $\psi_{a,b}$ is an appropriately chosen wavelet, with subsequent convolution by a High-Pass and a Low-Pass filter giving two sets of coefficients called "detailed" $\mathbf{d}_1[n; S]$, and "approximate", $\mathbf{a}_1[n; S]$. By continuing this process using the detailed coefficients up to the k^{th} level of decomposition the signal is represented as a first step by the vectors of coefficients obtained through this multilevel analysis. The approximate coefficients are kept at the final level only.

It has been shown in [1] that the coefficients of the wavelet coefficients of a typical underwater signal emitted from a Gaussian source obey a Symmetric Alpha Stable distribution (SaS) described by its characteristic function:

$$\Phi(t) = \exp(i\delta t - \gamma^a |t|^a) \quad (1)$$

where $0 \leq a \leq 2$ is the characteristic exponent which controls the marginal behaviour of the tails, $-\infty < \delta < \infty$ is the location parameter and $\gamma = 0$ is the dispersion of the distribution, which determines the spread of the distribution around the location parameter δ . t is the value of the coefficient.

In our case $\delta = 0$ and the signal S is eventually characterized by a vector \mathbf{d} of dimensions $2L+2$ as following:

$$S \leftrightarrow \{\Phi^0, \dots, \Phi^L\} \leftrightarrow \mathbf{d} = (a^0, \gamma^0, a^1, \gamma^1, \dots, a^L, \gamma^L). \quad (2)$$

L is the total number of levels considered.

2.2 Inversion Procedure

Following the formulation described above, the signal measured in a typical experiment of ocean acoustic tomography or geoacoustic inversion, is characterized by the vector \mathbf{d} . At the same time, as shown in [1], the vector is sensitive to small changes of the environmental parameters, which of course lead to different receptions of the same source. When these parameters are described by a vector \mathbf{m} , an appropriate propagation model provides the background for the definition of a discrete inverse problem of the form :

$$\mathbb{T}(\mathbf{d}, \mathbf{m}) = 0, \quad (3)$$

In the notation to follow, \mathbf{m}^{est} is the vector of the parameters estimated by solving the inverse problem.

The inverse problem is non-linear and is typically solved as an optimization procedure minimizing or maximizing an appropriate cost function and searching for possible solutions among a pre-defined search space. When the statistical characterization scheme is considered, the cost function is taken to be the Kullback Leibler Divergence (KLD) which expresses the difference (or distance) D_s between two acoustic signals S_1 and S_2 , when these signals are characterized by some statistical distribution of selected coefficients. In the case of two signals represented by the parameters of the SaS distributions of the wavelet sub-band coefficients as described above, the KLD is expressed in closed form according to the following equation:

$$D_s(S_1, S_2) = \sum_{k=0}^L \left\{ \ln \left(\frac{c_2^k}{c_1^k} \right) \right\} - \frac{1}{a_1^k} + \left(\frac{\gamma_2^k}{\gamma_1^k} \right) \frac{\alpha_2^k \Gamma \left(\frac{\alpha_2^k + 1}{\alpha_1^k} \right)}{\Gamma \left(\frac{1}{\alpha_1^k} \right)}, \quad (4)$$

where $\Gamma(x)$ is the Gamma function and

$$c_i^k = \frac{2\Gamma \left(\frac{1}{\alpha_i^k} \right)}{\alpha_i^k \gamma_i^k}, \quad i=1,2 \quad (5)$$

Formula (4) is based on the assumption that the statistical character of the wavelet coefficients at each level is independent to that of another level.

In the case of tomographic or geoacoustic inversions in underwater acoustics, the parameters to be recovered are typically the parameters describing the sound speed profile in the water column and/or in the sea-bed, the densities of the various layers of the ocean environment, the location of the interfaces, the attenuation coefficients in the various layers and the shear speeds in the sea-bed if an elastic bottom is considered. These parameters are normally treated as discrete unknowns forming the vector \mathbf{m}

The inversion procedure requires the calculation of the signal observables $\tilde{\mathbf{d}}$ based on the model parameters $\tilde{\mathbf{m}}$ taken within a pre-defined search space, using a suitable propagation model to obtain the corresponding acoustic signal \tilde{S} followed by the signal processing and characterization. Whatever the D_s is, the systematic search over the multidimensional search space is time consuming and in general is accelerated by some directive algorithm that reduces substantially the elements of the search space which are introduced in the optimization process.

In our work we have used the Genetic Algorithm (G.A.) described in [3], in association with the KLD. The G.A. is initiated by a random population of model parameters $\tilde{\mathbf{m}}_0$ and is terminated after a certain number of generations is reached, providing a population of "possible" solutions $\tilde{\mathbf{m}}_f$ to the optimization problem. In our work we present the possible solutions using an a-posteriori distribution of the individual members of the population. This representation has been shown to give an adequate indication of the possibility that a specific value of the model parameter is the actual solution to the inverse problem. The \mathbf{m}^{est} is taken to be the solution corresponding to the highest value in the distribution.

3 APPLICATION IN RANGE-DEPENDENT ENVIRONMENTS

The statistical characterization of the acoustic signal was tested so far for inversion purposes, in range-independent environments only. Now it is tested in range-dependent environments to assess its functionality. It should be noted that in all the cases the modeling is performed in axially-symmetric environments.

When a range-dependent environment is considered, the formulation remains the same but several key factors controlling the procedure should be taken into account. First of all, the initial concept of ocean acoustic tomography or geoacoustic inversion has been based on the hypothesis that range-average characteristics of the environment could be recovered. Later it has been shown (see for instance [5]), that even range-dependent parameters could be recovered provided that some a-priori knowledge of their character is available. For instance an eddy is described as a sound speed anomaly of compact support. This means that there is some indication of the start and of the end of the anomaly in range. The sound speed variation in depth can be treated using historical information and projecting the differences with respect to some mean velocity structure in terms of Empirical Orthogonal Functions (EOFs) with the corresponding coefficients varying in range.

We consider here, two typical cases: a shallow water environment with irregular water-bottom interface and a shallow water environment with flat bottom but including a cold eddy in the water column. For the first case, the geometry of the interface (a sea mount) will be recovered, while in the second case the structure of the eddy will be estimated.

In both cases, the Normal-Mode program MODE 4 based on a full coupling between modes [6] has been used to calculate the system transfer function (acoustic field at a specific frequency), which eventually leads to the reference signal which simulates the measurement at a single receiver by means of a Fourier transform. A Gaussian source has been considered, which is an adequate representation of an actual tomographic source.

3.1 Sea-mount

Table 1 presents the environmental parameters of the case with the sea mount. The mount is described as of bilinear symmetric shape (See Figure 1). The unknown parameters are four, namely the range at the start of the mount, the range at its maximum height, the depth of the summit and the range at the end of the mount. All the other environmental parameters are considered range-independent, but this is not a restriction in the application of the inversion procedure, as the forward model can treat any type of range dependency. The search space and the inversion results corresponding to the best solution obtained by means of the G.A. after 40 generations are indicated in the table as well.

Table 1. The parameters of the environment with the sea-mount

	Actual Value	Search Space	Estimated Value
Water depth (m)	100		
Sound speed in water (m/sec)	1500		
Density of the water (kg/m ³)	1000		
Starting range of the mount (m)	2000	1500-2500	1997
Range at maximum mount height (m)	4000	3800-4200	4020
Water depth at the mount summit (m)	50	40-60	49.7
Ending range of the mount (m)	6000	5800-6200	5998
Sound velocity at the bottom (m/sec)	1600		
Density of the bottom (kg/m ³)	1200		
Source depth (m)	25		
Receiver depth (m)	25		
Receiver range (m)	10000		
Central Frequency/Bandwidth (Hz)	50/50		

Figure 1 presents the “actual” and the reconstructed sea mount. The reconstruction is considered excellent as all the four unknown parameters are recovered with very good accuracy. Of course the case can be considered as very “simple” yet it gives an indication of the applicability of the inversion procedure in terms of the statistical signal characterization in range dependent environments.

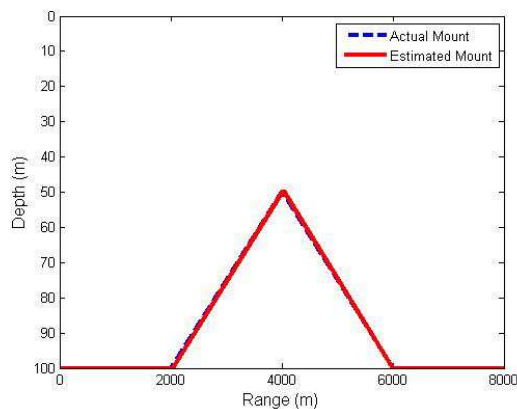


Figure 1. The actual and reconstructed sea mounts. There is no obvious difference between them.

3.2 Cold eddy

For comparison reasons we have also considered the environment studied in [5]. The case is more interesting for typical applications of acoustical oceanography when oceanographic structures of 2-D character must be estimated. In our case, the cold eddy is globally represented by means of three orders of EOFs $f_n(z)$ appearing in Figure 2 which represent the deviation from a reference sound speed profile $c_0(z)$, according to formula 6. In the real world the EOFs are obtained by analyzing historical data representing typical anomalies in the water column. In order to assess the range-dependent structure of the eddy, five segments of equal width are considered. In each of these segments the sound speed profile is given by the following formula.

$$c_i(z) = c_0(z) + \sum_{n=1}^3 a_{i,n} f_n(z), \quad i = 1-5 \quad (6)$$

The coefficients $a_{i,n}$, $i = 1-5$, $n = 1-3$, are the unknown parameters to be recovered. Thus, the total unknowns of the inversion scheme are 15 as the location of all the segments is considered known. The bottom structure is considered known as well. The reference sound speed profile $c_0(z)$ is described as piecewise linear between the values $c_0(0) = 1500$, $c_0(100) = 1495$, $c_0(400) = 1509$.

Table 2 presents the environmental parameters. A single receiver is again considered. The central frequency of the source as in the previous case has been considered low (may be non realistic for a typical tomography experiment) for reasons related to the speed of the inversion process.

Table 3 presents the actual and the recovered EOF coefficients at the various segments obtained by applying the G.A in connection with the a-posteriori statistical analysis of the final population, after 50 Generations . The search space is exactly the one used in [5].

Table 2. The parameters of the environment with the cold eddy

	Actual Value
Water depth (m)	400
Density of the water (kg/m ³)	1000
Starting range of the eddy (m)	2000
Ending range of the eddy (m)	3200
Sound velocity at the bottom (m/sec)	1600
Density of the bottom (kg/m ³)	1500
Source depth (m)	50
Receiver depth (m)	50
Receiver range (m)	5000
Central Frequency/Bandwidth (Hz)	50/20

Table 3. The actual and recovered coefficients of the EOFs at the five segments – single receiver

Segment	α_1		α_2		α_3	
	Actual	Recovered	Actual	Recovered	Actual	Recovered
1	-19.21	-42	27.85	27.4	-11.1	-11
2	-33	-35	34.35	34.8	-11	-12.5
3	-44.71	-38.5	44.44	10.6	-14.89	-22.4
4	-25.66	-27	32.82	6.5	-13.01	-4
5	-8.72	-29.5	22.88	22.7	-12.01	-15.8

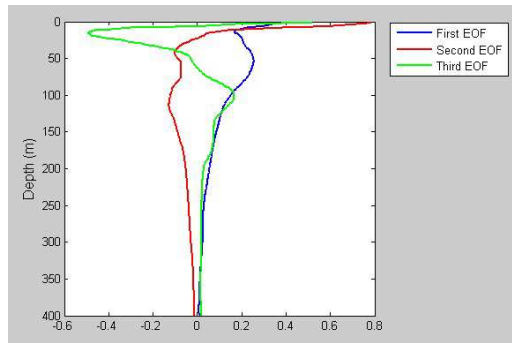


Figure 2. The Empirical Orthogonal Functions representing the cold eddy.

Figure 3 presents the “actual” (simulated of course) structure of the eddy. By applying the signal characterization scheme and a GA, the estimation of the EOF coefficients after 50 Generations as in Table 3, lead to the eddy structure appearing in Figure 4. The results are not as good as one could expect when considering the same inverse problem treated with Matched-Field processing as in [5]. As it can be seen by examining the results of the EOF coefficients (Table 3) the main problem appears in segments 3 and 4 and this can be easily observed in Figure 4 when comparing the structure with the actual one (Figure 3).

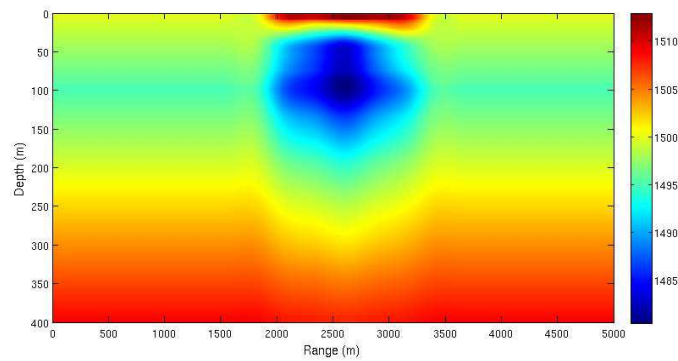


Figure 3. The “actual” eddy. The color scale represents sound speed in water

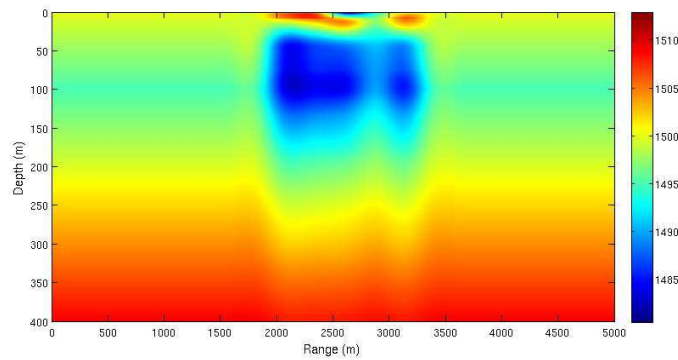


Figure 4. The eddy reconstructed using the statistical signal characterization at a single depth

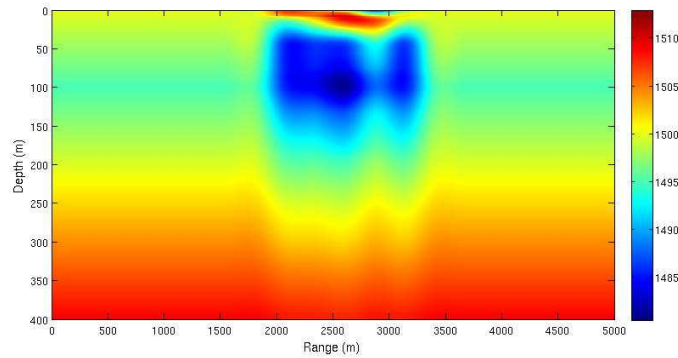


Figure 5. The eddy reconstructed using the statistical signal characterization at two depths.

Of course, in our case, only one receiver is considered while in [5] the acoustic field was measured at an array of hydrophones, thus providing more information on the acoustic field. However, the idea of the proposed signal characterization is to avoid expensive experimental set-ups by using as few receivers as possible. In this respect, it is interesting to note that by considering a second receiver at the depth of 75 m, processing a second signal in exactly the same way as described in 2.1 and seeking for the average between first and second signal wavelet sub-band coefficients, the results are somehow improved especially in what concerns the structure of the eddy close to the sea-surface, as shown in Figure 5 representing the reconstructed eddy when two receivers are used. Of course further research is needed to improve the inversion results at least for the case of the eddy.

4 CONCLUSIONS

It has been shown that the statistical signal characterization scheme introduced in underwater acoustics as a tool for general inversion purposes, can in principle be applied in range dependent environments for the recovery of structures in the water column and the sea bed which are of compact support. This is a very important conclusion as it helps in the establishment of the proposed method as an efficient tool for ocean acoustic tomography and geo-acoustic inversions in realistic environments. The range of possible applications is wide and includes pollution monitoring, oceanographic processes monitoring, identification of the shape of objects lying in the sea bed and in general oceanographic structures of any type, having a range-dependent character.

However, it should be noted that the case representing the cold eddy does not provide as good results as the one representing the sea mount. The reconstructed eddy structure does not repeat the details of the actual one which might be of specific interest for the oceanographers or the environmental engineers. Of course, by studying just a few cases no definite conclusions can be derived as regards the applicability or specific limitations of the method. It is obvious that much additional work is needed to assess the potential of the method in realistic environments with actual data obtained in the presence of noise. The study of de-noising procedures is among the future research plans of the authors as well as the study of hybrid approaches which we expect to lead to a further improvement of the results in more or less the same way as suggested in [5].

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