MONITORING THE SEA ENVIRONMENT USING ACOUSTICS THE ROLE OF THE ACOUSTICAL OBSERVATORIES

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ABSTRACT

The presentation deals with theoretical factors and technical specifications pertinent to the design of an acoustical observatory for the monitoring of the marine environment. Two types of observatories are mentioned, namely active and passive. Among the various cases of active observatories, the ones related to ocean acoustic tomography are presented in some detail and the inverse problem of retrieving information from measured acoustic data is explained. Some basic issues related to the type of measurements that should be made for optimal use of the acoustic field are also given with related references. Finally, the basic features of passive observatories are underlined without going into details.

1. INTRODUCTION

The sound is widely used in marine observatories as an alternative means to retrieve information about environmental data in the sea area under surveillance. In other words it is used as an alternative carrier of information on processes which occur in the marine environment. The reason that the sound used so much used in the sea has to do with the fact that unlike the electromagnetic waves, water has the ability to transmit sound at very large distances without significant impairment. 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.

The purpose of this presentation is to underline the main specifications of the acoustical observatories in connection with the basics of the mathematical techniques which are necessary in order to exploit the information obtained at the acoustic field. Main emphasis will be given to active acoustical observatories, for which the presence of a specific acoustic source is needed, but the main concepts behind the design and development of a passive acoustic observatory will also be given.

2. INVERSE PROBLEMS OF UNDERWATER ACOUSTICS

Inverse problems in underwater acoustics have recently drawn the attention of the scientists working on underwater technology, due to importance of the acoustic waves as carriers of information concerning environmental and operational parameters in the marine environment including acoustic characteristics of acoustic sources from where they originate but also concerning the structure of the objects located in water or buried in the seabed. They can also give information about the geological characterization of the marine sediments. The recovery of these parameters using measurements of the acoustic field is the main goal of the inverse problems in underwater acoustics. Consequently, the inverse problems are at the core of the acoustic methods for the monitoring of the marine environment and are formulated according to the specific technology adopted in the marine observation.

In accordance with the classification proposed by Collins and Kuperman [1], inverse problems in underwater acoustic fall into two main categories:

- Remote sensing of the marine environment and
- Localization.

In the first category fall those problems for the estimation of the structure of the water column (acoustic tomography) but also of the basic parameters of the sea floor, while the second category includes problems of source or target identification as well as tracking of the location of a sound source. Remote sensing is implemented by both passive and active observatories, as it will be explained later, whereas localization is mainly achieved in passive mode

Conceptually, the formulation of the inverse problems is relatively simple. We begin by considering the functional relationship between measurements (data) d and retrievable parameters m of the form

$$f(m, d) = 0 \tag{1.1}$$

where m and d are functions of the space and/or time. The relationship is dictated by the specific model describing the acoustic propagation in the environment under consideration and of course the type of data and the parameters. The model is formulated as a boundary value problem with its main core being the acoustic equation. For typical applications of acoustical oceanography, retrievable parameters are the sound speed profile in the water columns 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. The relationship between water temperature (which is the main parameter of the oceanographic models) and sound speed, is obtained by means of empirical relationships. Additional useful parameters retrievable by acoustic means are the current velocities. With respect to the measured data, there are several possibilities according to the type of the signal and its exploitable features. See Table I for more information. Almost all the inverse problems in underwater acoustics are formulated as discrete problems after appropriate discretization in space, while time is in general excluded as independent variable, as the inverse problem is solved for stationary values in specific time intervals. Thus, data and parameters are represented by vectors:

$$\boldsymbol{m} = [m_{1,} m_2, \dots \dots m_M] \tag{1.2a}$$

$$\boldsymbol{d} = [d_1, d_2, \dots \dots d_N] \tag{1.2b}$$

And the vector m is retrieved by using a non-linear vector equation of the general form

$$f(\boldsymbol{m}, \boldsymbol{d}) = 0 \tag{1.3}$$

The function *f* is generally complicated and not subject to linearization. Consequently, the problem is nonlinear and very difficult to solve. Moreover is in general 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 [2]. 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. It should however be underlined that whatever the application is, it is important to collect data in the most appropriate way so that the inverse problem expressed by equation (1.3) can be reliably solved.

3. OCEAN ACOUSTIC TOMOGRAPHY

Ocean Acoustic Tomography was introduced by Munk and Wunsch in 1979 [3] following an observation in the 1970s' that about 99% of the kinetic energy of ocean circulation is associated with oceanographic features of medium-scale, which are phenomena that are studied in lengths of up to 100 kilometers. Monitoring the changes of medium to larger scales can therefore lead to useful conclusions about the earth dynamics and to the study of climate change at a global scale. Acoustic tomography was the basic concept upon which the first marine observatories were created.

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.

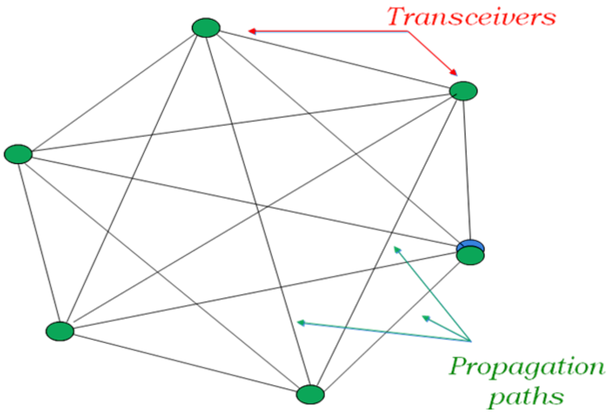

Figure 3.1. Schematic layout of an observatory related to ocean acoustic tomography

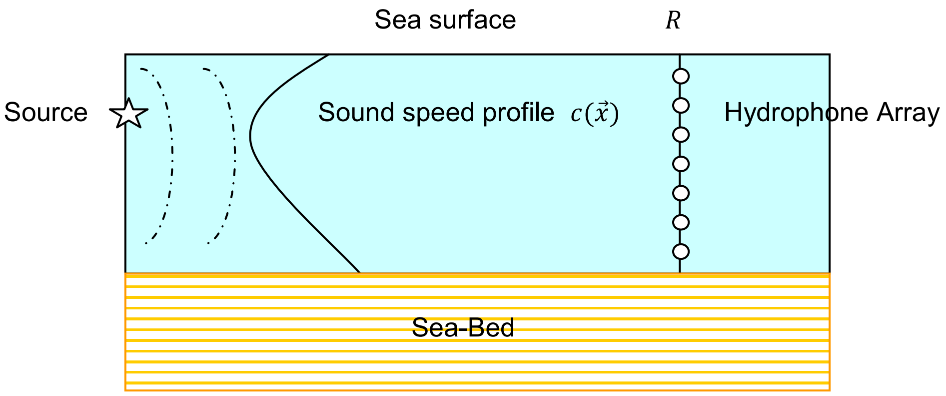

Figure 3.2 A vertical slice defined by a pair of transceivers in observatories for ocean acoustic tomography. Simplified version with horizontal plane water-bottom interface.

Figure 3.1 describes the typical layout of an acoustical observatory for ocean acoustic tomography. The green oval points represent anchored moorings housing sources and receivers. Each pair of moorings define a vertical slice of the acoustic environment as in Figure 3.2 which shows a single source and a vertical array of hydrophones at range *R* from the source which are the main elements of a tomographic pair.

The source emits signals (short pulses) at regular intervals. The power transmitted is of low intensity so that no problems are created to marine cetaceans. Moreover, they are of low central frequency to achieve maximum propagation range. If the moorings are autonomous, appropriate power ensures the continuous (up to a certain time period) transmission of the signals, while power is also needed at the recording devices connected to the receiving hydrophones. If sources and receivers are close to the shore, cabled installations are possible in which case the power requirement is limited. However, for operational reasons the tomographic observatories may be located at remote areas and therefore the power consideration is an important issue. The signals received at the hydrophones can be transmitted to a shore base station either by cable (cabled observatories) or by radio link or they can be kept at an appropriate storage device for future exploitation. In the last case no real time monitoring is possible.

Number of Hydrophones	Observables	Signal processing required
Single Hydrophone	Arrival times of acoustic rays [3]	Ray identification
	Arrival times of modes [4]	Mode identification [11]
	Statistical characteristics of the signal [5]	Fourier or Wavelet transform.
	Dispersion curves [6]	Fourier or Wavelet transform
Hydrophone arrays	Modal phase [7,8]	Mode filtering [12]
	Full-Field [9,10]	Fourier transform

Table I Observables for Ocean Acoustic Tomography

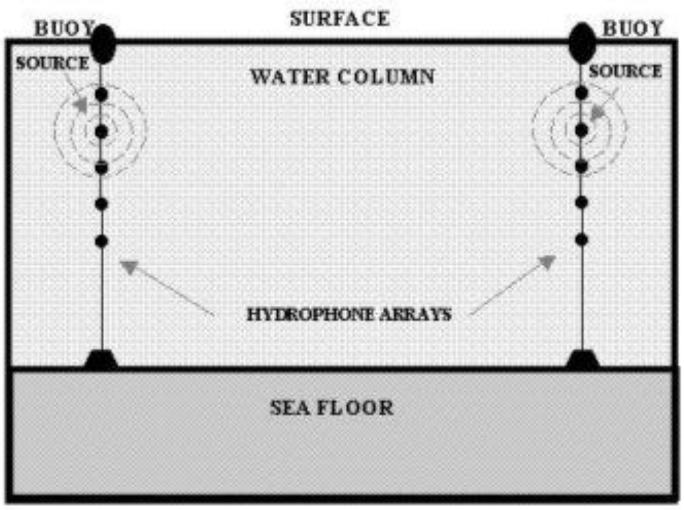

Figure 3.3 An optimum configuration of moorings for ocean acoustic tomography observatories.

As regards the exploitation of the acoustic signals received at the hydrophones, several possibilities exist. Table I summarizes the most important cases and the signal pre-processing required in order that the appropriate observables which are associated with the data (equations 1.1-1.3) are obtained. Some typical references for each case are mentioned

Finally, figure 3.3 presents the mooring configuration at the vertical slice for optimum exploitation of the acoustic measurements in a reciprocal way. In simple cases a single source and a single receiver can be used under restrictions with respect to the full exploitation of the acoustic field.

4. PASSIVE OBSERVATORIES

Passive acoustic monitoring of the marine environment can also 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 [13]. 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
- the rain
- the earthquakes
- biological noises (for instance marine mammals)
- breaking of the ice (in the Arctic regions).

As anthropogenic causes we can consider:

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

For the implementation of a passive observatory, no specific sources are needed. In this respect, the passive observatory can be viewed as of “green technology” and “biologically friendly”. With respect to the case of active observatories, the processing of the signals and the inversion methods are different. For instance, in passive listening mode it is frequently necessary that the model relying measurements and parameters should not include precise 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 the environmental parameters for any source define the vertical and horizontal structure of the acoustic field. Also by appropriate beam-forming it is possible to exploit the directionality of the acoustic field measured at a vertical hydrophone. On the other hand in some other cases (e.g monitoring of the earthquake activity in a region, or identifying the type of a specific marine mammal) the type of source is of primary importance and the signal processing leading to the source classification should be carried out accordingly. In this respect, passive observatories are extremely useful in marine bioacoustics and for the monitoring of the geological processes.

5. TECHNOLOGICAL CONSIDERATIONS

Following the presentation above, we underline the main components of an acoustical observatory which consist of the following elements:

- Emission, reception and recording of the acoustic signal
- Signal transmission to the processing station
- Signal processing
- Information visualization and decision-making unit connection

Each one of these elements should be designed and treated in a different way. In the following we underline the basic specifications for each one of them Q

5.1 Acoustic Signals

In the case of active observatories, the signals are acoustic pulses of low power and low frequency. Typically the tomographic signals may have central frequencies of as low as 150 Hz and in general narrow bandwidth, with highest frequency not to exceed 1 KHz. The exact source excitation function of the pulse may be programmed, in which case optimum signals may be generated and transmitted. In general, low frequency sources are heavy, big in dimensions and expensive but are able to generate signals to be transmitted at very long distances without severe loss. For applications of ocean acoustic tomography, in medium or small areas, less expensive sources of higher frequency may be used. On the other hand, for non-stationary (mobile) observatories, one can use very cheap sources (e.g light bulbes that explode at a certain depth in the water column [14]) which provide the appropriate bandwidth for the exploitation of the acoustic field. The acoustic sources should be omnidirectional for a full exploitation of the existing forward propagating models which are formulated for point harmonic sources, without additional processing. For passive observatories no specific sources are installed.

The receiving devices are hydrophones with appropriate response bandwidth. For the case of active observatories, the bandwidth should be tuned to the specifications of the signals emitted by the source. Thus, relatively narrow response bandwidth is adequate to record the essential part of the tomographic signal. In the case of passive observatories, a broader bandwidth should be ensured in order that signals from all possible sources including signals from marine mammals which emit signals in the ultrasound region are recorded.

5.2 Signal Transmission to the Processing Station

As already mentioned the acoustical observatories may be autonomous or cabled. For autonomous observatories, especially when they are remotely located, it is generally necessary that a storage device is ensured for the recordings of the acoustic field. If no real-time transmission of the data is necessary, the retrieval of the acoustic data is done on regular intervals using oceanographic vessels. For real time transmission of data, radio link to a shore station or to a satellite is the appropriate means, although there is in general the risk of the destruction of the antenna, when the observatory is unsupervised. Recently the idea of underwater transmission of the data using acoustic link with the help of appropriate modems has drawn the attention of the scientists. This type of transmission has been studied experimentally and it is still at the stage of further development.

For cabled observatories, the transmission and also the power consumption is ensured by cable. In any case, an appropriate coding and compression of the data to be transmitted, has to be designed so the transmission of the data is ensured by the most efficient way.

5.3 Signal Processing

The signal processing task is very important as it will exploit the information on the acoustic field obtained at the shore stations. After decoding, the acoustic signals should undergo the appropriate processing in order that the observables (as mentioned in Table I) are defined. The next step is related to the inverse problem itself and has to do with the inversion of equation 1.3 for the estimation of the model parameters. This modulus is open for further research as the goal of the acoustical oceanographers is to develop inversion schemes that could make optimal use of the data and obtain parameter estimations with narrow confidence limits.

5.4 Data Assimilation and Information Visualization

The final step is the data assimilation, which will provide the necessary predictions of the dynamics of the ocean environment which is the ultimate goal of the acoustical observatories. It is also important that the information on the environmental changes is provided in such a way so that they are usable by non-experts and could help the authorities in their decision making. To this end, appropriate visualization of the parameters with the help of Geographical Information Systems (GIS) is used to produce data geophysical maps, integrating static and dynamic information..

6. DISCUSSION

The acoustical observatories play an important role in the monitoring of the marine environment. They can be designed as stand-alone or complementary systems integrated in traditional oceanographic observatories. Of primary importance for active observatories is low energy transmission in the environment but keeping the benefits of the ability of acoustic waves to propagate in the ocean at long ranges. Modularity and mobility are two important issues that should be taken into account in the design and development of an acoustical observatory. Real time transmission and processing of the acoustical data are also challenging issues that dictate recent advances in both the theoretical and technological aspects of the ocean acoustic observatories.

7. ACKNOWLEDGMENTS

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