Acoustic Signal Processing for Ocean Exploration

Edited by

José M. F. Moura and Isabel M. G. Lourtie

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Preface

This volume collects the lectures, the tutorials, and the advanced research papers presented at the Nato Advanced Study Institute (ASI) on Acoustic Signal Processing for Ocean Exploration. The ASI was held from July 26 to August 7/ 1992 at Hotel Savoy, Funchal (Madeira), Portugal.

The present book, like the ASI, has two major goals: (*i*) to present signal processing algorithms that take into account the models of acoustic propagation in the ocean and (ii) to give a perspective of the broad set of techniques, problems, and applications arising in ocean exploration.

Matched field processing (MFP), which has been loosely defined as solving an inverse problem by studying an *infinite* number of forward problems, is one of the basic themes underlying the book. MFP is studied in Chapter II, which contains an overview of MFP and also discusses such specific topics like performance of localization algorithms in the presence of multipath and wideband MFP in random ocean channels.

MFP couples to signal processing detailed prior knowledge about the ocean propagation as provided by acoustic propagation models. These are the theme of Chapter I, which provides an overview of CW and pulse propagation in ocean acoustics, studies mechanisms of bottom loss, and describes directional measurements of deep sea ambient noise spectra.

Chapter III of the book considers array processing methods. A geometrical perspective for direction determination is presented, as well as a comparison study of the most common array signal processors in the presence of realistic data. Localization and detection are the topic of the papers in Chapter IV. Included are papers concerned with detection in uncertain ocean environments or that review narrowband localization and tracking methods.

Chapter V enlarges the more traditional contexts of underwater acoustics to include imaging and mapping and its applications. Two papers address the mathematical underpinnings of 2 D spatial random field processing. Two papers study sea floor swath mapping by swath bathymetry and side scan sonar and a third paper addresses applications of acoustics to fisheries.

The ocean is a nonstationary environment. Classification and recognition of nonstationary possibly transient-type underwater sounds is of interest. In Chapter VI of the book, time/frequency methods are considered. Two papers discuss basic tools in time/frequency analysis. Additional papers consider the direction of transient signals by wavelet methods, time/frequency approaches to sonar target description in fisheries applications, and the comparative behavior of statistical and neural net classifiers for the recognition of sonar returns.

A different dimension in underwater exploration applications is provided by autonomous underwater vehicles (AUV) and communications in underwater, which are the topics of Chapters VII and VIII, respectively. Two papers consider AUV issues, in particular 3D vision and guidance for autonomous vehicles. Several other papers address equalization of the underwater channel and coherent communications over long-range acoustic telemetry channels.

In a sense, the book aims at providing a snapshot of a topic (ocean exploration by acoustics) which is bursting into new areas, new applications, and at the crossroads of complementary aspects like propagation modeling and processing algorithms. More realistic signal processing achieves higher resolution at the cost of a significant added computational complexity. What makes these approaches and attacking these new problem areas increasingly viable is of course the availability of powerful computational engines. Two papers in Chapter IX overview algorithmic engineering methods for signal processing and software issues in parallel processing.

As a rule, there are several other papers that broaden or complement the main theme in each chapter of the book. We refer the reader to the table of contents for a complete account of all papers included in this volume.

Given the broad range of subjects covered, the reader should not expect an exhaustive treatment of them all. In assembling such a wide range of experts, it was not our intention to follow the same format in all subject areas. In fact, this would hardly be possible or desirable. Different areas are at different degrees of maturation, or have available recently published overviews. Our goal is to assemble a collection of papers in a variety of complementary fields that is of interest to the signal processing researchers working in ocean exploration by acoustic methods. The ocean is too hard a problem to be dealt with in isolation. It is too rich and exciting that individual researchers must be aware of the wealth of techniques and challenges that are ocean related. With its broad coverage, the book aims just at that—to provide a comprehensive path to the many aspects relevant in ocean acoustics.

The ASI on Acoustic Signal Processing for Ocean Exploration was the latest of a long series which started in 1964 and has been held ever since at periods of four years. For underwater acoustic signal processing researchers, these ASI have become a feature as regular as the Olympics, the two weeks they last usually overlapping part of the Summer Olympics. The succession of prior ASI, with their respective directors, is:

1964	Grenoble (France)	Prof. Bonnet
1968	Enschedé (Netherlands)	Prof. Gröneveld and Prof. van Schooneveld
1972	Loughborough (UK)	Prof. Griffiths, Dr. Stocklin, and Prof. van Schooneveld
1976	Porto Venere (Italy)	Prof. Tacconi
1980	Kollekolle (Denmark)	Prof. Bjorno
1984	Lüneburg (Germany)	Dipl. Ing. Urban
1988	Kingston (Canada)	Prof. Y. T. Chan

The next ASI in this series is scheduled to be held in France in 1996, at a location to be determined sometime possibly in 1993. The director of the forthcoming event is Dr. Georges Bienvenu.

In organizing this meeting, we had the help of many that we now have the chance to publicly acknowledge. The site was chosen, the initial proposal to Nato Scientific Affairs Division written, and the final program put together with the help of the organizing committee whose members are listed on page xi. Further, Dr. Cliff Carter was always forthcoming with advice in the many occasions we sought it.

In choosing the site of the meeting, we traveled to Madeira twice. Our trips were organized by Mr. Luis Gomes at the time with Agency Euromar. Hotel Savoy's excellent facilities, the magnificent surroundings provided by the Island of Madeira, and the hospitality of the people of Madeira made it quite obvious to us, after our first visit, that it was here that we should hold the meeting. The challenge was to come up with a viable financial deal meeting the budget constraints of Nato. That we were successful is due in large part to the enthusiasm and forcefulness of Mr. Luis Gomes and to the professionalism of Ms. Graça Guimarães, marketing director of Savoy.

During the two weeks of our meeting, Governo Regional da Madeira and Câmara Municipal do Funchal were kind enough to honor the whole group of about 150 people (participants and their companions) with a dinner at the Quinta da Magnólia and a sundowner followed by dinner at the Complexo Balnear do Lido, respectively. We thank Dra. Ana Isabel Spranger and Dr. J. Costa e Silva from Governo da Madeira, and Mr. Sílvio Silva from Câmara Municipal do Funchal and Dr. Nélio Mendonça from Assembleia Regional, who hosted these events for us.

The poster advertizing the ASI as well as the covers of the program and preproceedings were designed by Ms. Maria João Gomes. During the meeting, the registration and information desk

as well as many of the day to day organizational details were handled by Mr. Miguel Lourtie. His energetic resourcefulness and good humor were highly praised by all attendees.

Putting together this event required an endless number of massive mailings, letters to be typed and sent, faxes, phone calls, photocopies, programs to be organized, data to be entered in databases, airplane tickets to be booked and mailed, preproceedings and camera-ready proceedings to be put together, and many other small tasks that needed to be accomplished just-in-time. The help in all these and many other details of Ms. Fernanda Serrenho (from CAPS), of Ms. Debbie Scappatura (CMU), and, in the period after the meeting, of Ms. Carol Patterson (CMU) was greatly appreciated.

Several institutions supported the organization of this ASI. Foremost, the ASI program of Nato which provided the basic grant. The office of the Chefe de Estado Maior da Armada (Portugal), Instituto Nacional de Investigação Científica (INIC, Portugal), and Junta Nacional de Investigação Científica e Tecnológica (JNICT, Portugal) provided additional support. We used prodigally in countless ways the resources of Carnegie Mellon University (CMU, Pittsburgh, USA) and Centro de Análise e Processamento de Sinais (CAPS) from Instituto Superior Técnico (IST, Lisboa, Portugal). We gratefully acknowledge this support.

Even on such a beautiful environment as Madeira, an ASI has to be of necessity mostly work with only a bit of fun. As directors, we were concerned that it would be hard to keep our participants within the confinements of the lecture room for seven hours a day for 10 days. That our concerns were unfounded was demonstrated by the continuous involvement of most during the whole duration of the ASI. This, of course, reflects the high quality of the lectures, tutorials and advanced research papers, the intensity of the technical discussions, and the enthusiasm that all participants demonstrated in their chosen field. We just hope that some of this enthusiasm is captured by the present book.

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Lisboa, October 1992

Contents

Chapter I

The Ocean Environment and Propagation

CW AND PULSE PROPAGATION MODELING IN OCEAN ACOUSTICS

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ABSTRACT. The question of predictability of sound propagation in real time-varying ocean environments is addressed. It is argued that intermediate and lower frequencies generally constitute the best choice, simply because high-frequency sound is strongly affected by boundary scattering and microstructure variability in the ocean, while low-frequency sound is strongly affected by "unknown" sea floor properties. Acoustic modeling at lower and intermediate frequencies can efficiently be performed by wave-theory techniques. The most commonly used CW (continuous wave) propagation models are presented and their areas of applicability are indicated. Furthermore it is shown how these numerical codes can be extended to provide pulse results by Fourier synthesis of CW solutions. The ability of the acoustic models to describe sound propagation accurately in complicated ocean environments is demonstrated through a sequence of numerical examples involving both CW and pulse-propagation results.

1. Introduction

It is well established that all types of electromagnetic waves (light included) propagate poorly in turbid, saline sea water, and that only acoustic waves constitute an effective tool for communicating and sensing at long range underwater [1–4]. The use of sound to explore the ocean and the sea floor is an ever-evolving science, which has seen remarkable progress in military (sonar) as well as in civilian applications (sea-floor mapping, fish finding, etc.) over the past few decades.

The range of useful frequencies in ocean acoustics covers almost five decades of frequency—from a few hertz to several tens of kilohertz—with wavelengths from around 1 km down to a few centimeters. Since attenuation of sound in sea water increases approximately with frequency squared, the high-frequency devices (> 10 kHz) are used primarily in short-range high-resolution systems such as bottom profilers and fish sonars. The lower frequencies propagate to long ranges with little attenuation and are therefore preferred in acoustic surveillance systems for military use as well as for acoustic sensing on a global scale, e.g. to monitor ocean warming.

The usefulness of acoustic models as an analysis and prediction tool depends entirely on the general predictability of ocean acoustic propagation. The ocean is a complex environment with both temporal and spatial variability not always

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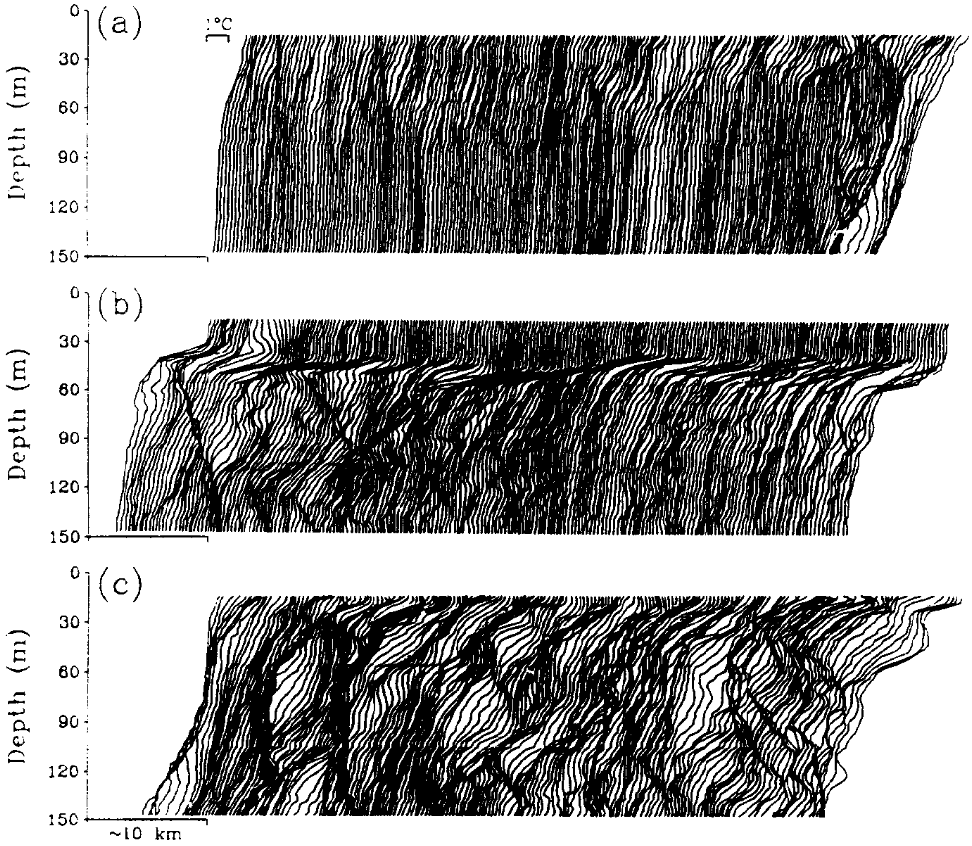

Figure 1. Temperature profile sections recorded in the Norwegian Sea. (a) Laterally stable ocean. (b) Stable surface layer with some lateral variability below the thermocline. (c) Strong lateral variability in upper 150 m.

suited for a deterministic modeling approach. As an example let us look at some thermistor chain data recorded in the Norwegian Sea [5]. Figure 1 displays three different temperature-profile sections each covering a range of approximately 50 km and depths between 15 and 150 m. Even though these data were all recorded in the same area within a period of two weeks in June 1987, we notice strong differences in lateral variability along the three tracks. Thus Fig. 1(a) displays a stable water column well suited for deterministic modeling at all frequencies of practical importance in ocean acoustics. Figure 1(b), on the other hand, shows a section with a stable surface layer, but with some microstructure variability below the thermocline causing scattering of high-frequency sound. Hence this situation is suited for deterministic modeling only at intermediate and low frequencies. Finally, Fig. 1(c) shows a section with strong lateral variability suited only for a stochastic modeling approach, except, maybe, at very low frequencies.

An important question is which of the three situations shown in Fig. 1 is the most likely one to encounter in a given area and for a given season. Unfortunately,

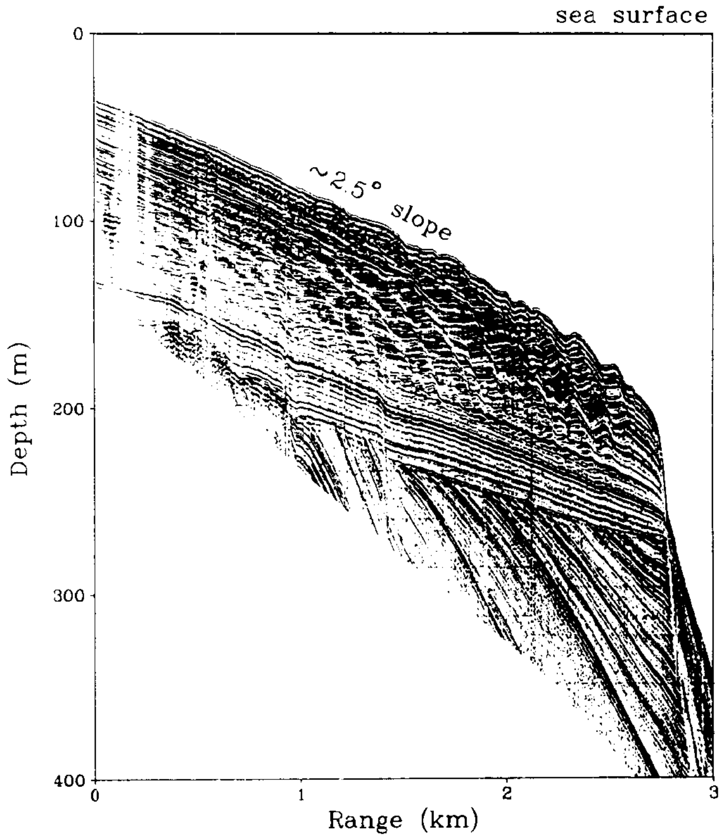

Figure 2. Seismic profile section from coastal-water area of the Mediterranean.

detailed measurements of water column properties as a function of range are generally not available, and, consequently, we can only guess whether we are dealing with a situation similar to (a), (b), or (c). This lack of information about the real ocean environment clearly affects the reliability of acoustic propagation predictions. However, lower source frequencies are preferable in order to minimize boundary and volume scattering effects.

If we now turn to the seabed which constitutes the lower boundary of the ocean waveguide, we are again dealing with a strongly inhomogeneous medium, as illustrated in Fig. 2. Shown here is a seismic profile of the seabed in a shallow-water area of the Mediterranean. The track is approximately 3 km long and the water depth varies from around 40 m near the shore to 200 m at long ranges with a mean slope of approximately 2.5°. Figure 2 reveals a very complicated bottom structure with the upper layers ($<$ 100 m) running almost parallel to the water/bottom interface, but with strongly inclined deeper layers.

Since sound interaction with the sea floor increases with decreasing frequency, detailed information about the spatial variability of the geoacoustic properties (speed and attenuation of compressional and shear waves plus the material density) is essential for reliable predictions of low-frequency propagation in the ocean waveguide. However, since the geoacoustic parameters are generally not known to the accuracy needed for reliable low-frequency propagation prediction, we essentially end up with an intermediate band of frequencies (from a few tens of hertz to a few hundred hertz in deep water) which clearly favors the predictability of sound propagation in the ocean.

Apart from the use of acoustic models as analysis and prediction tools, we could also envision wave-theory models being an integral part of sophisticated localization algorithms based on matched-field processing techniques [6,7]. These techniques require the calculation of accurate replica fields to be used together with measured data in a parameter estimation algorithm. The feasibility of this approach is again strongly dependent on the predictability of the propagation situation, and, hence, can be be expected to perform well only at lower frequencies in real ocean waveguides.

The ocean is an inhomogeneous, irregular waveguide limited above by a reflecting boundary (the sea surface) and below by a penetrable boundary (the sea floor). The forward modeling problem consists in solving the acoustic wave equation with appropriate boundary and radiation conditions in order to estimate the frequency-dependent spatial and temporal properties of the sound pressure field in the ocean waveguide. This problem is generally too complex for analytical solutions, and hence we must resort to numerical methods.

The development of a numerical modeling capability in ocean acoustics has been in continuous expansion over the past 20 years. Up till around 1970 the only practical technique for solving propagation problems in underwater acoustics was based on ray theory, which is a computationally efficient but approximate (infinite frequency) solution of the wave equation. The ray techniques are still in use for solving high-frequency deep-water problems in ocean acoustics.

In the early 1970s powerful digital computers became available in most research establishments, stimulating the development of more accurate frequency-dependent solutions of the wave equation. These wave-theory solutions (all numerically based) encompass normal mode, wavenumber integration, and parabolic equation techniques [8]. Today general-purpose numerical codes based on the above solution techniques are widely used for modeling acoustic propagation in complex ocean environments.

Even though wave-theory models provide accurate field solutions at any source frequency, the required computational effort is strongly frequency dependent. At best the calculation time increases linearly with frequency. However for most solution techniques the calculation time increases with frequency squared, which in practice restricts the applicability of these models to low-frequency problems. In any event, with present-day computing power it is entirely feasible to apply wave-theory models to deep-water problems ($H \approx 5000\,\mathrm{m}$) for frequencies up to a few hundred hertz, and to shallow-water problems for frequencies up to a few kilohertz.

2. The Ocean Waveguide

The goal of ocean acoustic modeling is to estimate the frequency dependent spatial

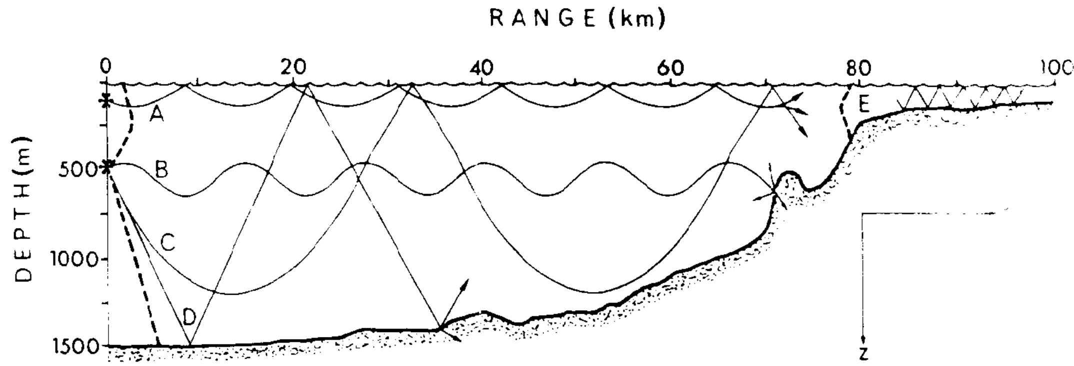

Figure 3. Schematic of sound propagation in the ocean.

and temporal properties of the sound pressure fields in ocean waveguides. To illustrate the complexity of this modeling problem, let us briefly review the acoustics of the ocean waveguide. Figure 3 is a schematic of some important sound propagation paths; two possible sound-source locations are on the left, and sound is propagating from left to right. The two dashed lines at 0 and 80 km range are sound-speed profiles that indicate two of the innumerable ways in which the sound speed can vary with depth from place to place (or from time to time). Lines A, B, C, and D represent four possible sound paths whose shape is determined by the location of the source and the sound-speed structure over the extent of the propagation. Path A from the shallow source is surface duct propagation, because the sound-speed profile is such that sound is trapped near the surface of the ocean. Paths B, C, and D are from the deeper source. Ray B, leaving the source at a small angle from the horizontal, tends to propagate in the deep sound channel without interaction with the sea surface or the sea floor. At slightly steeper angles (path C) we have convergence zone propagation, which is a spatially periodic phenomenon of zones of high sound intensity near the sea surface. Here sound interacts with the surface but not with the bottom. Path D is the bottom bounce path, which has a shorter cycle distance than the convergence zone path. The right-hand side of Fig. 3 depicts propagation on the continental shelf (shallow water) where a complicated bottom structure combined with variable sound-speed profiles result in rather complicated propagation conditions not always suited for a ray representation.

Our ability to model acoustic propagation effectively in the ocean is determined by the accuracy with which acoustic loss mechanisms in the ocean environment are handled. Aside from geometrical spreading loss (spherical, cylindrical, etc.) the main loss mechanisms are volume absorption, bottom reflection loss, surface and bottom scattering loss.

Volume absorption in sea water, caused by viscosity and chemical relaxation, increases with increasing frequency. This loss mechanism is the dominant attenuation factor associated with path B in Fig. 3, since this path does not interact with the boundaries. Because there is very little volume absorption at low frequencies, deep-sound-channel propagation has been observed on global scales to thousands of kilometers.