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Ocean Acoustic Tomography

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Summary

The idea of using the sound to monitor the changes in the marine environment motivated the oceanographers to develop the concept of ocean acoustic tomography. 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 lecture note is an attempt to summarize the basic concepts of ocean acoustic tomography methods and address the main issues of this new area of underwater acoustics.

Introduction

The term "Ocean Acoustic Tomography" is referred to the inverse problem of inferring from precise measurements of travel time or other properties of acoustic propagation, the state of the ocean traversed by the sound field [1]. Inverse problems in underwater acoustics have recently drawn the attention of scientists working in underwater technology, due to the relatively high efficiency of the sound waves as carriers of information related to the environmental and operational parameters of the sea environment, including acoustic source characteristics and shapes of objects in the water or the bottom layers. The recovery of these parameters using measurements of the acoustic field is the main objective of a general class of inverse problems in underwater acoustics.

According to the classification proposed by Collins and Kuperman [2], the inverse problems in underwater acoustics fall in two main categories: *Remote sensing of the sea environment* and *localization*. In the first category problems such as the estimation of the sound speed structure and current field in the water column, bottom properties and roughness parameters are encountered while in the second one, problems of source recognition and localization as well as source path estimation are faced. Ocean acoustic tomography according to this definition is related to the remote sensing of the water column, although the term "remote sensing" does not reflect the fact that acoustics sources and receivers are placed within the environment to be studied.

Ocean acoustic tomography is now widely accepted as a powerful alternative tool for the monitoring of the marine environment being complementary to other traditional methods of physical oceanography. Due to the challenging problems associated with the concept of ocean acoustic tomography, this new area has initiated the collaboration between oceanographers, physicists, mathematicians and engineers who have developed together the experimental procedures and inversion techniques for getting the desired results, that is an image of the ocean structure over large areas.

The idea of ocean acoustic tomography was quickly spread among oceanographers, and acousticians and soon became an important area of research in the field of Oceanography and Marine Technology.

Several feasibility studies have been conducted since the mid 80's and today in both mesoscale and large-scale basis to validate the concept, while at the same time alternative techniques for extracting the useful information from the acoustic fields were developed and studied. Some of the characteristic experiments are mentioned in the relevant chapter. Among them, the Heard Island experiment [3] featured the largest scale (global-wide) and provided the scientific community with valuable research items in the field.

The structure of the tutorial course will cover the following items: Principles of ocean acoustic tomography including a short historical review of the area, forward modeling of acoustic propagation, methods of ocean acoustic tomography, characteristic experiments and perspectives.

I hope that it is well understood that it is not possible to cover all the achievements in this interesting field of Underwater Acoustics in the necessarily reduced length of a paper, and therefore I expect the understanding of the reader for possible deficiencies.

The principles of 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 [4]. 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, while at the same time the other alternative tool available at that time, that is the remote sensing by satellite, could not give depth resolving information for deep water, the sound propagating in the water between moorings was proposed as a possible carrier of information and techniques for extracting and exploiting this information started to be studied.

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 (τομές – tomes in the Greek language) on which an inverse problem is solved. The integration of the solutions obtained in each one of the slices provides the "image" required by the specific application.

In the case of ocean acoustic tomography, the ultimate information required is the temperature structure of the ocean, sometimes associated with the current structure of the same area. This type of information is generally what the oceanographers need in order to either directly derive the necessary information on the changes of the oceanographic processes, or feed appropriate numerical models that would make the prediction. It should be noted that the concept of "temporal change" introduces the necessity for repeated measurements at different time spots.

Ocean acoustic tomography takes advantage of the fact that measurable acoustic properties such as travel-time, phase or even the full-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.

A general inverse problem is formulated by means of a relationship associating measurements and parameters to be retrieved. As the term "measurement" is general, the actual relationship is defined on the basis of the data **d** derived from the measurements, according to the method to be followed and the parameters **m** to be recovered.

The relationship between these two factors may be complicated and in general it takes the form [5]

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

where the vector equation above summarizes what is known about how the measured data and the unknown parameters are related. Of course there is no evidence that the equations thus defined for a general inverse problem contain enough information to specify the model parameters uniquely or that they are consistent. A general inverse problem is known to be *ill-posed.* Given the set of the unknown parameters, it is the task of the researchers to define the kind of data, which will have the property to lead to equations amenable to easy implementation being at the same time self-consistent.

In the case of ocean acoustic tomography, model parameters are the sound speed c and current velocity v in the water column. In general, both parameters are functions of the spatial and temporal co-ordinates $c(\vec{x},t), \quad v(\vec{x},t)$. To simplify the problem, it will be assumed that model parameters are functions of the spatial co-ordinates only, the time dependence being retrieved by successive experiments.

An ocean acoustic tomography experiment involves sound sources and receiving stations. A single source emitting a known signal and a single receiving station define the tomographic pair. In most cases the receiving station consists of a single hydrophone or a vertical array of hydrophones and recording devices (Figure 1). Thus, vertical slices (τομές) in water are considered. The 3-D image of the environment is obtained by combining results from multiple slices.

Forward Propagation Modelling

The way an inverse problem is defined depends on the modelling of the forward problem. The structure of the arrival pattern of the signal can be explained by alternative ways. It is of critical importance to isolate and exploit in the inversion procedure, the characteristics which are associated with the forward propagation model. Thus, a relationship of the form (1) can be defined.

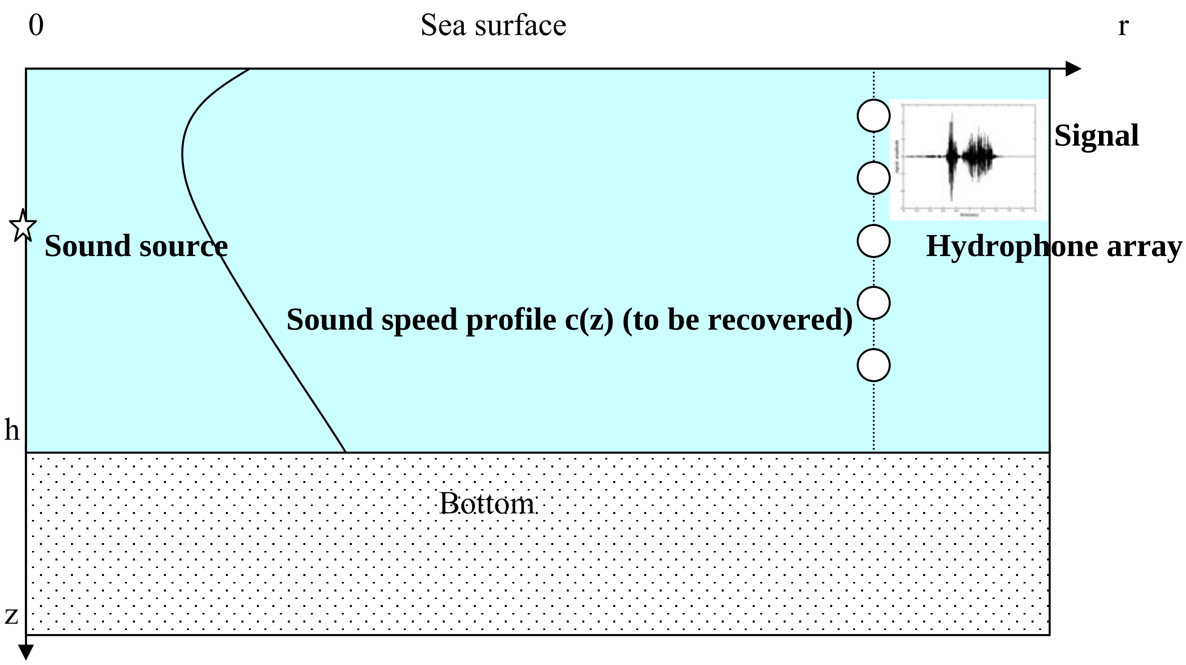


Figure 1. A tomographic pair at a vertical slice

The starting point for the forward acoustic propagation modelling is the definition of the elliptic problem governing propagation of monochromatic signals in the ocean environment. The core of the problem is the Helmholtz equation for the acoustic pressure $p(\vec{x})$, written in the form

$$\nabla^2 p(\vec{x}) + \frac{\omega^2}{c^2(\vec{x})} p(\vec{x}) = -\delta(\vec{x} - \vec{x}_0) \tag{2}$$

where c is the sound speed, ω is the circular frequency and $\vec{x}_0$ is the position vector of a point source. The problem is completed by assigning appropriate boundary conditions. When a broadband source is considered, as it is the case in the problems of ocean acoustic tomography, a Fourier transform from the frequency to the time domain enables the representation of the acoustic field in the time domain.

$$p(\vec{x},t) = \Im^{-1}[p(\vec{x};\omega)];\omega \to t] \tag{3}$$

where $p(\vec{x};\omega)$ is solution of equation (2) for the frequency ω.

When ray acoustics is considered, the signal is described as a superposition of ray arrivals. In other words the acoustic energy is considered as propagating along distinct rays. This multipath propagation is mathematically reflected in the calculation of the acoustic field by means of a series expansion of the acoustic pressure, which takes the form:

$$p(\vec{x};\omega) = \sum_{n=1}^{N} p_n(\vec{x};\omega) = e^{i\omega\tau(\vec{x})} \sum_{n=1}^{N} \frac{A_n(\vec{x})}{(i\omega)^n} \tag{4}$$

where, p_n is the acoustic pressure corresponding to the n[th] eigenray and N is the total number of eigenrays reaching a specific receiving location. Solutions for $\tau(\vec{x})$ and $A_n(\vec{x})$ are obtained through the *eikonal* and *transport* equations respectively [6].

The pressure field in the time domain can be written in the form

$$p(\vec{x},t) = \sum_{n=1}^{N} a_n(\vec{x})\delta(t - \tau_n(\vec{x})) \tag{5}$$

where τ_n is the arrival time of the n[th] ray (eigenray) and a_n is the corresponding amplitude.

Using ray acoustics, the inverse problem is defined on the basis of the ray arrivals. The arrival time of a specific eigenray is related to the sound and current velocity profiles along the propagation direction through a relationship of the form

$$\tau_n = \int_{\Gamma_n} \frac{ds}{c(\vec{x}) \pm v(\vec{x})\cos\theta} \tag{6}$$

for a transmission in the positive $\vec{x}$ direction. ds is the infinitesimal ray path and Γ_n is the ray-path for the eigenray of order n and corresponding to a specific angle of reception. θ is the angle between the ray and the horizontal. It is well known that the sound speed profile determines the ray-paths and therefore the forward problem of determining the ray arrival times from the sound speed and current velocity profiles is uniquely solved. In the ray-theoretic approach of ocean acoustic tomography the actual value of the acoustic pressure has no particular use.

Another alternative is to apply normal-mode theory and consider the acoustic field as a superposition of normal modes that is distinct ways of energy distribution in depth. The normal mode solution of the acoustic field is of the form

$$p(\vec{x}) = \sum_{n=1}^{N} p_n(\vec{x}) = \sum_{n=1}^{N} B_n(\vec{x}) u_n(z) \tag{7}$$

where $u_n(z)$ is the eigenfunction of order n, being the solution of a Sturm-Liouville type problem for an Ordinary Differential equation defined in depth z (depth problem) [6]. $B_n(\vec{x})$ is defined by solving a problem derived from the Helmholtz equation when substituting expression (7) for the sound pressure. Note that for range-dependent environments $u_n(\vec{x})$ is defined for each range step.

Each one of the terms in the sum corresponds to a modal component. Given the sound speed profile the geometry of the environment and the acoustic frequency, propagating modes are uniquely defined. Normal-mode solution can be exploited for inversion purposes in various ways to be analyzed below.

Finally, alternative ways of modeling acoustic propagation (Parabolic Approximation, Hankel transform) lead to a solution for the acoustic pressure, which is not easily exploited for inversion purposes, unless the full field is considered.

No further details are required at this stage. For a complete reference to the state of the art in forward propagation modeling in Underwater Acoustics, the interested reader is addressed to a series of related books among which we point out the comprehensive text by Jensen at al. [6].

Methods of ocean acoustic tomography

Ray inversions

Originally, ocean acoustic tomography was based on ray theory, since the vehicle, carrying the information on the environment was the acoustic ray. It was the ray travel time, which gave the necessary information for the calculation of the sound speed. This approach is still very popular among acoustical oceanographers due to its simplicity and its inherent physical meaning. Broadband sources are used and the signal is recorded at a single hydrophone.

The original idea for solving the inverse problem of ocean acoustic tomography was based on the assumption that a reference environment (background state) is always known and that the actual one differs from the background very little. The background environment normally corresponds to a historical mean. Thus, a relationship of the form

$$c(\vec{x}) = c_0(\vec{x}) + \delta c(\vec{x}) \tag{8}$$

with δc very small, can be written..

Linearizing the expression (6) with respect to the known background state, and assuming that there is no current in the area of the tomographic experiment, the travel time variation $\delta\tau_n$ along a certain ray Γ_n defined for the reference environment is associated with sound speed variation through the formula

$$\delta\tau_n = -\int_{\Gamma_n} \frac{\delta c(\vec{x})}{c_0^{\,2}(\vec{x})} ds, \quad n = 1,2,\ldots,N \tag{9}$$

Provided that ray arrivals can be identified at the receiver location, the use of N measurements (N eigenray arrivals) could result in the extraction of the sound speed along the ray path and finally at discrete points in the water column. The problem is normally solved by discretization of the ray path and the use of orthogonal functions to describe the sound speed variations in depth (see below). The method has been extensively used especially in deep-water areas with good results. It should be noted that the identification of the peaks, that is relating the peaks of the signal at the background environment with those of the actual measurements, is essential for the application of the method.

When current is added, the problem is solved by performing reciprocal transmissions from the source to the receiver. By subtracting the reciprocal times we come up with an additional relationship of the form

$$d_n = \int_{\Gamma_n} \frac{v(\vec{x})}{c_0^{\,2}(\vec{x})} ds, \quad n = 1,2,......N \tag{10}$$

where $d_n = \frac{1}{2}(\tau_n^{\ +} - \tau_n^{\ -})$, the times $\tau_n^{\ +}$ and $\tau_n^{\ -}$ being travel times for eigenray n in the reciprocal directions.

Linear ray inversion has been for several years the traditional way for implementing ocean acoustic tomography and several techniques have been developed for treating the problem defined by equations (9) or (10). Typically this problem, falls within the class of inverse problems following continuous inverse theory defined by expressions of the form

$$d_i = \int G_i(\vec{x}) m(\vec{x}) d\vec{x} \tag{11}$$

In general, traditional ocean acoustic tomography using ray theory is applied in range-independent environments or for the range average of the sound speed variations. Thus, model parameters (sound speed differences) are functions of depth only ($m(z) = \delta c(z)$).

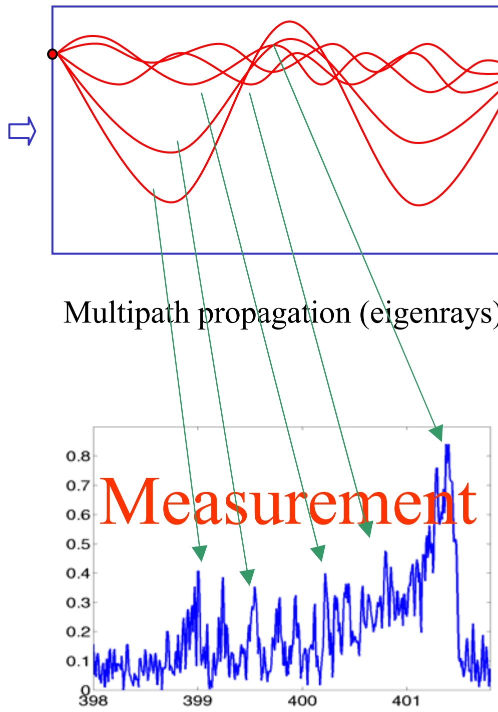
Discretization of the sound speed differences in the water column and the description of the acoustic field in terms of empirical orthogonal functions, expressing sound speed differences as

$$\delta c(z) = \sum_{\ell} \theta_{\ell} f_{\ell}(z) \tag{12}$$

where $f_l(z)$ is the EOF of order l and θ_l is its amplitude, lead to the formulation of a discrete inverse problem of the form

$$d_i = \sum_{j=1}^{J} G_{ij} m_j, \quad i = 1,2,.......I \tag{13}$$

solved by appropriate methods of linear algebra as G_{ij} is a known matrix calculated at the background environment. Here J is the total number of unknowns and I is the total number of discrete data values



(a)

Multipath propagation (eigenrays)

(b)

Arrival paterm (time in sec)

(sec)

Figure 2. The concept of ocean acoustic tomography using ray theory

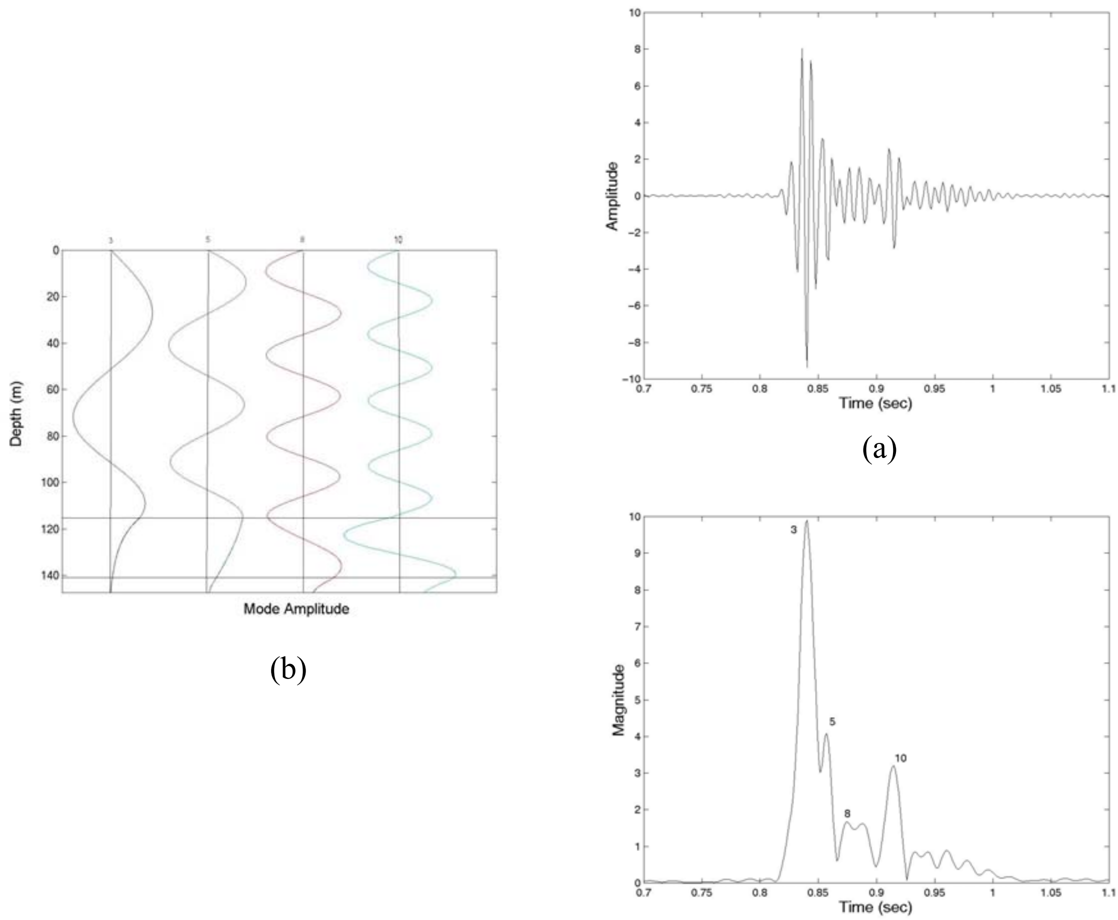
The concept of ray tomography is schematically represented in Figure 2. The multipath propagation in the ocean environment (a) results in an arrival pattern of the signal as shown in (b). Association of the ray-paths with the peaks of the signal followed by subtracting the actual arrival times for the eigenrays from those of the reference environment, result in the formulation of equation (9).

Modal travel time inversions

An alternative approach is to identify modal arrivals instead of rays. This approach could be applied in shallow water areas where there is better modal resolvability than in the deep-water case. The acoustic field in the time domain can be written in a form similar to (5), with the amplitude a_n corresponding to the modal amplitude. The Modal travel time is defined as the travel time of a modal packet propagating in the water column. A modal packet is defined as a discrete energy distribution in depth corresponding to a specific eigenfunction. The modal velocity, that is the speed of propagation of a specific modal packet is defined as :

$$v_{gn} = \left.\frac{\partial \omega}{\partial k_n}\right|_{\omega_0} \tag{14}$$

where k_n is the eigenvalue of order n, corresponding to the eigenfunction u_n and ω_0 is the central circular frequency of the acoustic signal. In order that this theory is applicable in problems of ocean acoustic tomography, some of the peaks of the arrival pattern of the acoustic signal should be identified as modal arrivals [7] (See Figure 3).



(a)

(b)

(c)

Figure 3 Identification of modal arrivals in the arrival pattern of a tomographic signal. a) The signal in the time domain (measurement) b) The eigenfunctions for the identified modal arrivals c) Arrival pattern with identified modal arrivals [7]

Linear inverse theory can also be applied here and neglecting current influence in the field, the arrival time variations of the modal packets with respect to a background environment defined as above, could be the basis for the inversions.

The formula associating modal travel time variations with respect to a background environment is of the form:

$$\delta\tau_n = \int_S \left.\frac{\partial Q_n}{\partial \omega}\right|_{\omega_0} \delta c(\vec{x}) d\vec{x} \tag{15}$$

and the integration is over the area of the sound speed variation. The function Q_n is calculated for the parameters of the background environment [8-10].

By appropriate discretization of the water environment, the application of this formula for N measurements of the modal travel time, result in the linear system

$$\delta\tau_n = \sum_{j=1}^{M} G_{nj}\delta c_j, \quad n = 1,2,......N \tag{16}$$

where M is the number of discretization points.

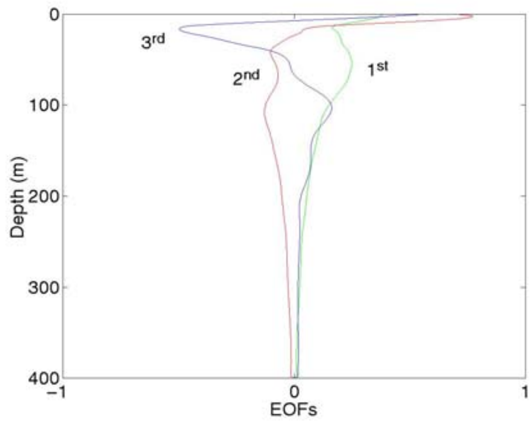


Figure 4. Empirical Orthogonal Functions

The method works well for the recovery of range-average sound speed profiles or structures where the recoverable parameters are local variations described by means of empirical orthogonal functions (EOFs) [10].

It should be pointed out that the use of EOFs has a twofold effect as regards the inverse problem. First it leads in a decrease of the number of the unknowns (normally 2 or 3 orders of EOFs are enough to determine the field), thus rendering the problem more easy and second ensures the physical meaning of the results by forcing them to be smooth functions.

Figure 4 presents an example of EOFs (three orders) determined for the environment of the Gulf of Lions in France [11]. They are scaled for simulation reasons to the depth of 400 m. They correspond to the sound speed variation with respect to a linear reference profile.

Using EOFs, equation (15) is referred to the amplitudes θ_ℓ of the EOF's *instead* of the sound speed values c_j

When inverting for a range-dependent environment the amplitudes are functions of range.

It should be mentioned here that a very good study on ray and mode duality as regards their use for ocean acoustic tomography can be found in the work by Munk and Wunsch [12].

Peak inversions

When neither ray arrivals nor modal arrivals are identifiable, an alternative approach has been introduced allowing inverting for the local maxima of the arrival pattern of the tomographic signal. If the amplitude of the pressure at the receiver's location is

$$a(t;c(\vec{x})) = a(t;\vec{\theta}) \tag{17}$$

the arrival times of the local maxima satisfy the equation

$$a'(\tau_\iota;\vec{\theta}_0) = 0 \tag{18}$$

where prime denotes differentiation with respect to time.

Using this approach, a linear relationship between travel time variations of the peaks and associated sound speed variations in the same way as in equation (9) can be defined. [13]

This approach has been used extensively for processing the data of the THETIS and THETIS-2 experiments in the Mediterranean Sea with excellent results [11,13,14]. Range average sound speed profiles have been obtained so far, but progress is underway to assess the conditions of applicability in range-dependent environments.

Modal-phase inversions

A similar approach is to invert for the amplitudes of the EOFs or the sound speed values using measurements of the modal-phase differences, defined as the phase of each normal mode filtered at the receiver's location.

This approach is based on adiabatic normal-mode theory and exploits the far field representation of the acoustic field in the form

$$p(\vec{x}) = p(r, z; z_0) = \sum_{n=1}^{N} D_n(r, z_0) u_n(z; r) e^{i\bar{k}_n r} \tag{19}$$

where z_0 is the source depth, $\bar{k}_n$ is the range average eigenvalue associated with the eigenfunction $u_n(z; r)$ defined for each range *r*. A cylindrical co-ordinate system is assumed. If the exponential term (model phase) can be measured, the range average eigenvalue can be extracted and a relationship between this value and the sound speed profile can be written in the form [9]

$$f(\bar{k}_n, c(r, z)) = 0 \tag{20}$$

It can be proven that the relationship is linear when variations from a reference background environment is considered in much the same way as in the traditional ocean acoustic tomography using ray theory (see equation (8)).

However, in order that this approach is applied, an array of hydrophones is needed to determine the modal structure in the frequency domain. Both theoretical [9,15,16] and experimental studies [17] of the method have been performed with encouraging results.

Matched-field inversions

All these approaches are linear, and in general variations from a known background state can be obtained. This means that a-priori information for the sound speed structure at the area of interest exists and that it is enough to define the background environment. When this is not the case, non-linear schemes have to be applied. So far, inversions based on Matched-Field Processing (MFP) are very popular, despite the limited number of experiments that have been performed for their validation.

The sound speed structure at a specific area is determined by "matching" replica fields with measured ones, the replica fields being determined by means of a suitable direct propagation model. The matching over a generally wide search space is controlled using an objective function $L(\mathbf{m})$, which has its maximum when its input set consists of the real model parameters [18,19]

When the problem is treated in the frequency domain, it is necessary to convert the sampled data to the frequency domain. This can be done by Fourier transform of the form

$$p(\vec{x}; \vec{\omega}) = \Im \; [p(\vec{x}; t); \quad t \to \omega] \tag{21}$$

In practice, the signal in the hydrophone *n* (*n=1,2,…N*) is sampled in the time domain using *K+1* points, a time window *T* and a weighting function $w(t_k)$ by means of a discrete Fourier transform :

$$F_n(\vec{x};\omega) = \sum_{k=0}^{K} p_n(\vec{x};t_k)w(t_k)e^{-i\omega t_k} \tag{22}$$

where $t_k = k\Delta_t$, $\Delta_t = T/K$.

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 obtained as above. Considering a candidate parameter set **m**, one can easily calculate replica fields $\hat{\mathbf{F}} = (\widehat{F}_1, \widehat{F}_2, ...\widehat{F}_N)^T$. A typical objective function is the *Bartlett* processor defined as

$$L(\mathbf{m}) = \mathbf{w}^+ C\mathbf{w} \tag{23}$$

where $\mathbf{w} = \widehat{\mathbf{F}}$, $C = <\mathbf{FF}^+>$ 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. 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 [20].

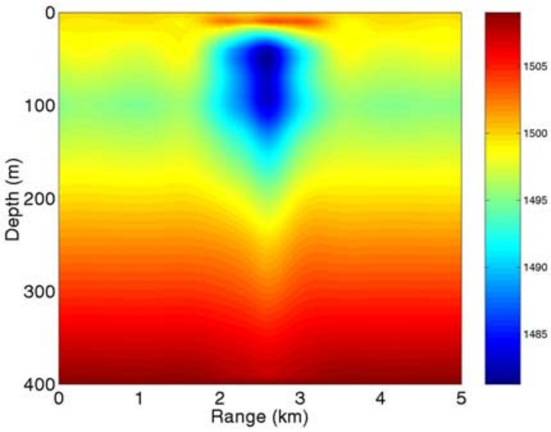
The approach is very simple in its concept but it is computationally expensive, due to the great number of estimations for the replica fields that have to be performed. Of course, the process is controlled by a suitable algorithm aiming at reducing the number of the required calculations. This can be done by directing the search towards most probable solutions or to a population of acceptable solutions. Simulated Annealing [21], Genetic Algorithms [22,23] and others such as the "RIGS" method [24] are typical examples of procedures developed to control the directive search. Hybrid approaches combining non-linear and linear techniques have also been applied [25].

Figure 5 present examples of the use of such a hybrid approach using simulated data. The approach is based on the use of a background environment for a modal-phase approach, which has been the result of the application of a matched-field scheme. Figure 5a is the actual environment corresponding to a cold eddy, described by means of EOFs of the type of Figure 4. 5b presents the recovered structure, when a matched-field processing scheme with a Genetic Algorithm is applied and Figure 5c corresponds to same environment recovered by a hybrid scheme.

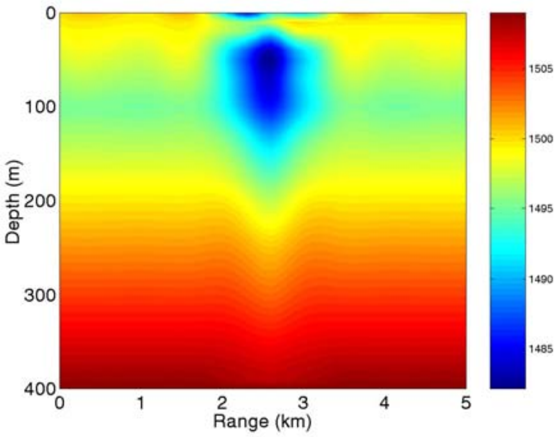
Alternative approaches in the context of non-linear schemes include matched-mode schemes in which the sound speed structure is calculated by matching the modal structure rather that the pressure field [26], neural networks [27] in which the field matching is preceded by a learning phase, aiming at teaching the network to understand the differences in the fields and a possible reason for these as well as matching-modal arrivals [28] or matched-peak inversion schemes [29] .

Matched-field processing is extensively used for bottom geoacoustic inversions as well. The concept in these applications is similar to ocean acoustic tomography with the basic difference being in the fact that the recoverable parameters include bottom properties [30-32].

Numerous simulations studies and application of MFP with data from actual experiments have demonstrated the potential of MFP for tomographic and geoacoustic inversions. Of course the accuracy of inversions depend on the available resources and especially the length and hydrophone spacing of the vertical array as well as the number of sources used for sampling a great area [33,34]



(a)



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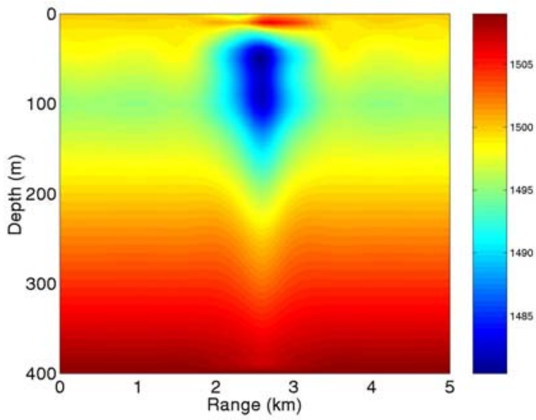

(c)

Figure 5. Simulated structure of a cold eddy (a) . The structure of the cold eddy recovered using matched-field processing (b). The structure of the cold eddy recovered by the hybrid approach (c)

Characteristic Experiments of Ocean Acoustic Tomography

Since the introduction of the new technique for the acoustical monitoring of the marine environment, several experiments have been performed in the sea for its testing and validation. During the ‘80s most of the efforts of the oceanographic community were focused on the validation of the tomographic measurements and the understanding of the capabilities and limitations of the technique. The first experiment ever held explicitly dedicated to the demonstration of ocean acoustic tomography was called “Tomography Demonstration Experiment” and was conducted jointly by the Woods Hole Oceanographic Institution (WHOI), the Scripps Institution of Oceanography (SIO), the University of Miami (UM) and the Massachusetts Institute of Technology (MIT). It covered an area of 300 km x 300 km in the Northwest Atlantic and demonstrated the possibility of mesoscale sound-speed pattern reconstruction [1].

Since then a number of experiments were performed in various areas around the globe, each one bringing new knowledge and may be new questions in the field. During the decade of ‘90s the experiments brought evidence that ocean acoustic tomography can indeed be used for the study of large scale long term changes in the marine environment. In the subsections to follow, four of the experiments will be briefly presented. A full list of experiments performed until 1994 can be found in [1]. Some of the experiments performed after 1994 are the ATOC, which started in 1995 in the Pacific Ocean [35-36] the TAP (started in 1994) [37] and ACOUS (started in 1998) [38] both aiming at the demonstration of ocean acoustic tomography in the Arctic Ocean and INTIMATE96 [39] and INTIMATE98 [40] in the Atlantic Ocean aiming at the study of the internal tides using acoustic tomography. On going efforts include the NPAL [41] and the Labrador sea tomography experiments (see below).

The Heard Island Feasibility Test

This was the largest scale experiment ever conducted in the world associated with the problems for which ocean acoustic tomography was developed. The main objectives of the Heard Island Feasibility Test (H.I.F.T.) was to establish the limits of usable, long-range acoustic transmissions to be used for the measurement of average temperatures over large ocean ranges. The experiment was carried out in January 1991. It was co-ordinated by Walter Munk from SIO and a large number of Institutes participated. Coded acoustic signals were transmitted from a vertical array of sources each capable of transmitting a nominal level of 206 dB re 1 μPa @ 1 m at 57 Hz central frequency (bandwidth 14 Hz), deployed near Heard Island in the southern Indian Ocean. The location was chosen so that acoustic rays emitted from a source there, could reach isolated areas around the globe. 16 receiving locations were prepared in the North and South Atlantic, the North and South Pacific, the Indian Ocean and the Southern Ocean. The issues of the HIFT were: can signals generated by currently available acoustic sources be detected at ranges of order 10 Mega meters and by appropriate processing to measure travel time at an accuracy better than 0.1 s. This accuracy is considered necessary in order that the trend of global warming is predicted by the appropriate measurement of the change of the average sea temperature.. A large amount of data measured in several receiving stations were available for processing after the end of the experiment. The details of the experiment and a series of studies resulted from the measurements were reported in scientific journals and presented in Conferences. A comprehensive collection of papers related to the HIFT can be found in J.A.S.A [42]. HIFT was successful in the sense that it was able to prove that conceptually the idea of ocean acoustic tomography works well at a global scale but also due to the fact that several problems of global acoustics appeared and gave the motivation to the scientists to deal with. Also the expertise gained, led to a reconsideration of the tomographic sources for smaller-scale experiments (lower intensity, higher frequency).

The THETIS experiment.

In the early 90's a European group of Institutes working in acoustical oceanography and acoustic propagation modelling was formed aiming at the demonstration of ocean acoustic tomography as a tool for ocean process monitoring. The group consisted of the Institute of Oceanography of the University of Kiel (IFM-Germany), IFREMER (France) and the Institute of Applied and Computational Mathematics of FORTH (IACM-Greece) and was funded by the European Commission for the conduction of two experiments in the Mediterranean. The first experiment (THETIS) was held in 1991-1992 in the Gulf of Lions (France) and the second one (THETIS-2) in the western Mediterranean basin in 1994.

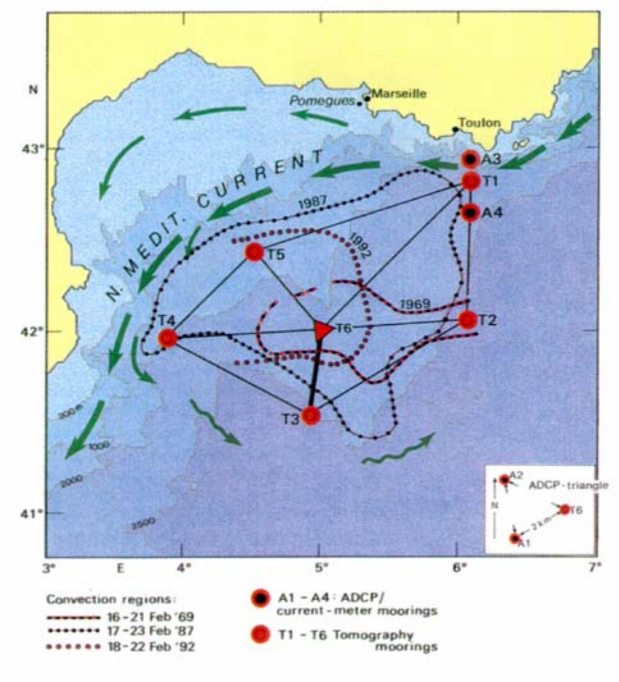

Figure 6. The tomographic network of the THETIS experiment

During the THETIS experiment ocean acoustic tomography was applied in conjunction with conventional and advanced physical oceanography observations to measure the effects of deep convection on the water mass distribution and resulting circulation in the Gulf of Lions [11,43]. The data used in the tomography inversions were travel times of acoustic arrival peaks corrected for mooring motion. Inversion results compared with in-situ obtained data showed that tomography can sample very well the near-surface layer. Sources used were emitting BPSK signals with central frequency 400 Hz and bandwidth 100 Hz. They were fixed at the depth of 150 m.

The THETIS-2 experiment

The objectives of the THETIS-2 experiment were to demonstrate the capabilities of tomography for basin-scale measurements and heat flux calibrations, to provide a data set for assimilation studies and to prove the concept for long-term acoustic monitoring in climate studies or operational systems. The tomographic network appears in Figure 7. It consisted of 7 tomographic moorings with sources operated at the central frequency of 400 Hz (as in the THETIS experiment) or 250 Hz. The sources were fixed at the depth of 150 m. The measurement principle was the standard acoustic tomography approach, where the discrete ray arrivals provide a vertical sampling of the ocean. Inversion tools applied were based on ray and peak arrivals. Results from this experiment were encouraging as potential temperature anomaly along the paths that have been analysed obtained by tomography compared very well with in-situ measurements (XBT and CTD sections) and climatology. (Figure 7). In addition, it became clear that separate heat-content time series could be obtained for the depth ranges corresponding to the different water masses (surface layer, Levantine Intermediate Water and deep water). Finally, the THETIS-2 project has also demonstrated that the large-scale fluctuations and evolution of a basin like the Mediterranean could be sampled and monitored by acoustic transmissions between shore-based stations [44].

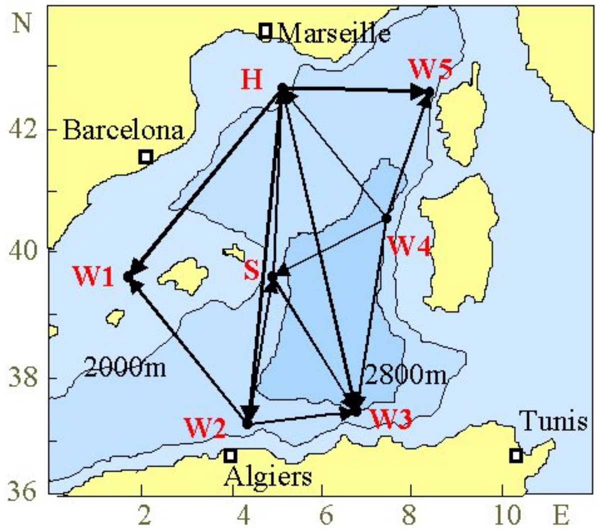

Figure 7. The tomographic network of the THETIS-2 experiment

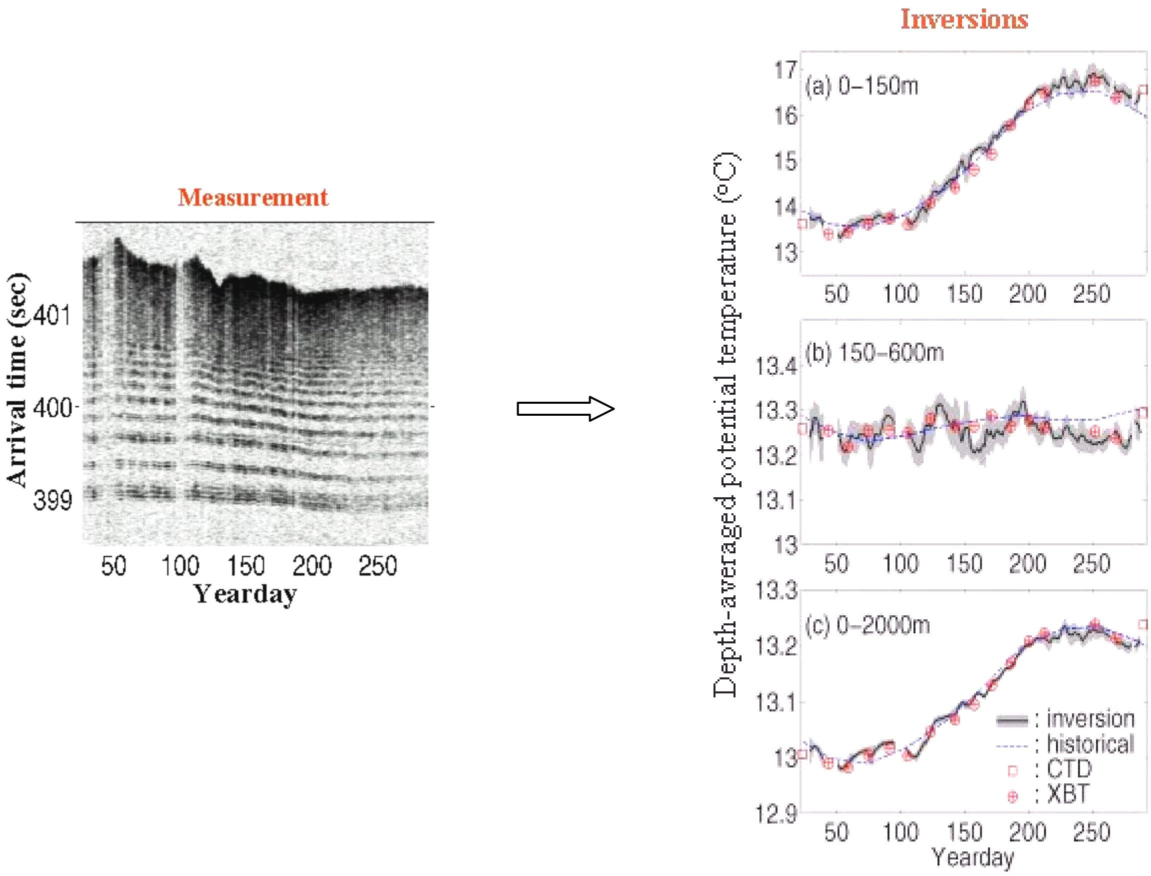

Figure 8: Processed acoustic data and comparison of inversion results for the H-W3 path of the THETIS-2 experiment. Vertical scale in the figures in the right, represent temperature in Celsius degrees.

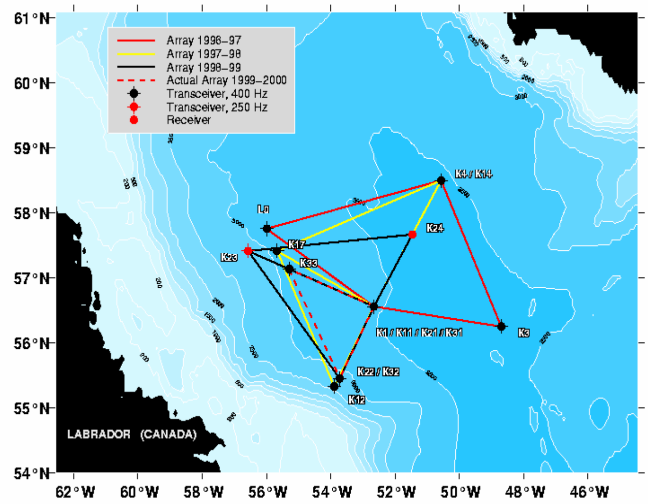

Figure 9. The tomographic network of the Labrador experiment

The Labrador Sea acoustic tomography experiment

The Labrador Sea acoustic tomography experiment is an ongoing tomography experiment that was initiated in the summer of 1996 as part of a research project at the Institute of Marine Science of the University of Kiel addressing the dynamics and variability of the thermocline circulation in the North Atlantic Ocean. The acoustic measurements were aiming at the study of the large-scale effects of winter cooling, deep mixing by convection and subsequent warming and restratification on the mesoscale [45,46]. The tomographic array of the experiment was first deployed in 1996 and redeployed every year resulting in the largest time series of tomography data (6 years of data until today). In every period of its operation it consisted of 3 or 4 moored tomographic instruments with sound sources at the depth of 150 m, some emitting signals of 400 Hz central frequency (effective bandwidth 100 Hz) and the rest emitting signals of 250 Hz central frequency. Typical distances between mooring pairs ranged between 150 km and 330 km. After appropriate preprocessing of the received acoustic signals and correction for mooring movement, ray arrivals were predicted and a matched-peak inversion scheme [29] was used for obtaining the amplitudes of five empirical orthogonal functions, which have shown to describe most of the ocean states observed in the area [46].

Preliminary inversion results obtained so far have showed that inverted oceanographic information in terms of vertically averaged temperatures, as deduced from the measured sound-speed field, were well compared with hydrographic observations in the area over large periods of time, adding an additional evidence that ocean acoustic tomography is a valuable tool for the monitoring of the ocean environment [46].

Perspectives

Ocean acoustic tomography has already demonstrated its potential as a tool for the monitoring of the ocean environment . Of course there are several issues that remain to be studied thoroughly. For instance range-dependent environments are very difficult to handle by traditional methods which produce range-average results. Despite the fact that several methods have been proposed for handling the problem (see e.g. [15], [24]) general range-dependency is very difficult to be resolved solving an ill-posed problem such as that of ocean acoustic tomography, unless very accurate a-priori knowledge is assumed. Despite the fact that ocean acoustic tomography was not originally developed explicitly to solve range-dependent issues, the possibility of inverting for local inhomogeneities remain a challenging problem to be studied in the future.

Real-time processing of the tomographic data is a need if the concept of ocean acoustic tomography is to be applied for the real time monitoring of the ocean change. So far both the forward and inverse procedures involve calculations in the frequency, which are time consuming. The development of fast models in both forward and inverse procedures and relatively automatic sequences of calculations is therefore necessary in order to accelerate the production of results. The development of integrated software environments such as "TOMOLAB" [47] is considered a first step towards this direction.

Another issue under consideration is coastal-zone tomography. As ocean acoustic tomography was originally developed for the monitoring of the deep ocean, most of the relevant techniques were tuned for this type of environments. However, ocean acoustic tomography seems to be a valuable tool for monitoring the quality of water in shallow water and coastal zones. Tomographic stations in estuaries and near busy straights and ports in connection with almost real-time inversion techniques could lead to a continuous observation of the quality of water.

Internal waves and tides could also be monitored using ocean acoustic tomography techniques [48]. This area has recently drawn the attention of acousticians and physical oceanographers establishing a new field of application for ocean acoustic tomography. Combining information on internal waves, currents and thermometry one would expect that a complete image of the ocean environment could be obtained by suitable inversion of acoustical data. It should be pointed out that several works are dedicated to acoustic tomography for the current field. The area is open to relevant studies and experiments. However the focus of this article is mainly on methods for the retrieval of the sound field only.

Another aspect that has drawn the attention of physical and acoustical oceanographers is data assimilation. By this term we mean the adaptation of data obtained by tomographic or alternative ways (e.g satellite altimetry) into oceanographic water circulation models amenable to predict changes in the ocean eco-system. The integration of ocean acoustic tomography and physical oceanography via data assimilation is perhaps the ultimate goal of people working in the area of acoustical oceanography. Thus it will become possible to obtain a powerful tool for the long-term monitoring of the ocean environment in critical areas for the global climate (e.g. Labrador Sea, Arctic regions, Gibraltar straits)

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