

## **VERSO UN AMBIENTE MARINO SILENZIOSO: IL RUOLO DEGLI OSSERVATORI ACUSTICI PASSIVI**

## **TOWARDS A SILENT MARINE ENVIRONMENT: THE ROLE OF PASSIVE ACOUSTIC OBSERVATORIES**

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### **RIASSUNTO**

Il suono è ampiamente impiegato nelle osservazioni marine come strumento alternativo per ottenere informazioni su dati ambientali nella zona marina oggetto di monitoraggio. L'idea originaria di utilizzare specifiche sorgenti sonore artificiali per inviare segnali nell'ambiente marino ha dato origine alla tomografia acustica oceanica e numerosi metodi alternativi sono stati sviluppati per poter utilizzare le onde sonore come mezzo di raccolta di dati ambientali. Per contro vi è la necessità di ridurre al minimo il rumore generato da sorgenti non naturali per preservare l'ambiente marino e le sue caratteristiche acustiche. Per questo motivo, l'idea di poter utilizzare misure ottenute da sorgenti sonore occasionali o anche il rumore ambientale per l'attuazione di analisi inverse sta costantemente guadagnando l'attenzione dei ricercatori.

### **ABSTRACT**

The sound is widely used in marine observatories as an alternative means to retrieve information about environmental data in the sea area under surveillance. The original idea of using specifically man-made sound sources to send signals in the marine environment triggered the idea of ocean acoustic tomography and many alternative methods have been developed to exploit the acoustic measurements towards the retrieval of the environmental data. It is however desirable to reduce the noise originated from not natural sources in the marine environment to obtain a more silent marine environment. Thus the idea of using measurements of signals due to acoustic sources of opportunity or even the ambient noise for inversion purposes is continuously gaining the attention of the scientists.

Parole chiave: Ambiente marino; Osservatori acustici passivi.

Keywords: Marine environment; Passive acoustic observatories.

## 1. Introduction

The quality of the marine environment is critical in human life. It is well known that sea covers the 70 % of the globe. It is an unstable meteorological system in the sense that even small variations of the temperature in a marine area can have significant effects in the temperature of the atmosphere and the meteorological phenomena in the world! Therefore it is not possible to predict large scale variations of the climate without taking into account the dynamics of the water circulation in the oceans. Moreover 99% of the kinetic energy due to water circulation is associated with medium scale phenomena of diameters around 100 km. Monitoring of the changes of medium to large scale is therefore necessary for the understanding of the global changes.

Today, mathematics and technology provide the necessary tools for the understanding of the complex marine systems aiming at the better treatment of the delicate biosphere in which we live. Current research and development within the field of 'Operational Oceanography' aims at:

- Increasing in reliability and period of validity of the models for the prognosis of critical phenomena,
- Expanding the number of models and predictions to encompass additional prediction products such as :
  - Indicators for marine pollution;
  - Predictions for water quality;
  - Erosion and sediment transportation;
- Expanding the areas of research to include for instance :
  - The prediction of possibility for physical disasters (e.g earthquakes, tsunami);
  - The study of marine biodiversity.

The idea of setting a network of ocean observatories to cover the critical areas of the marine environment is well accepted by the scientists and the international administrative institutes and several individual or nested stations have been installed around the globe.

What is relatively new in this respect is the inclusion of sound as a carrier of information on the quality of the marine environment. The reason that the sound is so much used in the sea has to do with the fact that unlike the electromagnetic waves, water has the ability to support the transmission on sound at very large distances without significant loss. Thus, the sound may play the role of the electromagnetic waves in the air. On the other hand, of course, the acoustic waves undergo severe changes as they propagate in the sea environment, which means that a systematic study of the propagation conditions has to be carried out in order that optimum exploitation of the acoustic field in water is achieved.

The acoustical observatories today are parts of oceanographic observatories installed in areas of critical importance for the monitoring of the marine environment and provide data which are used supplementary to information retrieved by traditional measurements for a complete assessment of the environment.

This article summarizes main facts on the use of sound for the monitoring of the marine environment giving emphasis to the "green" observatories that is observatories operating in passive mode by just listening to the ocean sound without sending sounds to it. This is considered an important step towards achieving a "quite" marine environment with reduced contamination of ambient noise by man-made acoustic signals.

## **2. Inverse problems of underwater acoustics**

Monitoring of the marine environment is associated with the calculation or estimation of critical parameters of the water column and the sea-bed. Typically, these parameters include the sound speed profile in the water column and the sediment layers, the density of the water and the sediment layers, and current velocity. The sound speed in the water is associated with the water temperature, which is the parameter of interest for the oceanographers. Direct measurement of these parameter involves the use of a measuring devices in situ. It is well understood that when a large area is to be monitored, a grid of sensors that should be installed in order to provide spatial distribution of the parameter of interest is not the most efficient solution. What is the alternative? The use of sound. Sound propagates in the sea at long distances. Moreover, the acoustic field due to a specific source is rich of information on the environment through which it had propagated. The retrieval of this information and its appropriate projection on the critical parameters is among the main goals of Acoustical Oceanography which dictated the idea of ocean acoustic tomography and supports the wide area of geoacoustic inversions.

Of course human was not the first to use sound for estimating the parameters of the marine environment. The marine mammals since their appearance in the world have been used the sound for finding food, for communication, for navigation. They had developed a sophisticated emission reception and acoustic processing system for exploiting sounds in active and passive mode. Humans just imitate the marine mammals. The human first attempts towards the use of sound for estimating parameters of the marine environment were focused on bathymetry estimations followed by military applications of localizing and characterizing ships or submarines by instruments installed onboard these vessels. Later the scientists realized the importance of sound for communication, for fishing industry (localizing fish shoals) and lately for the monitoring of the marine environment.

A breakthrough on the use of sound for the monitoring of the marine environment was the introduction of Ocean Acoustic Tomography (OAT) by Munk and Wunsch in 1979 [1]. It was the basic concept upon which the first experiments to validate the feasibility of this method were based (see for instance [2] for the first global experiment and [3,4] for experiments held in the Mediterranean) and the first marine observatories were designed. The principles of ocean acoustic tomography are similar to that of the medical tomography: A wave due to a known source propagates through a domain (environment) supporting this specific type of wave. Any changes in the parameters characterizing this environment are reflected in the changes of the wave field received in some receiver array. By appropriate processing of the wave field and taking into account the theory of wave propagation in this domain, these parameters can be estimated, leading to the recovery of the properties of the environment which are associated with the recoverable parameters. In medical tomography, the wave is electromagnetic whereas in ocean acoustic tomography the wave is acoustic. Similar applications in ultrasound are well known since a long time, with the only difference being in the fact that ultrasound applications are local. There is no need to proceed to further details in this article as they fall beyond its scope. It is sufficient to stress out that traditional ocean acoustic tomography is based on the use of sound from a man-made source. The interested readers can find many details on the specifications of these sources by going through the extended literature existing for these experiments (see for instance the collection of papers for the Heard Island experiment in J.A.S.A starting from [2]).

Problems of estimating physical parameters from measured data which are referred to a different quantity fall in the general area of Inverse Problems. Conceptually, the formulation of the inverse problems is relatively simple. Based on the modeling of the forward problem, there is always a functional relationship between measurements (data)  $d$  and retrievable parameters  $m$  of the form;

$$(1) \quad f(m, d) = 0$$

where  $m$  and  $d$  are functions of the space and/or time. In the case of inverse problems in acoustical oceanography, retrievable parameters as stated in the beginning of this section are the sound speed profile in the water column and the sediments, the density and location of interfaces of the sediment layers, the attenuation coefficients and if an elastic bottom is considered, the shear speed in the sea-bed layers. Additional useful parameters retrievable by acoustic means are the current velocities. The relationship between data and parameters is dictated by the specific model describing the acoustic propagation in the environment.

The model is mathematically formulated as a boundary value problem with its main core being the acoustic equation. With respect to the measured data, there are several possibilities according to the type of the signal and its exploitable features. For instance, the data set may consist of arrival times of signals travelling on a specific acoustic rays, arrival time of individual modes, pressure field at different depths or ranges, or even statistical features of transformed versions of the measured signal. Almost all the inverse problems in underwater acoustics are formulated as discrete problems after appropriate discretization in space. Thus, data and parameters are represented by vectors:

$$(2) \quad \mathbf{m} = [m_1, m_2, \dots, m_M]$$

$$(3) \quad \mathbf{d} = [d_1, d_2, \dots, d_N]$$

The vector  $m$  is retrieved by means of a non-linear vector equation of the general form:

$$(4) \quad f(\mathbf{m}, \mathbf{d}) = 0$$

The function  $f$  is generally complicated and not subject to linearization. Consequently, the problem is nonlinear and very difficult to solve. Moreover, it is ill-posed. A great amount of literature is devoted to the study and application of optimization algorithms that lead to the most likely solution of the inverse problem in a deterministic sense, while there are methods treating the inverse problem in a stochastic sense as well. We will not expand more on the details of the problems and their solutions for which there is an extensive bibliography (see for instance [5-7] as an introduction to inverse problems in underwater acoustics). Whatever the method for the solution of the mathematical problem is adopted, a data assimilation procedure is in general required to map the parameters retrieved by means of the inverse problem to the parameters which are used by the oceanographers to assess the dynamics of the marine environment, when the main goal is the monitoring of the environment. On the other

hand, Geographical Information Systems (GIS) and appropriate imaging algorithms are also needed in order that a clear view of the environment is obtained using the solutions of the inverse problem. It should however be underlined that whatever the application is, it is important to collect data in the most appropriate way so that the observables are clearly determined and the inverse problem expressed by equation (4) is reliably solved.

### 3. Ocean acoustic observatories

The mission of Ocean Acoustic Observatories is to collect acoustic data in a continuous basis, which would be eventually processed in order to be used for the estimation of the parameters of the environment. In this respect, we can distinguish between active and passive observatories. Active observatories involve arrays of acoustic sources and receivers. A source is emitting a known signal which is recorded at the receiver location and stored for further processing or transmitted to a shore based station. Ocean Acoustic Tomography is based on this concept. Figure 1 illustrates the principle of a stationary acoustic observatory with a couple of moorings carrying the acoustic instrumentation.

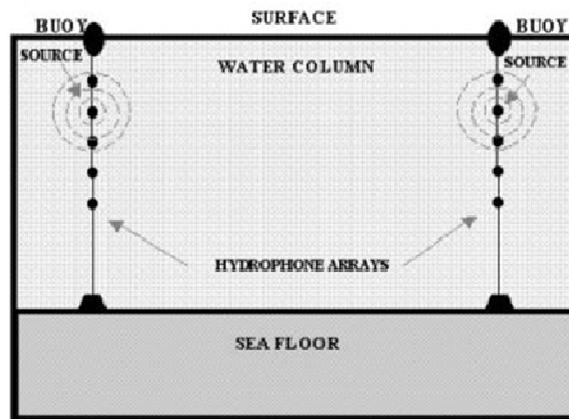


Fig. 1 – An optimum configuration of moorings for ocean acoustic tomography observatories.

The simplest case involves a single source and a single receiver whereas the more typical cases involve arrays of sources and receivers. For practical reasons (cost of the acoustic source) the configuration of a single source and a vertical array of receivers is frequently encountered in real applications. The configuration depicted in Figure 1, defines a geometrical domain to be considered at a vertical slice (τομή– tomi in Greek) as in Figure 2 upon which a problem of Partial Differential Equation with boundary conditions based on the acoustic equation is formulated. Multiple slices can be combined together to provide a 3-D description of the environment. The term “tomography” is based on this concept.

It should be noted that the sources utilized for ocean acoustic observatories are of relatively high power (significantly lowered during the recent years) and their frequency range is typically between 50 Hz to 1kHz in order that the acoustic signal propagates at long distances without significant attenuation.

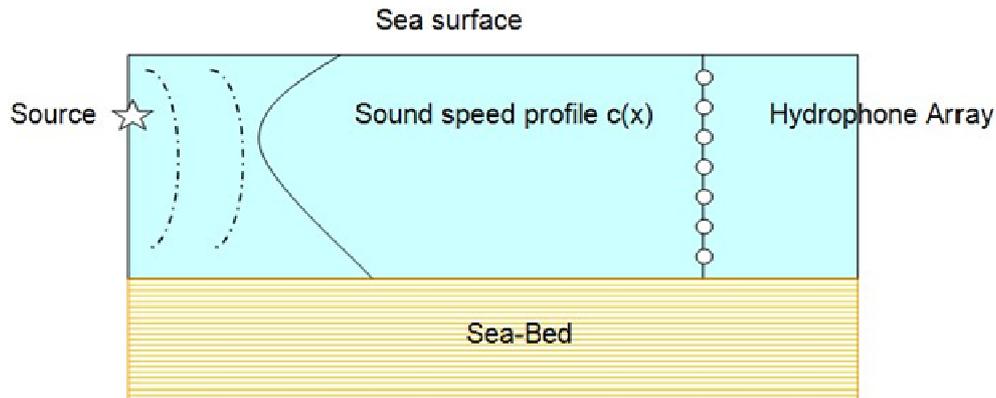


Fig. 2 – A vertical slice defined by a pair of transceivers in observatories for ocean acoustic tomography. Simplified version with horizontal plane water-bottom interface.

The author of this paper is not aware of permanent active observatories existing within the network of ocean observatories. Active observatories are created for a limited time in critical areas (e.g. Labrador [8], Mediterranean [3, 4], and Arctic [9]), mainly for the validation of the concepts of ocean acoustic tomography. Limitation on the use of high power sources and on the storage of the recorded data, dictate the temporary function of these observatories.

With respect to the use of loud sources for acoustic observatories in the sea, it is true that a great concern was raised among marine biologists and environmental engineers on their impact to marine mammals. Acoustic applications in the marine environment involving the use of loud sources (e.g from military vessels, for seismic exploration etc.) are blamed for harming the ecosystem leading to disorientation of the marine creatures using the sound for their life or even to damage of their hearing system. This concern dictated the issue of national legislation reducing the allowed levels of sound sources to be used in the marine environment including those to be used for ocean acoustic tomography. Still it is possible to use low power acoustic sources for the acoustical monitoring of the marine environment without violating the regulations. However, taking into account the necessity for keeping the ambient noise in the sea at a very low level the use of sound sources for the active acoustic monitoring of the marine environment is now under reconsideration.

At the European level, the aim of the European Union's ambitious Marine Strategy Framework Directive is to protect more effectively the marine environment across Europe. The Marine Directive was adopted on 17 June 2008, after several years of preparation and extensive consultation of all the relevant actors and the public, and came into force on 15 June 2008 [10]. The following sentences are extracts from the official web-page of the EU on the environment [11]: *“Human activities can take a disproportional amount of energy out of a system or add to it. This can have a negative impact on the marine environment (...). Attention has been raised on the topic of underwater noise and its effects on marine life. Yet, the effects of underwater noise are not fully understood. One reason for this is that only for a few species of mammals and fish, tests have been performed to identify hearing range and sensitivity. But even if an individual hears the noise, we are not sure how it will react or what damage will be done. It could avoid the source and be chased out of important areas, for example spawning grounds. It might influence its ability to detect food. Its hearing could get*

*damaged at close ranges with further effects on communication about food, danger and reproduction”.*

In view of these concerns, it is obvious that besides keeping the noise levels in the marine environment as low as possible, thus reducing the human activities producing noise or adopting low power sources, it is desirable to study alternative ways for the acoustical monitoring of the marine environment.

#### **4. Passive observatories**

An alternative to active acoustical observatories is the passive ones. The idea of listening to the marine environment to get information on its character and dynamics was recently introduced to marine science and technology. Passive acoustic monitoring of the marine environment can give important information about the marine environment with proper exploitation (after processing) of the measured sound field. In this respect, the ambient noise of the marine environment is not entirely unwanted, but it may be proven as a very useful source of information and data provider for the inverse problems. The noise of the marine environment can be considered as natural or as anthropogenic, depending on its source.

As natural sources of noise production in the marine environment we can consider:

- the breaking of the surface (gravity) waves due to wind;
- the rain;
- the earthquakes;
- marine mammals to small creatures like shrimps (biological sources);
- breaking of the ice (in the Arctic regions).

As anthropogenic causes we can consider:

- the navigation (traffic noise);
- the activity at offshore facilities.

A spectrum of the ambient noise has been reported by Wenz [12] and Table 1 reflects the frequency range of the main sources. The lower values of spectrum levels correspond to the higher frequencies of the spectrum.

Table 1 – Sources of Ambient Noise in the Sea and their Spectra. The Spectrum levels correspond to long term noise. Intermittent man-made noise sources contaminating the ambient noise may be 100 dB higher.

Source of Ambient Noise	Frequency range (Hz)	Typical Spectrum Levels (dB re 1 $\mu$ Pa)
Earthquakes and Explosions	1-100	40-140
Ships	10-1000	30-110 (Depending on density of ship traffic)
Biological sources	10-100000	
Surface Agitation (Wind Generated Noise)	100-10000	20-90 (Depending on sea-state)

So far, the passive acoustic observatories are concentrated on gathering and analyzing the signals from some of the most prominent sources of ambient noise such as bubble oscillation, wind and rain, earthquakes and animal sounds [13]. These signals are primarily analyzed for the understanding of the physical processes in the sea, for the monitoring of the marine mammal population and their behavior [14], and for seismic studies [15].

On the other hand, signals from sources of ambient noise propagate in the environment in the same way as signals from sources intended for ocean acoustic tomography or geoacoustic inversions. In this respect they can be used for inversion of the critical parameters of the marine environment in more or less the same way as in typical ocean acoustic tomography cases [16]. The only difference is in the “observables” of the measured acoustic field, which have to be defined in such a way so that the functional relationship (1) or (4) can be exploited. For instance, for passive imaging, it is necessary that the model relying measurements and parameters may not include information on the source (as it is actually unknown) but should exploit the correlation of recordings from different hydrophones in the array of hydrophones. This is due to the fact that noise, although a stochastic phenomenon, exhibit statistical features such as the spatial coherence, which are stable and may be used to invert for the environmental parameters [17].

Among the first applications of passive imaging in the marine environment we may mention the recovery of the sea-bed structure using measurements of the ambient noise. This application is perhaps the most widely studied so far. Already in the early 90's the first ideas came to the literature. According to the work by Carbone et al. [17] and Buckingham and Deane [18] estimates of the compressional and shear wave speeds are determined from ambient noise measurements over shear supporting sea-beds. Using a model of wind-generated noise over an elastic seabed, an inversion procedure is developed based on a matched field of the complex, broadband coherence from a single hydrophone pair. Further studies in this area involve the use of ships of opportunity as sources to be exploited for inversions using vertical or horizontal arrays of receiving hydrophones [19, 20].

Recently, experiments have been carried out to test alternative inversion techniques for the exploitation of measurements taken by both known sources specifically deployed for the experiments (active inversion mode) and by sources of ambient noise (passive inversion mode). In the MREA/BP'07 sea trials ship noise has been used for the estimation of water and sediment parameters [21] using inversion techniques.

As the scope of this article is not to emphasize on the inversion techniques to be applied in passive mode, it suffices to stress out that research is underway to adopt optimum inversion procedures for the processing and the exploitation of data collected in listening mode of acoustical observatories, thus validating the idea of passive imaging of the marine environment using traditional measuring devices. Among them the work by Quijano et al. [22] should be mentioned, as the Bayesian inversion technique studied, seems to be promising for the statistical inversion of multiple water and bottom geoacoustic parameters using measurements of wind generated noise taking into account the uncertainty in the estimation of the location of the source.

It is interesting to note that passive observatories can also be used for the detection and classification of objects in the marine environment. The Acoustic Daylight Ocean Noise Imaging System (ADONIS) [23, 24] is intended for the creation of images in the ocean from consonification provided by the incident ambient noise field. The receiver is not similar to traditional receivers of active or traditional passive systems in the sense that it consists of a spherical reflector, 3 m in diameter with an elliptical array of 130 hydrophones at the focal surface. The studies performed using the ADONIS system indicate the feasibility of detecting individual images of objects in the marine environment in passive mode which is a great step towards the development of integrated multipurpose passive acoustic observatories for the monitoring of the marine environment.

It seems that the technology to be used in passive acoustic observatories for the monitoring of the marine environment does exist. Still there are many open questions in what concerns the use of ambient noise for inversions. Some of these questions can be summarized as following:

- As most of the observables for ambient noise inversions are based on its vertical or horizontal directionality, it is not obvious that this feature can be exploited under any conditions of ambient noise. The potential limitations have to be carefully studied.
- The surface generated noise is correlated with sea-surface agitation. Is there enough acoustic power induced in the water column under low sea-state conditions?
- Is it possible to use traffic noise in the same way as surface generated noise for inversions? So far, the main source of ambient signals to be exploited comes from individual ships (ships of opportunity) being actually a different concept.

In any case, as the passive observatories are based on sources (natural on anthropogenic) existing anyway in the marine environment and are part of ambient noise, the related technology can be considered as of “green technology” and “biologically friendly” aiming at achieving the goal of using acoustics for the continuous monitoring of the environment without probing it with unwanted sound. The ambient noise is not totally unwanted in this respect!

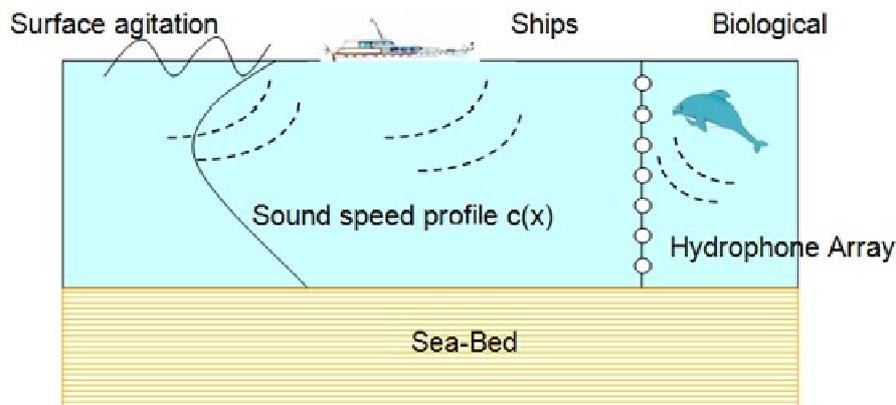


Fig. 3 – A vertical slice in the marine environment with potential sources of sound for passive acoustic tomography.

## 5. Technological considerations

In this section, the basic technological considerations of a passive acoustic observatory are summarized, indicating the potential subjects of future research towards the development of feasible and sustaining passive acoustic observatories in the sea. Most of these considerations are not different than those of the active observatories as reported in [25].

The acoustic signals exploited in passive acoustic observatories are of broad-band character. According to the type of source, they may be in the lower (earthquakes) medium (ships) or upper frequency bandwidth (wind generated noise, biological noise). For general purposes the receiving hydrophones should be of broad bandwidth to be able to receive signals from all possible sources and for optimum performance they

should be clustered in arrays (vertical as in Fig 3 or horizontal, or even in special shapes as in the case of the ADONIS system [23]).

With respect to acoustic signal handling, the passive acoustic observatories can be autonomous or cabled. For autonomous observatories a radio link is necessary for the transmission of the acoustic data to a shore station. Old concepts involving storage of data in a specific device seem to be abandoned in favor of the on-line listening of the marine environment which is absolutely necessary for modern applications. Still there is a need for ensuring power for the continuous functioning of the receiving system and the transmission of the data. An additional need is an appropriate encoding of the transmitted electromagnetic signal which should keep all the information provided by the acoustic data to be further exploited at the shore station. To this end, appropriate compression of the signal is necessary. A cabled observatory is another alternative, under the additional benefit that power can be ensured from the shore station. Of course cabled observatories can be installed only in coastal areas.

The signal processing is totally dependent on the type of observables and the specific application. No general rules can be mentioned and the designers of the passive acoustic observatories should take into account the possibilities of getting observables from the ambient noise field answering the questions of section 4. Next step is the formulation of the inverse problem as in equation (1) or (4) according to the functional relationship between the observables and the parameters to be retrieved, followed by appropriate treatment of the inversion procedure taking into account the analysis of the solvability of the inverse problem. An additional task for passive observatories is the tracking of the sources whenever this is necessary, for instance in cases that a marine mammal is under monitoring or when the mammal is used as source for ocean acoustic tomography applications.

None of these considerations violate the idea of a green technology with respect to noise.

## **Discussion**

The necessity for keeping the marine environment under low ambient noise levels, reducing the power of intermittent sources but, on the other hand, being able to exploit the potential of acoustic signals in the water to provide information on the marine environment, dictate the development of new types of acoustic observatories which will be able to monitor the environment without probing it with additional sound. These are the passive observatories, the technology of which differs from that of the active observatories only in the use of noise sources existing in the ambient noise spectrum instead of specific sources installed for active imaging. Of course the treatment of the ambient noise sources in the context of the associated inverse problem is different with respect to the treatment of sources in active observatories, but, according to the preliminary studies, there are several alternatives which result in reliable data inversion procedures.

An additional benefit of the passive observatories is that they can detect signals in water which can be used for the direct studying of acoustic processes in the marine environment. Monitoring of the underwater seismicity or studying the behavior of marine mammals are two totally different applications, which may be both fully developed using data from passive acoustic observatories.

The area is open to extended further research, and according to the author's opinion it is going to be the basis of the acoustic tomography of the near future.

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