# ACOUSTICAL METHODS FOR THE MONITORING OF THE MARINE ENVIRONMENT WITH APPLICATIONS TO SHALLOW WATER

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## ABSTRACT

The idea of using the sound to monitor the changes in the marine environment motivated the acousticians and oceanographers to develop different methods following the associated technological developments and the available modelling and numerical techniques. Starting from the early 80's when the pioneers started to pave the way leading to the acoustical monitoring of the ocean change and coming to the beginning of the new millennium, several achievements in the field can be reported vindicating the scientists who believed in this new idea. This presentation is an attempt to summarize the basic concepts of the methods developed at the Foundation for Research and Technology-Hellas and address the main issues of this new area of underwater acoustics. The following text can be viewed as an extended summary of the presentation.

## INTRODUCTION

It is well known that the ocean environment is transparent to acoustic waves, whereas electromagnetic waves attenuate quickly and therefore they cannot propagate at long distances. Therefore the acoustic waves are efficient carriers of information of the interior of the ocean environment and they can be used for monitoring its changes. There is no need to emphasize on the role of the ocean in the global climate and change, as it is well known that most of the meteorological phenomena are associated with oceanographic processes in the ocean, which interact directly with the atmosphere. It is therefore well understood why the scientific community shows significant interest in the methods for monitoring the changes in the water environment.

Of course, ocean observatories which are created in critical areas around the globe are not based solely on the acoustic waves. As a matter of fact, acoustics plays a complementary role in the group of means applied by the scientists to follow the processes in the water. Traditional oceanographic measurements are still used and satellites play their own role in the field. However, the importance of acoustics is continuously growing and the methods recently developed for the associated applications cover the main part of the scientific efforts in the field of underwater acoustics.

The presentation deals with the methods developed and applied by the group of wave propagation at the Foundation for Research and Technology-Hellas (FORTH) for treating problems of marine environment monitoring in shallow water areas. The methods will be briefly analyzed and results based mainly on synthetic (simulated) data will be presented.

The methods fall into two main categories: a) Methods utilizing local measurements of the acoustic waves and b) Methods utilizing measurements of the acoustic field at long ranges. In both cases a known source is emitting acoustic waves, which are recorded in appropriate locations in the water column. In every case an inverse problem is defined of the form

$$\mathbf{f}(\mathbf{d},\mathbf{m}) = 0 \qquad (1)$$

where, $\mathbf{d}$ is the vector of the data (taken from the measurements) and $\mathbf{m}$ is a vector of the recoverable parameters. Of course there is no evidence that the equations thus defined for a general inverse problem contain enough information to specify uniquely the model parameters, or that they are consistent. A general inverse problem is known to be ill-posed. Therefore a thorough analysis of the corresponding inverse problem is required.

Speaking about the recoverable parameters which are of interest for the monitoring of the marine environment, we are referred to the sound speed profile in the water column $c(\vec{x})$, the current velocities $v(\vec{x})$, the geometry of the interfaces in the water column and the bottom, the compressional $c_b(z)$ and shear $c_s(z)$ velocities in the bottom and the compressional and shear wave attenuation parameters $a_p(z)$ and $a_s(z)$. Note that in this notation, water parameters are in general considered 3-Dimentional, whereas those of the bottom are functions of the depth only. This is dictated by the physics of the marine environment backed by the necessity for simplifying the problem. It should be noted that the monitoring of the oceanographic processes in the water column is associated with the monitoring of the water temperature changes and the ocean currents. Since the sound speed is a function of temperature, retrieving the sound speed profile is equivalent to retrieving the temperature profile.

In the following, the main concepts and techniques for the acoustical monitoring of the marine environment will be presented.

## OCEAN ACOUSTIC TOMOGRAPHY

Ocean acoustic tomography was introduced by Munk and Wunsch in 1979 following a demonstration in the '70s that about 99% of the kinetic energy of the ocean circulation is associated with mesoscale features, that is features that are about 100 km in diameter [1,2]. Monitoring the changes of the mesoscale and larger-scale features is therefore a useful process on the way of understanding global changes. As the continuous monitoring of these features by traditional in-situ sampling tools may be proven extremely expensive and non practical, they suggested the use of sound waves as an alternative monitoring tool.

The term "tomography" was well known in medical and seismic applications and reflects the fact that the carrier of information on a specific medium penetrates the area under investigation. The processing method is based on the definition of several slices (t?µ?? – tomes in the Greek language) on which an inverse problem is solved (Figure 1). The integration of the solutions obtained in each one of the slices provides the "image" required by the specific application.

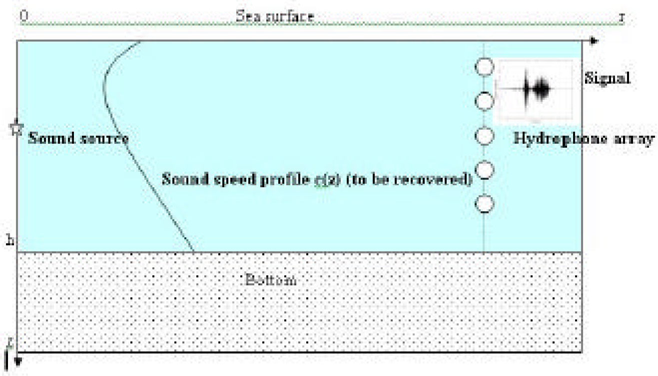


Figure 1. A typical vertical slice for ocean acoustic tomography. In the figure, the sound speed profile is considered depth dependent only (range independent environment)

Ocean acoustic tomography takes advantage of the fact that measurable acoustic properties such as travel-time of rays and modes, modal phase or the full acoustic field are related to the temperature and current velocity of the ocean. The derivation of the temperature and current velocity profiles from the sound field measurements is the main goal of ocean acoustic tomography. An additional feature of the ocean is that low frequency sound propagates at long distances in the water column, and thus long acoustic propagation paths can be exploited. Experimental procedures, forward propagation modelling and inversion schemes are all interrelated and constitute the ingredients for the development of the ocean acoustic tomography methods. In addition, temperature is related to the sound speed through semi-empirical functions, and thus the directly derived parameter is the sound speed in the water column.

Original tomographic methods were applied to deep water and were relied on measurements of the ray travel time (see for instance [3] and [4]). Acoustic rays are much more easily identified in deep water. Recent studies have shown that tomographic techniques can be applicable in shallow water too. There are several differences however in the analysis of the inverse problems related to ocean acoustic tomography in shallow water with respect to same problems of deep water. First of all, bottom plays an important role in acoustic propagation over shallow water and therefore its knowledge is critical. On the other hand the number of propagating modes is reduced and therefore, modal techniques not applicable in deep water may be used in this case. In addition, range dependence should be taken properly into account.

The methods developed so far for shallow water ocean acoustic tomography could be classified as linear or non-linear. Linear methods are based on the assumption of a good knowledge of a reference environment. Thus the sound speed (or the current velocity) is expressed as

$$c(\vec{x}) = c_0(\vec{x}) + d\,c(\vec{x}) \tag{2}$$

where index zero corresponds to the reference environment. The model parameters **m** defined in (1) are in this case discrete values of the sound speed difference (following an appropriate discretization of the environment) or coefficients of the empirical orthogonal functions describing the sound speed structure. As regards the data, it is possible to use ray arrivals whenever rays are identifiable (difficult in shallow water), modal arrivals, or modal phase. The latter is applicable only when a vertical array of hydrophones is available [5]. In all these cases a linear system of equations is formed, associating data (time of arrival for rays or modes, or modal phase) and model parameters. The system takes the form

$$d_i = \sum_{j=1}^{N} G_{ij} m_j \tag{3}$$

where $G_{ij}$ is a known kernel matrix defined using the theory of the forward propagation problem in terms of the type of observables and their association with the recoverable parameters for the reference environment. The index *I* spans the number of discrete data points, whereas the index *j* spans the number of recoverable parameters. Eventually an appropriate method is utilized for solving this generally ill-posed problem of linear algebra [5].

In the context of nonlinear theory, matched field (MFP) [6] or matched modal arrivals methods [7] can be used as well. In these cases the acoustic field measured at a vertical array of hydrophones, or the other type of observables (modal travel times) are associated with the recoverable parameters via a nonlinear relation of the form (1). The inverse problem thus defined can be formulated as an optimization problem, involving a large search space over the recoverable parameters. This space is in general multidimensional and the procedure seems to be time consuming if a systematic search over the whole space of the recoverable parameters **m** is applied. Instead, modern techniques based on genetic algorithms [8] or neural networks are used to reduce the time required before reaching an acceptable solution. Caution should me paid in order to avoid trapping in local maxima of the cost function which is defined to control the optimization process. To this end- any a-priori information on the recoverable parameters is utilized.

As an example of MFP consider the vector $\mathbf{F} = (F_1, F_2, ...F_N)^T$ of the measured acoustic field values at the *N* hydrophones of a vertical array of hydrophones (Figure 1). Considering a candidate parameter set **m**, one can easily calculate replica fields $\hat{\mathbf{F}} = (\widehat{F}_1, \widehat{F}_2, ...\widehat{F}_N)^T$ using an appropriate forward propagation model. A typical objective function is the *Bartlett* processor defined as

$$L(\mathbf{m}) = \mathbf{w}^{+} C \mathbf{w} \tag{4}$$

where $\mathbf{w} = \widehat{\mathbf{F}}$, $C =< \mathbf{F}\mathbf{F}^{+} >$ and the superscript + denotes the conjugate transpose. When the measured and replica fields are normalized (e.g $\|\mathbf{F}\| = 1$), the processor takes its maximum value (=1) when replica fields perfectly match the measured fields.

Several alternative processors have been proposed to improve the efficiency of the optimisation procedure [9]. Moreover, the broadband character of the signal can be exploited by means of "broadband" processors which can be either coherent or incoherent in both hydrophone and frequency domains [10] and can be applied for bottom classification too (see next section).

All the above methods can be applied in both range-independent and range-dependent environments and can be used in connection with linear techniques, once a solution close to the actual one is defined, following the optimization procedure [11].

Recently, the idea of statistical characetrization of the acoustic signal has been introduced to deal with problems, where no clear observables can be identified [12]. By applying a suitable transform of the signal (e.g a wavelet transform), the statistics of the coefficients of the transformed version of the signal is analyzed and the signal is characterized by the coefficients of the appropriate statistical distribution. These coefficients form the data set **d** of the observables of the inverse problem.

## BOTTOM CLASSIFICATION

The classification of the sea-bottom by acoustic means has been a subject of research since a long time. The reasons are obvious. Knowledge of the nature of the sea bottom is an important factor governing all applications of underwater-acoustics especially in shallow water areas. All problems involving calculation of the acoustic field at a specific location in the water column and especially in shallow water, need as input the bottom geoacoustic parameters and a simple method for their determination is by exploiting acoustic data. Also, various other applications related to the sea-bed are based on same type of information As an example we can mention problems of identification of objects in the sea-bottom (underwater archaeology for instance) for which the classification of the sea bottom is a pre-request and finally one should not forget that the exploitation of the sea-bottom is by itself a field where the knowledge of the sea-bottom structure is an inherent component.

The methods that have been developed for the acoustic classification of the sea bottom are mainly dictated by the type of the available instrumentation and the progress made in the solution of the forward problem, which is the calculation of the acoustic field in the sea when the environmental parameters that govern the acoustic propagation are known.

The presentation is devoted to a short review of two of the methods developed at the Institute of Applied and Computational Mathematics of FORTH aiming at the creation of a library of algorithms for solving the problem of sea-bed reconstruction that could be applied under various experimental conditions The first method is based on the calculation of the reflected field obtained in short range from an acoustic source at either a horizontal or a vertical array of hydrophones for a certain number of angles of incidence. For this method knowledge of the calibration characteristics of the source is not needed. The method can be mainly applied using sources emitting acoustic energy in the form of a beam having characteristics of plane wave propagation [13,14] (See Figure 2).

The formulation of the associated inverse problem in this case is that of an optimization problem. The bottom geoacoustic parameters of the true environment maximize (or minimize) an appropriate cost function, which is however simpler than the ones presented before [14].

The second method (or rather a set of methods) can be applied when pressure field data are available at long range from a known source at a vertical (or horizontal) array of hydrophones. Thus, these methods are amenable to solving techniques equivalent to them presented in the previous section (methods of ocean acoustic tomography) as they are defined on the same principle [10,15]. The only difference is that the recoverable parameters are referred to the bottom only and they are different in type and significance. Linear techniques are devoted to the recovery of the compressional velocity only (a very restrictive requirement) whereas non-linear techniques being more general can be used for the recovery of the bottom and water parameters simultaneously, as there is no restriction on the type of the model parameters [7].

## SOURCE LOCALIZATION

In many applications of marine environment monitoring it is necessary to know exactly the location of the sound source. There are several techniques to deal with this problem, including the matched-field processing technique presented in the corresponding section [16]. For shallow water environment, the technological needs for the creation of a vertical array of hydrophones are less important and thus it is possible to obtain specific characteristics of the acoustic field such as the modal structure. Thus the problem is amenable to techniques exploiting the structure itself.

The method applied at FORTH is based on the application of the matched-mode technique [17, 18]. According to this method, the acoustic field measured at an array of hydrophones at a specific distance is used to extract the propagating modes by a simple procedure based on the solution of a linear system of equations in the complex domain. The modes thus defined, are associated with the source location, which can be retrieved via a matching procedure similar to the one presented in the ocean acoustic tomography section. The procedure involves the definition of a cost function which is minimized (or maximized) when the candidate source location coincide with the true one in exactly the same way as in the case of matched-field processing.

Applications of source localization are envisaged in different areas including the monitoring of the marine mammals (dolphins, whales etc.).

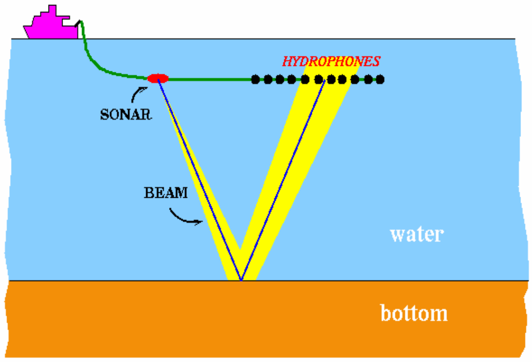


Figure 2: A typical layout of an experiment aiming at bottom classification. The inversion procedure makes use of the measurements of the acoustic field at the horizontal array of hydrophones

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