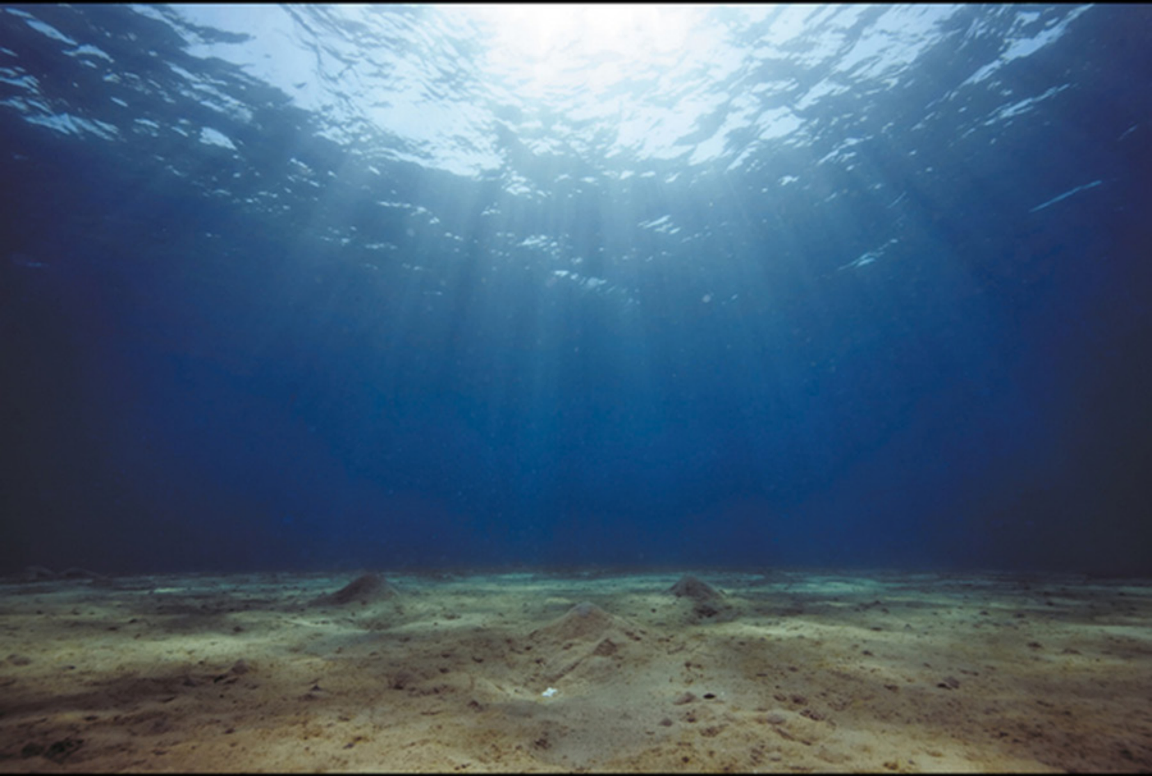
# HYDROACOUSTIC OCEAN EXPLORATION

## Theories and Experimental Application



I. B. ABBASOV

Scrivener Publishing

WILEY

# Hydroacoustic Ocean Exploration

**Scrivener Publishing**
100 Cummings Center, Suite 541J
Beverly, MA 01915-6106

*Publishers at Scrivener*
Martin Scrivener (martin@scrivenerpublishing.com)
Phillip Carmical (pcarmical@scrivenerpublishing.com)

# Hydroacoustic Ocean Exploration

## Theories and Experimental Application

**I. B. Abbasov**

Scrivener
Publishing

WILEY

Copyright © 2016 by Scrivener Publishing LLC. All rights reserved.

Co-published by John Wiley & Sons, Inc. Hoboken, New Jersey, and Scrivener Publishing LLC, Beverly, Massachusetts.
Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at http://www.wiley.com/go/permission.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at www.wiley.com.

For more information about Scrivener products please visit www.scrivenerpublishing.com.

Cover design by Kris Hackerott

***Library of Congress Cataloging-in-Publication Data:***

ISBN 978-1-119-32354-9

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

# Abstract

The book deals with the diagnostics of non-uniformities in a water medium using the hydroacoustic parametric antenna. The non-uniformities of the water medium in the study are of geometrically regular shape, i.e., the shape of a sphere, a cylinder, and a spheroid.

An account is given of theoretical and experimental studies of wave processes that occur in the event of the scattering of non-linearly interacting acoustic waves at a sphere, a cylinder, and a spheroid. Scattering problems are formulated; solutions to the inhomogeneous wave equation are found in the first and second approximations using the successive approximations method.

For the first time, high-frequency asymptotic expressions of acoustic pressure for all spectral components of the secondary field are obtained for the nonlinear scattering problem. The scattering diagrams are calculated and plotted, and then analyzed and compared. Results of experimental studies of the parametric acoustic antenna field scattering at solid steel spheres are presented. Experimental scattering diagrams both for the parametric antenna pump waves and for the secondary field waves including the difference frequency wave, the sum frequency wave, and the second harmonic wave are presented. 3D modeling of wave processes is also considered.

The book is for researchers and specialists in nonlinear hydroacoustics and ocean acoustics; it also may be of use for postgraduates and students specializing in the mentioned areas.

# Contents

# Introduction

Exploration of the world ocean involves an extensive use of hydroacoustic systems, which utilize parametric radiating antennas. Ambient medium is one of the key factors for the formation of parametric acoustic antenna fields; therefore, differences between perfect and actual working conditions should be taken into account. In actual working conditions, a water medium always features non-uniformities of different origin. These include both local non-uniformities of the medium as it is and non-uniformities of a biological and artificial nature.

Sound propagation in water is a nonlinear process. Westervelt [Westervelt, 1961] shows that if two high-intensity sound beams propagating in a medium coincide the nonlinearity of the medium brings about the generation of new propagating sound waves whose frequencies are equal to the sum and difference of the initial frequencies of the interacting fields. The difference frequency is especially attractive for technical applications due to the fact that its use involves formation of a rather narrow sound beam at a relatively low frequency.

Sound waves of new frequencies are generated over the entire zone of intensive interaction of the initial beams; therefore, it may be safely suggested that what occurs here is a volumetric distribution of secondary wave sources, which is essentially referred to as "acoustic parametric antenna".

As opposed to other secondary sound waves which are of a higher frequency, the difference frequency sound has a relatively low attenuation coefficient; therefore, it propagates farther than the rest of the waves. On the other hand, the difference frequency sound features, along with the narrowness of the beam (which is much narrower than could have been expected taking into account the size of the existing piston radiators of the original beams), absence of lateral lobes.

Another advantage of the parametric antenna consists in the expansion of the secondary waves' frequency range. An added advantage is that the width of the radiated beam remains almost unchanged when the difference frequency changes.

However, the advantages of the parametric antenna are offered at the cost of very low efficiency. There are three obvious ways to enhance the efficiency, namely, to increase the difference frequency, to increase energy of the original beams or to reduce the beam width.

Enhancing the efficiency without losing the advantages of a nonlinear source is achievable solely by increasing the power of the original radiation. This method is restricted by the saturation effect, the radiator structural strength, the beam spreading, and cavitation at high intensities of the sound. When gas bubbles get in the way of a high-intensity beam, the sound brings about nonlinear high-amplitude oscillations of such bubbles at the resonant frequency or at a frequency close to the resonant one. Such an effect can considerably increase the resonant frequency signal level (though, with certain losses in terms of radiation directivity). The presence of gas bubbles in water makes the medium non-uniform, and causes the scattering of the propagating acoustic waves.

Scatterings may be brought about by gas bubbles as well as by biological objects. A scattered signal from a fish's swimming bladder is often so high that an individual fish becomes observable, i.e., it is the gas bubble that mostly allows detecting a fish.

Analytical solutions to scattering problems exist solely for simply shaped bodies such as spheres, cylinders, spheroids, disks or plane portions; for a random body, the scattering problem is usually solved using numerical mathematical modeling methods.

This work considers investigations of water layers using the acoustic parametric antenna. It is assumed that non-uniformities of the water medium are of a geometrically regular shape, i.e., have the shape of a sphere, a cylinder or a spheroid. Both natural and artificial items may behave as such objects.

First, the sphere will be considered, since this case is of high practical importance. Scattering from a lot of bodies of a more complex shape can be described using scattering results for spheres (i.e., a small acoustic non-spherical body whose size is less than the sound wave length scatters sound in the same way as a sphere of the same volume and the same average physical parameters does).

Depending on the wave size of scatterers, the acoustic singles out three scattering zones, the first zone being Rayleigh scattering (small spheres, $ka << 1$), the second zone being resonant scattering (with the size of the scatterer being commensurate to the sound wave length, $k\ ka \approx 1$), and the third zone being the geometrical scattering (large spheres, $ka >> 1$) [Clay & Medwyn, 1980].

For the small spheres area, the expression of the scattering indicatrix for a small non-resonant sphere ($ka << 1$) was first found by Rayleigh [Rayleigh, 1955]. The Rayleigh scattering zone lies within the wave number range of 0 to 1. In terms of physics, it means that the acoustic section of the Rayleigh scattering is much less than the geometrical cross section of the body, since the sound waves envelop acoustically small resonant bodies almost without interacting with them. The effect of the Rayleigh scattering of wideband signals exists in the optics as well (i.e., for electromagnetic waves) and brings about the blue area of the solar spectrum.

In the second (resonant, $ka \approx 1$) scattering area, a rigid sphere behaves in a more complex way, with its behavior depending, to a large extent, on the frequency. For any liquid sphere, when the length of the sound wave inside the sphere is comparable to its radius or is less than such radius, propagation of waves inside the sphere becomes considerable, and the occurring coincident waves correspond to the natural resonant frequencies of the body. When waves are excited inside the body, scattering functions and sections feature spikes and troughs at frequencies which coincide with the sphere's natural resonant frequencies.

Certain sea organisms consist of liquid enclosed in a resilient shell (e.g., crustaceans). In this case, longitudinal waves may occur in the liquid inside the shell whereas longitudinal and transverse waves will appear in the shell itself. The back scattering is rather sensitive to the relative thickness of the shell.

The third scattering area ($ka >> 1$) is a geometrical area, since high-frequency ray approximation is used to analyze the process. This means that the back scattering function for a rigid sphere at $ka >> 1$ (within $\theta \neq \pi$ area) is an approximately constant value. Therefore, the back scattering intensity is directly proportional to the scatterer's cross section area. Combination of the Rayleigh scattering with the geometrical scattering causes a rigid sphere for back scattering act as a high-frequency filter with the boundary frequency corresponding approximately to the $ka \approx 1$ equality. For gas bubbles, in conditions of the resonant scattering, the bubble scattering and absorption cross sections exceed its geometrical cross-section approximately $10^3$ times (i.e., a bubble scatters much more than a rigid sphere of the same size does).

Below, scattering is considered in greater detail (spatially), i.e., not only in the backward (monostatic) direction, but also within the entire $\theta$ range, from 0° to $2\pi$.

Figure I.1 shows indicatrices of scattering at a rigid sphere as calculated by Stenzel [Stenzel, 1938]. As the wave size $ka$ grows, a lobe develops on the circular scattering indicatrix; this lobe corresponds to forward scattering, and is generated by the shadow-forming wave. Virtually, the signal scattered at angles close to 180° is hardly separable from the incident wave, which propagates along the same path at approximately the same time (shown by the dashed line).

It should be also noted that resilient scatterers in the geometrical scattering area behave in a much more complex way, and their acoustic shadow at high $ka$ values should be determined taking into account a rather large number of modes.

One of the possible descriptions is based in the explanation by Zommerfeld [Zommerfeld, 1950] of radiowave bending in the course of propagation of radio waves near the earth surface. The method was used by Franz [Franz, 1957] to explain diffraction of electromagnetic waves on non-conducting cylinders and spheres. The same method is used in acoustics [Clay & Medwyn, 1980] for description of sound propagation when, near a body surface, non-uniform waves of a new type (creeping waves) appear. Velocity of such waves is lower than the velocity of waves within an unlimited volume of fluid, and depends on resilient properties

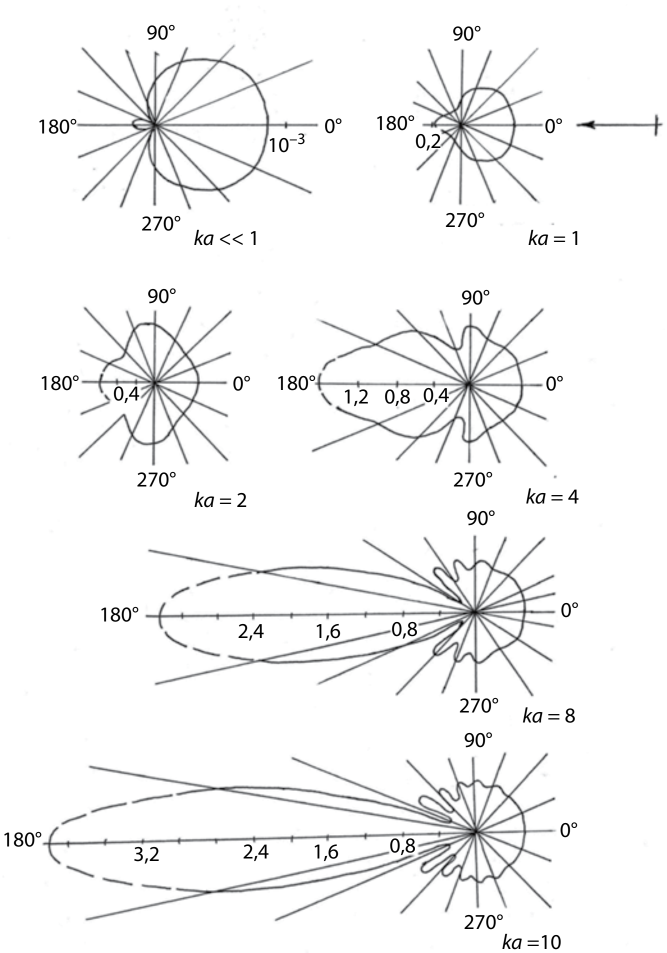


**Figure I.1** Indicatrices of scattering at a rigid sphere.

of the scatterer; attenuation of such waves is high and grows as the angle increases.

It should be noted that in scattering problems the interface (boundary) between two mediums plays a critical part; therefore, the acoustics categorizes boundary conditions as “acoustically soft boundary”, “acoustically rigid boundary” or “impedance boundary”.

The acoustically soft boundary conforms to the Dirichlet condition; this corresponds to the occurrence, at the boundary, of a particle-velocity standing wave antinode and an acoustic pressure node, whereas the phase jump at the boundary is experienced by the pressure wave.

The acoustically rigid boundary conforms to the Neumann condition. Here, a particle-velocity standing wave node and an acoustic pressure antinode occur at the boundary, whereas the phase jump at the boundary is experienced by the particle-velocity wave.

The above cases are idealized; they are never encountered in real conditions, and boundaries are always impedance ones.

The first chapter deals with wave processes occurring in the course of the parametric acoustic antenna field scattering at a sphere. It should be noted that here the determining factor is the location of the spherical scatterer relative to the parametric antenna. Two cases exist for such consideration, namely:

- The first case, when the spherical scatterer is located in the area of nonlinear interaction of the initial pumping waves, i.e., in the near zone of the parametric antenna, where the incident field is assumed to be plane; and;
- The second case, when the spherical scatterer is located beyond the area of nonlinear interaction of the pumping waves, i.e., where secondary waves already exist, and the pumping waves are almost entirely attenuated.

It should be noted that in the second case the scattering of secondary waves will be of a linear nature, and this classical problem is a thoroughly studied one. In spite of its naturalness, the problem corresponding to the first case has never been considered before; thus, physical processes which occur in conditions of the scattering of nonlinearly interacting acoustic waves at a sphere remain unexamined.

For the first case, the scattering process is of a more complex nature, since incident plane pumping waves, which are scattered within a certain volume around the scatterer, will interact both between each other and with incident plane waves. As a result, secondary waves generated in the course of such interactions will propagate beyond the said volume.

# 1

# Scattering of Nonlinear Interacting Plane Acoustic Waves by a Sphere

## 1.1 Review of Studies Dealing with the Scattering of Plane Acoustic Waves by a Sphere

The existing works dealing with the scattering of sound waves at a sphere may be subdivided into two groups as follows:

- The first group includes theoretical and experimental studies of the scattering of monochromatic acoustic waves at spherical bodies; and
- The second group includes studies which deal directly with the nonlinear scattering of acoustic waves at spherical scatterers.

Each of the mentioned groups, in turn, is subdivided into two subgroups as follows:

- The first subgroup includes studies of wave processes within the space around the scatterer (the volume effect); and
- The second subgroup includes studies of surface wave processes in conditions of the scattering of acoustic waves at spherical bodies (the surface effect).

Given the fact that the linear problem is a classical and thoroughly studied one and taking into account the linear scattering of the parametric antenna pumping waves proper in our problem under consideration, below we will review works for the linear case.

The classical work by Stenzel [Stenzel, 1938] (Figure 1.1) may be mentioned as an example from the series of studies of spatial wave processes occurring in conditions of the scattering of acoustic waves at a sphere. The wave sizes of the sphere lie within the range of 0.5 to 10, i.e., the range where a rigid sphere behaves in a rather complex way. As the wave size increases, the indicatrix turns, from the initial almost circular diagram, into a shape with a long "tail" in the forward direction. Further increase of the wave size results only in the sharpening of the said "tail". The work by Stenzel is essentially the principal one in the subgroup encompassing studies of spatial effects.

The second subgroup that deals with studies of surface effects includes a rather large number of works. Franz [Franz, 1957] was the first to pay attention to surface waves. He shows that the scattering of a sensing wave at a rigid spherical body involves the following components of a scattered wave field: first, the reflex wave; second, two successions of creeping waves propagating in the fluid around the object in the clockwise and counterclockwise directions.

Each wave from these successions corresponds to a single mode and propagates at its group velocity, with the amplitude of such wave reducing as a result of continuous radiation. Each wave envelops the object a theoretically infinite number of times. The number of such modes is infinite as well. It should be noted that such a phenomenon was detected in conditions of the scattering of electromagnetic waves at a non-conducting sphere by Watson [Watson, 1918] who provided a mathematical description of the phenomenon.

It should be emphasized as well that the study of surface effects is conducted in the monostatic mode; therefore, the angular parameters of scatterers are not needed. Works [Metsaveer *et al.*, 1979] and [Nigul *et al.*, 1974] are also concerned with surface effect studies. The works deal with the mathematical modeling of echo signals from such objects as a hollow resilient sphere with a filler, a hollow empty resilient sphere, a solid resilient sphere, a solid liquid or gaseous sphere, a rigid static sphere, and a spherical enclosure. The mathematical modeling is performed within the scope of the linear elasticity theory, linear elastic shell theory, and perfect compressible fluid theory.

Peripheral waves occur in an elastically deformed body and propagate within the body itself. In thick-walled and solid deformed bodies, along with the above-mentioned waves that generate the echo signal, waves of a different type also occur, which pass through the body and reflect from its back surface. Contributions of such waves to the echo signal from solid deformed cylinders are studied in work [Brill D & Uberall, 1971].

Works [Selivanov & Ivanov, 1982], [Selivanov & Viligzhanina, 1986] study the processes of sound wave scattering at a resilient sphere and cylinder and at a spherical shell with fluid. Work [Selivanov & Ivanov, 1982] presents experimental studies of acoustic wave scattering at solid steel cylinders and a sphere by means of a multi-frequency pulse ultrasonic spectroscopy method. Steel cylinders 50 mm and 30 mm in diameter and 180 mm long and a sphere dia.100 mm are used in the experimental studies.

Work [Selivanov & Viligzhanina, 1986] also analyzes time delays in the structure of the echo signal from a spherical shell with various fluid fillers. Unlike other works, this work provides circular diagrams of the scattering at the shells which show predominant scattering in the backward direction and certain levels in the forward and lateral directions.

After the review of works on linear scattering, below we proceed with a review of works on the nonlinear scattering of acoustic waves on spherical scatterers.

The problem of the scattering of interacting plane waves at a sphere has never been studied in detail. However, there are certain works on nonlinear interaction of waves having different wavefront configurations. Since the spatial interaction is the issue that is primarily focused on in our problem, below we will consider certain works on this subject. First, the works on surface effects will be considered.

Work [Piquette & Buren, 1986] describes nonlinear effects caused by the scattering of acoustic waves at radiators whose function is performed by vibrating regularly shaped shells. The problem associated with interaction