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AN HYBRID ACOUSTIC-OCEANOGRAPHIC METHOD FOR ESTIMATING THE SPATIAL DISTRIBUTION OF SOUND SPEED

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Abstract: *Several ocean phenomena, like internal waves or upwelling, give rise to spatial disturbances of the temperature/sound speed. The classical methods to find the spatial distribution of these disturbances is based on in-situ measurements with CTD, XBT, thermistor chains, etc. These direct methods are generally costly in time and resources. More recently, methods for remote sensing temperature disturbances in the ocean derived from acoustic tomography were introduced. Acoustic tomography is interesting specially if simple low cost acoustic systems could be used. This work starts from such an acoustic system and proposes a method for estimating the distribution of temperature/sound speed disturbances in the ocean. The proposed method is based on a two step procedure. First, a matched field tomography technique is used to estimate the "mean" sound speed disturbances between sound sources and receivers. In the second step, a spatial distribution of the sound speed disturbances is found using a ray tracing method. The method also allows to include in-situ measurements in the estimation, reducing the uncertainty. The applicability of the method is demonstrated by simulations based on real data from the INTIMATE'98 sea trials.*

1. INTRODUCTION

Estimate the spatial distribution of the sound speed field in a wide area of the ocean is a must in order to assure reliable operation of underwater acoustic instrumentation, such as sonar systems. In an operational scenario, where these estimates need to be available in real time, remote sensing techniques must be considered. Acoustic tomography methods, based on the estimation of sound speed perturbations using sound as probe signal, are very appealing, since sound waves in the ocean could propagate over large distances. In the other hand, very often, the ocean area to be observed is decided with short notice and it is subject to changes during the operation, what recommends the usage of light acoustic systems, easy to deploy and recover, and allowing to faster reconfigure the sampling geometry. At SiPLAB, prototypes of an acquisition system, known as Acoustic Oceanographic Buoy (AOB), that meet these requirements were recently developed and successfully tested at sea[1]. This paper will focus on a method of processing the acoustic signals acquired by such a simple system, in order to estimate the spatial structure of sound speed perturbations. In the literature the most reported approaches for estimating such parameters for ocean environments are Ocean Acoustic Tomography (OAT) and Matched Field Tomography (MFT) [2]. Historically, OAT is based on the linearization of the dependence of sound speed perturbation on travel time perturbations. Although ray travel time perturbations are the most widely used, modal travel time perturbations could be also considered [3]. OAT is computationally efficient, even if range dependent environments are considered although difficulties are experienced in the identification of ray (or modal) arrivals, specially in shallow water environments. Also, OAT is not well suited to account for the uncertainty in the localization of sources and hydrophones, that could be important when light systems are used, specially if some of them are in free-drifting operation. MFT is a more recent concept and it appeared as an extension of matched field source localization. MFT is an optimization technique, where a search is performed for the set of parameters that gives the best "match" between an acoustic field computed by a forward acoustic propagation model, known as a replica, with the measured acoustic field. The "match" metrics is embedded on the so called objective function. In MFT methods the uncertainty in the localization of the sources or hydrophones can be easily accounted for, by including it as a parameter in the search space. The computational load required by MFT methods depends mainly on the forward model used, the number of search parameters and their discretization, the search method and the frequency band of the signal. The computational load of MFT significantly increases when range dependent environments are considered. During the INTIMATE'98 sea trial, a range independent MFT approach was proven to be able to track "mean" sound speed perturbations along time in a highly dynamic environment [4]. This gives rise to a two stage method to estimate the spatial distribution of the sound speed perturbations presented herein. In a first stage one finds the "mean" (range independent) sound speed perturbation for different vertical cross sections of the area of interest. Here, a MFP method will be applied in order to account for the uncertainty in parameters like source/hydrophone localization and water depth. In the second stage, the spatial structure of the sound speed perturbations is obtained from the previous range independent estimates, using a linear model deduced from ray tracing theory. In this stage, if *in-situ* measurements are available, they can be included in the framework. This method will be depicted in section two. The application of the method to estimate the spatial structure of a simulated oceanic front is discussed in section three. The synthetic data in the simulation was generated from INTIMATE'98 sea trial data [4]. In the last section some conclusions are drawn regarding the applicability of the method.

2. The method

As discussed previously the method presented herein is a two stage method. In the first stage one finds the "mean" sound speed perturbations for different vertical cross sections of the area of interest. In real scenarios there is a certain level of uncertainty of various parameters such as the localization of sources and hydrophones, water depth, or bottom characteristics, and therefore these should be considered in the inversion procedure, otherwise the estimations of the "mean" sound speed perturbations could be affected by important biases. Herein, the MFT procedure based on the arrival matching processor, that was applied to track sound speed perturbations in the INTIMATE'98 data set [4] will be used. It is assumed that the "mean" sound speed perturbation $\tilde{\boldsymbol{c}}_j(z)$, estimated for the j-th cross section is expressed by two empirical orthogonal functions (EOF) coefficients, $\tilde{\alpha}_1$ e $\tilde{\alpha}_2$ respectively. Thus, one can write

$$\tilde{\boldsymbol{c}}_j(z) = \sum_{n=1}^{2} \tilde{\alpha}_{j,n} \boldsymbol{\phi}_n(z) \,, \tag{1}$$

where $\boldsymbol{\phi}_n(z)$ is the n-th EOF. The goal of the second stage of the proposed procedure is to estimate the spatial structure of the sound speed perturbations based on the information obtained in the first step, i.e., a vector of range independent inversions $\tilde{\boldsymbol{\alpha}} = [\tilde{\alpha}_{1,1}, \tilde{\alpha}_{1,2}, \ldots, \tilde{\alpha}_{J,1}, \tilde{\alpha}_{J,2}]^T$, where J is the number of cross-sections covering the area of interest. In this stage the area of interest is discretized into K horizontal cells. The k-th cell is characterized by the set of EOF coefficients $[\alpha_{k,1}, \alpha_{k,2}]^T$. The concatenation of the coefficients of all cells is represented by $\boldsymbol{\alpha}$. If a linear model is assumed, the second stage can be written as

$$\tilde{\boldsymbol{\alpha}} = \boldsymbol{L}\boldsymbol{\alpha} + \boldsymbol{n}_{inv} \,, \tag{2}$$

where $\boldsymbol{L}$ is the observation matrix and $\boldsymbol{n}_{inv}$ represents the errors, where an important component is linked to the first stage inversion. Next, it is assumed that the sound speed perturbation can be represented by solely one EOF, then the number of rows of matrix $\boldsymbol{L}$ is given by the number of cross sections considered in the first stage. The number of columns of matrix $\boldsymbol{L}$ is equal to the number of cells (K) in the horizontal plane considered. If the noise is ignored, $\boldsymbol{\alpha} = [\alpha_{1,1}, \ldots, \alpha_{k,1}, \ldots, \alpha_{K,1}]^T$ then the j-th row of $\boldsymbol{L}$ in the system (2) can be written as

$$\tilde{\alpha}_j = l_{j,1}\alpha_{1,1} + \ldots + l_{j,k}\alpha_{k,1} + \ldots + l_{j,K}\alpha_{K,1} \,. \tag{3}$$

A possible method to find the $l_{j,k}$ coefficients is based on the ray tracing model: $l_{j,k}$ represents the weight of rays crossing cell k regarding a set of eigenrays computed considering the j-th mean sound speed perturbation obtained in the first stage. In this case the coefficient $l_{j,k}$ can be written as

$$l_{j,k} = \frac{\sum_{i=1}^{N} e_{k,1}^{(i)}}{\sum_{m=1}^{K} \sum_{i=1}^{N} e_{m,1}^{(i)}} \,, \quad e_{k,1}^{(i)} = -\int_{\Gamma_i} \frac{\phi_1(z)\Pi(k,s)}{c_0^2(z)} ds \,, \tag{4}$$

where i is the eigenray number ($i = 1, \ldots, N$), m is the cell number ($m = 1, \ldots, K$), Γ_i represents the i-th eigenray path and $\Pi(k,s)$ is a gate function having value 1 when the integration path s crosses the k-th cell and value 0 otherwise. When the sound speed perturbations are represented by more than a single EOF coefficient, the extension of the above system is straightforward. In this framework, the *in-situ* measurements can be easily integrated. Assuming, that $\boldsymbol{\alpha}_s$ represents the vector of measured sound speed perturbations, $\boldsymbol{\alpha}_m$ is the vector of true sound speed perturbations at the measurement locations and $\boldsymbol{n_s}$ represents the measurement errors, than one can expand system (2) as follows

$$\begin{bmatrix} \boldsymbol{\alpha}_s \\ \tilde{\boldsymbol{\alpha}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{I}_s & \boldsymbol{0}_s \\ \boldsymbol{0}_l & \boldsymbol{L} \end{bmatrix} \begin{bmatrix} \boldsymbol{\alpha}_m \\ \boldsymbol{\alpha} \end{bmatrix} + \begin{bmatrix} \boldsymbol{n}_s \\ \boldsymbol{n}_{inv} \end{bmatrix}. \tag{5}$$

The dimensions of the identity matrix $\boldsymbol{I}_s$ and null matrices $\boldsymbol{0}_s$ and $\boldsymbol{0}_l$ allow for the consistency of the system. This system can be solved by different methods. In the next simulation a weighted least squares method is used [3], assuming a known correlation function of the sound speed perturbations [5] and using *a posteriori* probability distribution of the first stage inversions to characterize their uncertainty [6]. When using a weighted least squares approach to solve the system (5), one can also obtain an estimate of the "uncertainty" of the result, which reflects the available "uncertainty" of each piece of information used [3].

3. Simulations

As an example of application, the proposed method is used to estimate the spatial structure of a front in a shallow water environment. The sound speed perturbations in the different cells are represented by two EOF coefficients. Figure 1a) shows the mean sound speed profile and the first two EOF found in the INTIMATE'98 data set [4], which will be used in the current simulations. Figure 1b) shows the configuration of the hypothetical experiment. The area of interest is a 10km^2 square that was discretized in 16 square cells. The water depth is 146m in the whole area. Two arrays with 4 hydrophones each at depths 74m, 84m, 94m and 104m were considered ($\bigcirc$ marks), and a source that emitted around the square in 12 different locations ($\times$ marks). The spatial distribution of coefficients α_1 and α_2 is shown in figure 1c) and d), respectively . The area is split in 2 distinct parts: one is unperturbed (coefficients are 0) and the other where perturbation occurs (coefficients are different from 0). In the estimation procedure, it was considered that α_1 could range from -20 to 20, and α_2 from -10 to 10, in accordance with the perturbation bounds observed in real the data. In the first stage is it assumed that the probe signal was a LFM with frequency ranging from 300Hz to 1000Hz, and the estimates were obtained using MFT method discussed in [4]. Figures 1e) and 1f) present the spatial distributions of coefficients α_1 and α_2 respectively, estimated by the proposed method. In the estimation it was considered 5 *in-situ* measurements in locations labelled with "*" in figure 1e) and f). One can remark that the structure of the perturbation associated to first EOF is resolved. The transaction region that occurs in the interface between the perturbed area and unperturbed area is due to the relative weight between the assumed sound speed correlation matrix and the first stage inversion error covariance matrix. The result obtained for the second EOF coefficients was not so good as for the first EOF. The first EOF accounts for more than 80% of the energy of the sound speed perturbations, whereas the second EOF accounts just for 10%. Thus, one can expect that the second EOF coefficients are much more difficult to estimate. This is inline with a higher variance of the second EOF coefficient estimates observed in the first stage estimation.

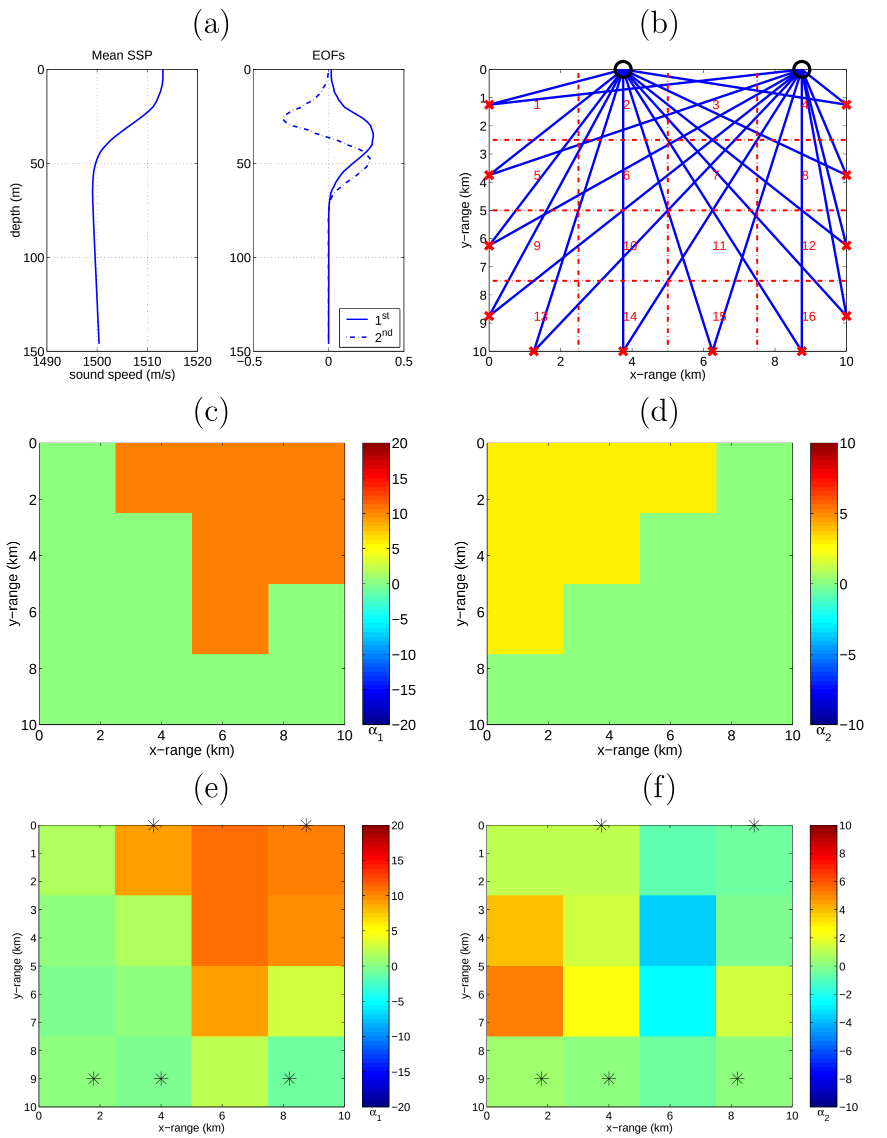

Fig. 1: a) Mean profile and the first two EOF b) Propagation paths (solid lines), hydrophone arrays (◯) and moving source (×). The cells (dot-dashed line) are identified by a number. Simulated spatial distribution of the first EOF coefficient c) and second EOF coefficient d). Estimated spatial distribution of the first EOF coefficient e) and second EOF coefficient f).

4. Conclusions

This paper proposes a two stage method to estimate the spatial structure of the sound speed perturbation in a given ocean area. In the first stage it is applied a range independent procedure that founds a "mean" perturbation in different cross sections of the interest area. This allows to obtain more reliable estimates with less computational load then those obtained by a range dependent procedure. Since, the method is intended to be used in association with a light acoustic receiving system, an MFT procedure is proposed in this stage. The advantage of MFT relative to classic OAT in the context of using such a light system is due to the fact that MFT do not requires an accurate source/receiver synchronization to estimate absolute travel times neither wide band signals with narrow correlation functions as OAT procedures do. The usage of MFT in the first stage also allows to include geometrical parameters in the search space, thus reducing the required precision of localization subsystems. The second stage estimates the spatial structure of the sound speed perturbations taking as input the first stage set of range independent estimates. Here, a linear system is deduced from the first stage acoustic estimates and *in-situ* measurements. The part of the system related to acoustic data is derived considering that the mean values obtained in the first stage are distributed throughout the cells according to a ray tracing based weighting function. The procedure to obtain the linear system is straightforward and need few computational resources. The linear system can be solved by weighted least squares. The presented simulation, based on realistic data, shows that the spatial structure of the most important component of a sound speed perturbation (associated to first EOF) could be recovered. Also the estimate could be obtained in *quasi* realtime, being the first stage the most limiting factor. Although, the method proposed herein were validate solely by simulations, whilst based on real data, it is expected that a suitable performance in real situation can be achieved. The validation of the proposed method is an objective to be attained in future sea trials.

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