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Sound transmission through a fluctuating ocean

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SOUND TRANSMISSION THROUGH A FLUCTUATING OCEAN

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TO
RENELDE
MARY
JUDITH
ELAINE
NANCY
AND
MIMI

I have long discovered that geologists never read each other's works, and that the only object in writing a book is a proof of earnestness, and that you do not form your opinions without undergoing labour of some kind.

Charles Darwin (1887)

PREFACE

A complex structure of motions, driven by winds, solar heat and tides, is continually at play in the ocean interior. The motions range from current and tidal patterns of planetary scale, through intermediate-scale processes like internal waves, to small-scale turbulence of sub-millimeter size. An appreciation of this complex and multi-connected system must form the basis of any understanding of the oceans, their physics, chemistry and biology, and of their interaction with the atmosphere above and the seafloor beneath. It must also form the basis of any purposeful intervention for the human good; whether it be for fishing, predicting weather and climate, or for communicating through the ocean.

The ocean is transparent to sound and opaque to electromagnetic radiation. Accordingly, there is a strong emphasis on acoustic methods in exploring the sea bottom, in locating fish, in communicating between ships and submarines, and in detecting vessels by active or passive sonar. 'If you let your ship stop, and dip the end of a long blowpipe in the water and hold the other end to your ear, then you can hear ships which are very far distant from you,' Leonardo da Vinci (1483) observed (see Frontispiece).

But even though conditions for acoustic transmission are remarkably favorable, the ocean structure sets the ultimate limit to what can be done. Ocean processes result in sound-speed fluctuations, typically $\delta C/C = 5\times 10^{-4}$ in the upper layers, 3×10^{-6} at abyssal depth. These are small, yet they have a pronounced cumulative effect over long propagation paths. They prescribe the capacity of undersea communication systems, and impose a limit to the acoustic resolution of objects, similar to the resolution limit of ground-based telescopes commonly referred to as *atmospheric seeing*.

In the 1950s, physical oceanographers were occupied largely with drawing deterministic pictures of ocean circulation; they had very little information on the space-time variability of ocean structure. Only in the last five years have measurements of ocean variability been made that allow a semi-quantitative understanding of the oceanographic processes that are involved. At the planetary scales the ocean seems to be dominated by *geostrophic turbulence*, and at the intermediate scale by *internal waves*; in both instances horizontal scales vastly exceed vertical scales. For scales below one meter, little is known; concepts of isotropic turbulence, if valid anywhere, are confined to these very small scales. Time variations are not due to a frozen spatial structure being carried by a horizontal current, but are intrinsic to the processes themselves.

This information has been gathered painstakingly by the traditional tools of the physical oceanographer: bathythermographs, thermistors, salinometers, and current meters. These tools are beginning to pale somewhat before the task of measuring variations within the wide expanse of the sea. A long-range, integrating probe is needed, and measurements of sound propagation through the fluctuating ocean can provide such a probe.

Over the last century progress in the theory of wave propagation through fluctuating media has sprung from studies of electromagnetic wave propagation; particularly visible light in the atmosphere, and radio waves in interplanetary plasma. The techniques that have been developed include the Rytov method for treating weak diffraction, the transport equation for the energy flux, and the method of the propagation of moments. These methods have provided solutions to a wide variety of wave propagation problems, many of which are of practical importance in electromagnetic wave transmission. Unfortunately very few of these solutions apply to the ocean case, due to the special nature of the ocean sound-speed fluctuations. Some *ad hoc* attempts to adapt existing solutions so as to apply to the ocean case have been made, but the predictive power of such approaches is limited.

In this book, starting from general wave propagation equations, we attempt a systematic search for solutions that apply to the ocean medium. To characterize the ocean medium, we make rather extensive application of a model of internal waves, because it appears to portray observed ocean fluctuations in the important period range of minutes to a day, because it allows quantitative illustration of general principles, and because some existing acoustic experiments appear to be dominated by internal-wave effects. In special geographical regions, and for experiments with different scales, processes other than internal waves will dominate. Work on the effects of these other processes has barely begun.

In the process of deriving solutions applicable to the ocean case, we have developed a new and useful tool for treating wave propagation through random media; we call it the *micromultipath* technique. It has its roots in the principle of least action as expressed by Fermat and Hamilton, and it draws particularly on the path-integral technique of Feynman. It is to be hoped that this technique may prove useful in electromagnetic wave propagation also. However, the main purpose of the book is to provide a connection between the ocean structure as it is now evolving from oceanographic experiments, and the measured signal structure of sound transmitted through the oceans. We hope this will be of help to users of sound in coping with the frustrating fluctuations they continually encounter; we also hope this can be helpful in the inverse problem of using acoustic probes to monitor the everchanging ocean structure.

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INTRODUCTION

Part I gives a description of the ocean environment through which sound is transmitted. The description is deliberately broad, from microstructure to planetary waves. Particular emphasis is placed on internal waves, for these form the basis of subsequent detailed calculations. But we wish to leave the reader with the clear realization that there is more to the oceans than internal waves. For example, it is well known that geographic variations are pronounced, and need to be taken seriously. Still, in a monograph such as this there is a need for a model ocean to provide an insight into the role played by various parameters, and to permit first-order comparison with experiment. The simplest model consistent with the warming in the upper kilometer at midlatitudes, and certain principles of water mass formation, is an ocean with a density gradient diminishing exponentially with depth. This same ocean model underlies both the shape of the ocean sound channel and the depth dependence of the internal-wave-induced sound-speed fluctuations.

Given an ocean with known structure, one method for obtaining sound-fluctuation predictions would be to create a computer-code simulation. We have done this, and the computer code has indeed provided a valuable tool for gaining insight into the character of sound-transmission fluctuations due to a particular ocean process, internal waves. However, any extensive computer code has its own approximations built in and is ultimately a rather cumbersome tool; accordingly, we have worked to develop analytical treatments for as many cases as possible.

Basic theoretical approaches to sound transmission in this book can be divided into two parts:

(1) The Rytov (or supereikonal) extension of geometrical optics valid in regions of *weak* scattering.

(2) A *micromultipath* theory capable of treating some aspects of *strong* scattering, and based on a formulation using path integrals.

These theories treat the fluctuations of a single deterministic sound-transmission path from a source to a receiver. However, it is well known that for transmission beyond a few tens of kilometers in deep water, sound travels along several well-separated paths simultaneously (see Chapter 4). The received signal on a single hydrophone in this *multipath* situation has additional fluctuations due to interference effects between paths. We have then a third area of theoretical treatment.

(3) *Macromultipath* effects – where the single path fluctuations can be added together to give predictions for multipath fluctuations.

The areas of application of these treatments can be understood more fully by referring to Fig. I.1: a range–frequency diagram. Transmission of sound in the sea to ranges within the area labelled 'absorption' is impractical due to the absorption of sound energy by seawater. Sound with frequencies below 10 Hz will be subject to effects of the surface and bottom acting as a waveguide. Between these two areas, treatments that are basically approximations or extensions to ray theory can apply.

The limit of validity of the supereikonal approximation is a function of the strength of sound-speed fluctuations. The line shown is a rough estimate of the limit of validity in the real ocean; the precise position of the line depends on factors other than range and frequency. The micromultipath area (also known as the *saturated* region) is basically that area where a single deterministic path can sporadically change into two or more paths due to the ocean fluctuations. Deterministic multipath effects are important for a single receiver beyond thirty kilometers, but a vertical array of hydrophones can separate the sound fluctuations from each path to a much larger range. (This is much easier in a computer than it is in the real ocean!) It is important to note that in much of the saturated region there are so many sporadic micropaths between source and receiver that *the essential sound characteristics are not altered by the additional imposition of deterministic multipath.*

Rays in the ocean are restricted to such small angles from the horizontal that the parabolic approximation to the wave equation is universally valid (Chapter 5). This approximation is the heart

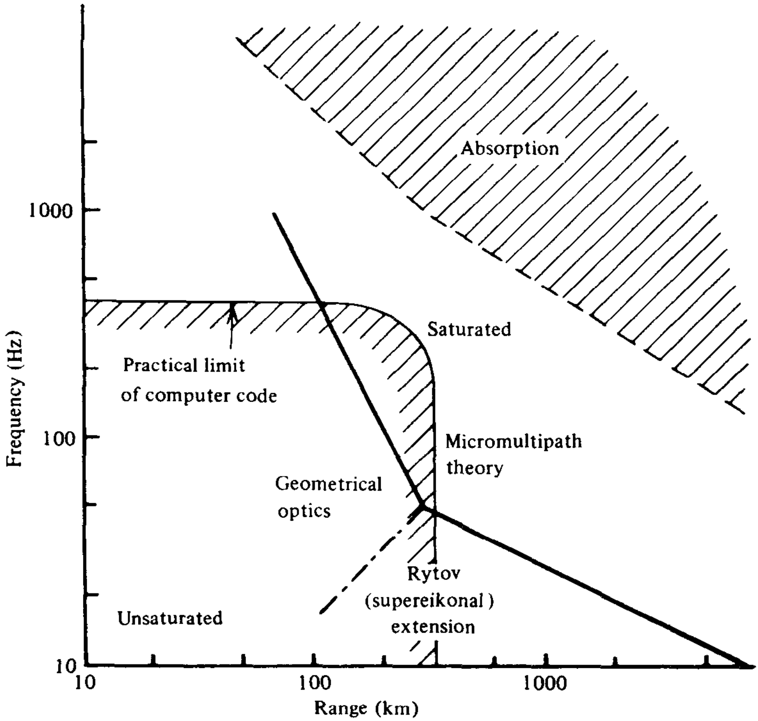

Fig. I.1. Limits and ranges of validity for various theoretical treatments discussed in this book. Seawater absorption of sound is greater than 20 dB in the shaded area.

of the computer code and is also used in most of the theoretical treatments.

In addition to these theoretical treatments we include a chapter on the transport equation, which treats scattering-angle distributions. This chapter provides a description of the connections between the micromultipath theory, the transport equation, and the method of the propagation of moments.

The description of all these theories of sound transmission is divided into three parts. Part II, an introduction to transmission theory, begins with a description of the most important feature in oceanic sound transmission: the sound channel (Chapter 4). In Chapter 5 a derivation of the wave equation and the parabolic approximation is given from first principles, and the particular method used in the computer code is described. This method leads naturally to a description of the path-integral formulation that is used in Parts III and IV. Chapter 5 concludes with a brief description of the geometrical-optics approximation and its region of validity.

Part III begins with a review of past work on sound transmission in homogeneous, isotropic media, and is important for establishing basic concepts and notation (Chapter 6). These concepts fall into two categories: (1) concepts required to characterize the sound–speed fluctuations; and (2) concepts of acoustic signal statistics and how to derive them from a knowledge of sound-speed fluctuations. Chapter 7 describes the fundamental differences between the ocean medium and a homogeneous, isotropic medium. Chapter 8 is a qualitative overview of the entire field of ocean sound-transmission fluctuations from the vantage points of the supereikonal and micromultipath theories. Part III ends with a description of multipath effects and includes a precise description of Gaussian statistics, which so often accompanies multipath phenomena (Chapter 9).

Part IV gives detailed justifications for the statements made in Chapter 8 as well as derivations of specific formulas based on the internal-wave model of Chapter 3. In addition, Part IV contains the transport-equation chapter relating the various wave propagation theories.

Part V compares the theories to field experiments at a variety of ranges and wavelengths. The reader who is experimentally oriented may find it most convenient to read Part III and then Part V, before plunging into the more detailed chapters in Part IV; the book has been organized to facilitate that order.

Previous books that have treated parts of ocean structure, particularly internal waves, in more detail than we have here are Phillips (1966) and Turner (1973). More recent progress is nicely summarized in an issue of the *Journal of Geophysical Research* devoted to internal waves. Previous books on sound transmission include Officer (1958), Tolstoy and Clay (1966) and Urick (1967 and 1975).

The quantitative connection between ocean structure and sound fluctuations has hardly been touched in the past. Phillips, Turner, and Officer do not consider the problem, while Urick and Tolstoy and Clay include very brief sections considering volume effects. Tolstoy and Clay view the ocean as a transmission channel, and describe its properties by certain correlation coefficients that are not readily identifiable with known physical processes. Urick, also in a brief section, considers quantitatively only isotropic inhomogeneities with a single scale size.

Other books of a more general nature, Brekhovskikh (1960 and 1975), Chernov (1960), and Tatarskii (1971) consider random media with a spectrum of scale sizes, but treat only isotropic cases without specializing to the ocean environment. Their results have been widely applied in ocean acoustics, but their neglect of anisotropy – so fundamental to the ocean environment – limits the usefulness of their results.

The present work is entirely devoted to the effects of fluctuating inhomogeneities in sound speed in the volume of the ocean. We admit that neglect of surface and bottom scattering is a fundamental difficulty for many practical problems; unfortunately, treatment of rough-interface scattering would require too much of an addition to an already thick volume. However, our knowledge that the ocean is nonisotropic (the scale sizes in the vertical being much smaller than in the horizontal) and that the strength of the inhomogeneities varies strongly with vertical position, has been taken into account in a basic way, as has the curved nature of unperturbed rays. These effects make the theorétical analysis more complicated, and the results are in many cases fundamentally different from those derived from homogeneous, isotropic turbulence theory.

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