ACOUSTIC METHODS OF SEA-BED RECONSTRUCTION

Michael Taroudakis
Department of Mathematics and Applied Mathematics
University of Crete,
Voutes University Campus
70013 Heraklion, Greece
E-mail: taroud@uoc.gr

Introduction

Acoustics plays a prominent role in the assessment of the sea-bed properties. Acoustic signals are efficient carriers of information on the medium through which they have propagated. By appropriate processing of the acoustic field due to some acoustic source measured in the marine environment, the properties of the sea-bed and/or the water column can be estimated. The estimation of the water column properties (mainly the sound speed profile but also the water currents) has been the main objective of Ocean Acoustic Tomography, whereas the recovery of the sea-bed parameters, a concept introduced in acoustical oceanography and the sea-bed exploration longer time ago, is the main objective of the geoacoustic inversion applications.

This presentation concerns sea-bed reconstruction by acoustic means. This area is associated with numerous applications. Oil exploration, assessment of the rigidity of the sea-bed for off-shore constructions, geological surveys of the sea-bed, seismic studies, are among the applications associated with the use of acoustics for estimating the sound speed, the shear speed and the density of the sediment layers and the substrate, the acoustic attenuation, the location of the interfaces determining the sea-bed layers etc.

We will divide the presentation in two parts. First part concerns local methods. By this term we mean methods that use an acoustic source-acoustic receiver configuration which gives information on the sea-bed for a relatively small area at the location of the associated experiment. Second part concerns methods of medium scale. By this term we mean methods that are based on measurements of the acoustic field made at some longer distance from the acoustic source.

1. Local Methods

Local (small scale) methods are associated with sonar techniques. An acoustic beam is sent to the sea-bed. The signal is reflected from the sea-bed and measured. The reflected signal after suitable processing provides the information on the sea-bed structure. The receptions are time series of the signal reflected from the various layers. The theoretical background of this technique is ray theory as well as theory of sound reflection and scattering. Ray theory provides the geometry of the beam propagation allowing the assessment of the angle of incidence and reflection from the sea-bed. Moreover it provides information on the exact time of flight of the acoustic beam which is necessary in order to estimate the depth of the water column and the location of the sea-bed interfaces. The reflected energy (reflection coefficient) depends on the properties of the sea-bed. Therefore, measurement of the reflected field can in principle be used to define an inverse problem of the form :

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

where $\mathbf{m}$ are the parameters to be recovered and $\mathbf{d}$ are the measured data, which are in fact features of the acoustic field that can be exploited for inversions. The vector function $\mathbf{f}$ depends on the theoretical model used to associate measurements and recoverable parameters.

Talking about technological aspects, the acoustic source can me mounted at the hull of a research vessel, towed behind it or mounted on an ROV or an AUV. The technology of ROVs and AUVs in connection with techniques for high resolution beams enables the use of optimum positioning of the measured devices for a most reliable estimation of the sea-bed properties. In addition, the use of an ROV and AUV enables the simultaneous function of a multi-beam sonar, side-scan sonar and sub-bottom profilers for a detailed description of the sea-bed interface, which enables the identification of buried objects as well, an application of great interest for underwater archaeology.

Figure 1 shows a typical configuration of a system for a small scale sea-bed reconstruction. It has been developed in the framework of the MAST/REBECCA and SIGMA projects in late 90’s and has been used successfully in various locations in the Mediterranean and the Atlantic ocean in relatively shallow water. The acoustic source mounted on a towed fish is a parametric one that exploits the non-linearity of sound propagation in the ocean.

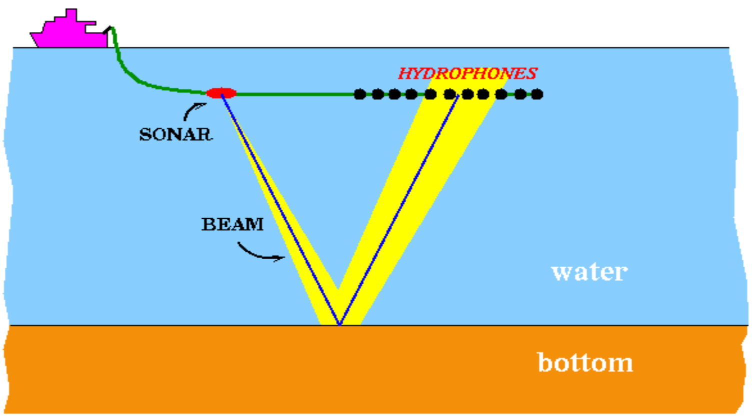

Figure 1. The configuration of a local system for sea-bed reconstruction. MAST/Rebecca and Sigma projects

The source emits two tones of frequencies having small difference between them. Due to the non-linearity of acoustic propagation, a signal with carrier frequency the difference between the two primary frequencies propagates in the water and the sea-bed. This technique allows the use of relatively low acoustic energy and a deep penetration in the sea-bed.

2. Medium-scale methods

These methods are derived from ocean acoustic tomography. They are based on the fact that by measuring the acoustic field at a long distance due to a known source, the average properties of the environment can be estimated. Noticeable that these techniques cannot in principle be used for a detailed reconstruction of the water-sea-bed interface geometry.

From a technological point of view, medium-scale techniques are effectively applied using acoustic observatories which can be of permanent or mobile character. Figure 2 illustrates the idea of a permanent observatory. The source(s) and the receiver(s) are mounted on appropriate moorings placed at great distance between each other. The acoustic field measured at the receiver(s) contains all the information on the acoustic medium through which it has been propagated, including that of the sea-bed. An inverse problem of exactly the same form as in equation 1 is defined.

The acoustic data are the "observables" of the acoustic signal. They depend on the determination of the inverse problem and the model used to associate observables and recoverable data. The sound source emits coded signals. Figure 3 shows a simulated signal due to a sound source modeled with Gaussian excitation function.

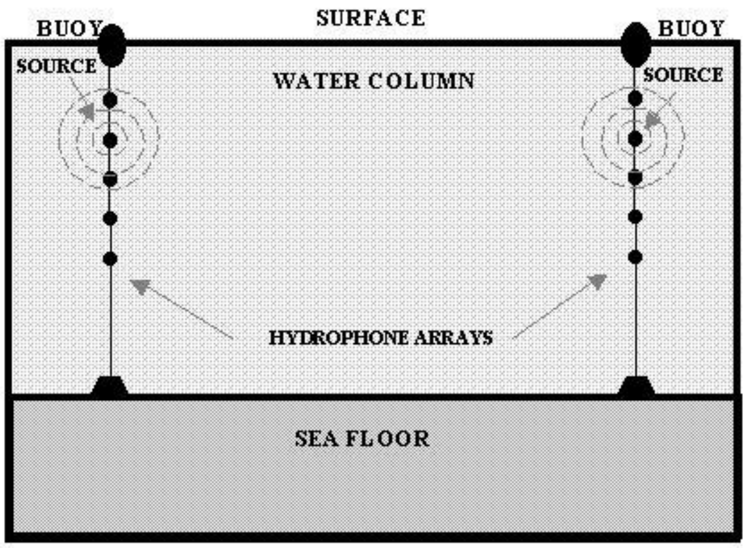

Figure 2. Schematic layout of an acoustical observatory

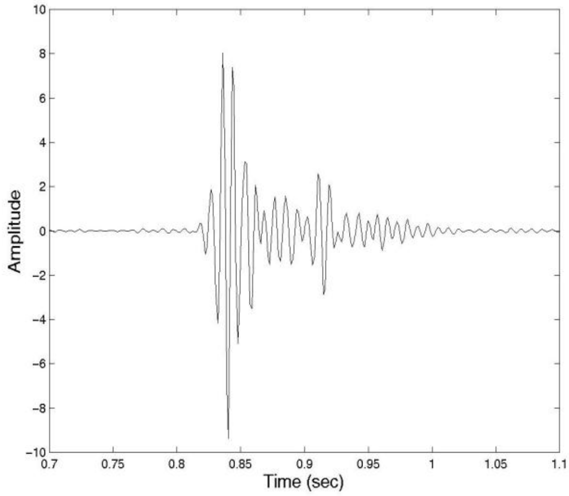

Figure 3. A typical signal as recorded in the hydrophone of an acoustical observatory, modeled with a Gaussian excitation function

Using normal mode theory of acoustic propagation, the simulated signal is modeled by inverse Fourier transform of the acoustic field calculated at each frequency within the frequency bandwidth of the source. The acoustic field in a range-independent axially symmetric environment in the frequency domain is given by a series expansion

$$p(r,z) = \sum_{n=1}^{N} A_n(r) u_n(z) \tag{2}$$

where $u_n(z)$ are the eigenfunctions of the so called "depth problem" which is a Sturm-Liouville type Ordinary Differential Equation problem defined on the basis of the boundary conditions in the water-air and the water-sea-bed interfaces and $A_n(r)$ are the mode amplitudes, which are also associated with the eigenfunctions at the source location.

Thus, the construction of the sea-bed is reflected in both the full field and the individual modes. Figure 4 shows the eigenfunctions of a series expansion of the acoustic field in a shallow water environment. It is clearly shown that energy propagates in the sea-bed and that each mode is associated with specific energy distribution in the bottom. Therefore, the acoustic field can in principle be used for estimating sea-bed parameters by appropriate choice of the observables.

We will now mention a few possible cases of potential observables on the basis of the signal shown in 3. If the peaks of the signal are recognized as modal arrivals, a model using the notion of modal velocity and its association with the eigenfunctions and the eigenvalues of the depth problem can be used to relate time of arrivals with sea-bed parameters. If the identification of modal arrivals is not possible, a scalogram, showing energy distribution in time and frequency can be equally used to associate model parameters and observables. Alternatively the full field can be used if a vertical array of hydrophones is available under the so called matched-field processing (MFP), which exploits the difference in the arrival pattern of the signal at the various hydrophones of the array. For the application of the MFP, the signal measured in the time domain is transformed to the frequency domain and the inverse problem is solved as an optimization process by defining an appropriate cost function.

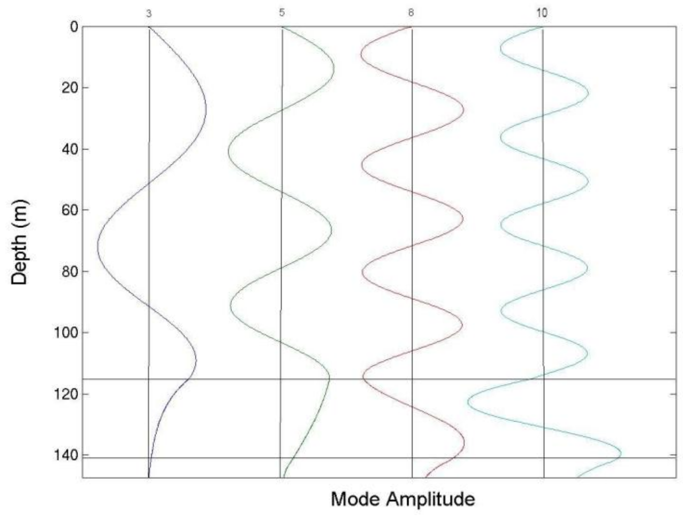

Figure 4. The eigenfuntions of order 3,5,8 and 10, for a typical shallow water environment. The sea-bed consists of a sediment layer over a substrate.

A recent approach associates the statistical characteristics of a wavelet transform of the signal with sea-bed parameters. In this case, the observables are the parameters of the probability distribution function describing the statistical characteristics of the coefficients of the wavelet sub-band coefficients.

In all the above cases the inverse problem, been non-linear and ill-posed, is modeled and solved through an optimization process for which several approaches are possible including neural networks, genetic algorithms, simulated annealing etc. They are all based on the definition of an appropriate cost function comparing the observables of the measured signal with them of signals obtained by calculation of the acoustic field given possible environmental parameters within a search space. A recently introduced Bayesian formulation has proven to be very efficient in determining not only the geoacoustic parameters of the sea-bed layers, if their geometry is known, but also the number of layers and the location of the interfaces.

It should be noted, that by medium-scale geoacoustic inversion methods, additional parameters, such as the sound speed profile in the water column and the location of source and receiver can also be estimated, as in principle the acoustic field depends on them as well. For all these parameters, including those of the sea-bed, modern approaches dictate the use of a-posterior distribution functions to depict the probability rather than a single estimated value of the recoverable parameters. The character of the distribution for each parameter, suggests the sensitivity of the method adopted for the specific parameter.

Finally, it should be added that hybrid schemes exploiting general knowledge of the sea-bed structure using local methods as an input to the medium-scale methods for a detailed recovery of the sea-bed parameters are also applicable to the problem of sea-bed reconstruction.

3. Final comments

Modern technology in association with recent developments in inverse propagation modeling provides efficient tools for sea-bed classification or even reconstruction of its properties using acoustic methods. If bathymetry mapping or buried object detection is additional concepts, local methods are applicable. If however the average sea-bed structure at some greater area is of interest the medium scale methods derived from ocean acoustic tomography are preferable. The field is open to new concepts for inverse propagation modeling or to answers of the specific problems encountered when dealing with a highly non-linear and ill-posed inverse problem as it is the problem of estimating multiple environmental parameters from few available measurements.