principles of underwater sound

SECOND EDITION

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preface to the revised edition

The eight years since the publication of the first edition have seen advances in many aspects of underwater acoustics—as befits an active, virile branch of engineering science. The aim of this revision is to include as much of this new knowledge as potential usefulness and the often irrationally stringent limitations of military security will allow. Some sections have been rewritten, both to include these recent findings and for greater clarity in presentation. The new American National Standard for acoustic pressure levels in fluids (1 micropascal) has been adopted throughout.

The objective and plan of the book remains the same: to present the method, the basic understanding, and some of the numerical data needed for practical sonar problem solving.

Robert J. Urick

preface to first edition

Underwater sound, as a specialized branch of science and technology, has seen service in two world wars. Although it has roots deep in the past, underwater sound, as a quantitative subject, may be said to be only a quarter of a century old. Its modern era began with the precise quantitative studies undertaken with great vigor during the days of World War II. In subsequent years, its literature has grown to sizable proportions, and its practical uses have expanded in keeping with man's continuing exploration and exploitation of the seas.

This book attempts to summarize the principles of underwater sound from the viewpoint of the engineer and the practical scientist. It lies squarely in the middle of the spectrum—between theory at one end and sonar technology at the other. Its intent is to provide a summary of the principles, effects, and phenomena of underwater sound and to give numerical quantitative data, wherever possible, for the solution of practical problems.

The framework of the book is the sonar equations—the handy set of relationships that tie together all the essential elements of underwater sound. The approach is, after an introductory chapter, to state the equations in a convenient form and then to discuss in subsequent chapters each one of the quantities occurring in the equations. The final chapter is largely devoted to problem solving, in which the use of the equations is illustrated by hypothetical problems taken from some of many practical applications of the subject.

In the desire to keep the book within sizable bounds, some aspects of underwater sound have had to be slighted. One is the subject of transducers—the conversion of electricity into sound and vice versa. Although transducer arrays are discussed, only one sound source—the underwater explosion—is dealt with at any length. It is felt that the design of electroacoustic transducers for generating and receiving sound is truly an art in itself, with a technology and theoretical background that deserves a book of its own. In addition, much of the basic theory of underwater sound is confined to references to the literature, and engineering matters of sonar hardware are omitted entirely. Although the book will therefore appeal neither to the theoretician nor to the hardware builder, it hopes to cover the vast middle ground between them and be of interest to both the design engineer and the practical physicist. It is based on a course given for several years at the Catholic University, Washington, D.C., and at Westinghouse Electric Co., and the Martin Co. in Baltimore.

The book owes a great deal to my colleagues at the Naval Ordnance Laboratory for many discussions and helpful criticism. In particular, Mr. T. F. Johnston, chief of the acoustics division, has been a constant encouragement and stimulant in the long and arduous task of writing the book. My students have been helpful too in providing me with a receptive and critical audience for whatever is original in the presentation.

Robert J. Urick

abbreviations used in the book

Abbreviation	*Unit*
A	ampere
dB	decibel
dyn	dyne
fm	fathom
ft	foot
ft/s	foot per second
g	gram
Hz	hertz
h	hour
kHz	kilohertz
kyd	kiloyard
kn	knots
μPa	micropascal
μs	microsecond
mi	mile
ms	millisecond
nmi	nautical mile
s	second
V	volt
W	watt
$W \cdot s/cm^2$	watt-second per square centimeter
yd	yard

contents

one

the nature of sonar

Of all the forms of radiation known to man, sound travels through the sea the best. In the turbid, saline water of the sea, both light and radio waves are attenuated to a far greater degree than is that form of mechanical energy known as sound.

Because of its relative ease of propagation, underwater sound has been applied by man to a variety of purposes in his use and exploration of the seas. These uses of underwater sound constitute the engineering science of *sonar,* and the systems employing underwater sound in one way or another are *sonar systems.*

Sonar systems, equipments, and devices are said to be *active* when sound is purposely generated by one of the system components called the *projector.* The sound waves generated by the projector travel through the sea to the *target,* and are returned as sonar *echoes* to a *hydrophone,* which converts sound into electricity. The electric output of the hydrophone is amplified and processed in various ways and is finally applied to a control or display device to accomplish the purpose for which the sonar set was intended. Active sonar systems are said to *echo-range* on their targets.

Passive or *listening* sonar systems use sound (usually unwittingly) radiated by the target. Here only *one-way* transmission through the sea is involved, and the system centers around the hydrophone used to listen to the target sounds. Communication, telemetry, and control applications employ a hybrid form of sonar system using a projector and hydrophone at *both* ends of the acoustic communication path.

1.1 Historical Survey

Although the "modern age" of sonar may be said to date back a quarter of a century to the start of World War II, sonar has its origins deep in the past. One of the earliest references to the fact that sound exists beneath the surface of the sea, as well as in the air above, occurs in one of the notebooks of that versatile, archetypal engineer, Leonardo da Vinci. In 1490, two years before Columbus discovered America, he wrote (1):* "If you cause your ship to stop, and place the head of a long tube in the water and place the outer extremity to your ear, you will hear ships at a great distance from you." Although this earliest example of a passive sonar system has the enviable merit of extreme simplicity, it does not provide any indication of direction and is insensitive as a result of the great mismatch between the acoustic properties of air and water. Yet, the idea of listening to underwater sounds by means of an air-filled tube between the sea and the listener's ear had widespread use as late as World War I, when, by the addition of a second tube between the other ear and a point in the sea separated from the first point, a direction could be obtained and the bearing of the target could be determined.

Perhaps the first quantitative measurement in underwater sound occurred in 1827, when a Swiss physicist, Daniel Colladon, and a French mathematician, Charles Sturm, collaborated to measure the velocity of sound in Lake Geneva in Switzerland. By timing the interval between a flash of light and the striking of a bell underwater, they determined the velocity of sound to a surprising degree of accuracy.

Later on in the nineteenth century, a number of famous physicists of the time indirectly associated themselves with underwater sound through their interest in the phenomenon of "transduction"—the conversion of electricity into sound and vice versa (2). Jacques and Pierre Curie are usually credited with the discovery in 1880 of piezoelectricity—the ability of certain crystals, when stressed, to develop an electric charge across certain pairs of crystal faces. Other physicists had dabbled in the subject before this. Charles Coulomb is said to have speculated on the possibility of producing electricity by pressure, and Wilhelm Röntgen wrote a paper on the electric charge appearing on the various faces of crystals under stress. The counterpart of piezoelectricity as a transduction process is magnetostriction, wherein a magnetic field produces a change in the shape of certain substances. The earliest manifestation of magnetostriction was the musical sounds that were heard when, about 1840, the current in a coil of wire was changed or interrupted near the poles of a horseshoe magnet. James Joule, in the 1840s, carried out quantitative measurements on the change of length associated with magnetostriction, and is commonly credited with being the discoverer of the effect.

These studies, and those of others in the 1840s and 1850s, were the founda-

* The parenthetical numbers throughout the text denote numbered references to the literature in a list of references at the end of each chapter.

tion for the invention of the telephone, for which a long-disputed patent was issued in 1876 to A. G. Bell. Another nineteenth-century invention that was the mainstay of sonar systems before the advent of electronic amplifiers was the carbon-button microphone, a device which became the earliest, and still probably the most sensitive, hydrophone for underwater sound.

About the turn of the century there came into being the first practical application of underwater sound. This was the submarine bell, used by ships for offshore navigation. By timing the interval between the sound of the bell and the sound of a simultaneously sent blast of a foghorn, a ship could determine its distance from the lightship where both were installed. This system was the impetus for the founding of the Submarine Signal Company (now part of Raytheon Mfg. Co.), the first commercial manufacturer of sonar equipment in the United States. The method was never in widespread use and was soon replaced by navigation methods involving radio—especially radio direction finding.

Another pre–World War I achievement was the embryonic emergence of the first schemes for the detection of underwater objects by echo ranging. In 1912, five days after the "Titanic" collided with an iceberg, L. F. Richardson filed a patent application with the British Patent Office for echo ranging with airborne sound (2). A month later he applied for a patent for its underwater analog. These ideas involved the then-new features of a directional projector of kilohertz-frequency sound waves and a frequency-selective receiver detuned from the transmitting frequency to compensate for the doppler shift caused by the motion of the echo-ranging vessel. Unfortunately, Richardson did nothing at the time to implement these proposals. Meanwhile, in the United States, R. A. Fessenden had designed and built a new kind of moving-coil transducer for both submarine signaling and echo ranging and was able, by 1914, to detect an iceberg at a distance of 2 miles. Fessenden "oscillators" operating at frequences near 500 and near 1,000 Hz are said (3) to have been installed on all United States submarines of the World War I period to enable them to signal one another while submerged. They remained in use until recently as powerful sinusoidal sound sources for research purposes.

The outbreak of World War I in 1914 was the impetus for the development of a number of military applications of sonar. In France a young Russian electrical engineer, Constantin Chilowsky, collaborated with a distinguished physicist, Paul Langevin, in experiments with a condenser (electrostatic) projector and a carbon-button microphone placed at the focus of a concave mirror. In spite of leakage and breakdown troubles caused by the high voltages needed for the projector, by 1916 they were able to obtain echoes from the bottom and from a sheet of armor plate at a distance of 200 meters. Later, in 1917, Langevin turned to the piezoelectric effect and used a quartz-steel sandwich to replace the condenser projector. He also employed one of the newly developed vacuum-tube amplifiers—probably the first application of electronics to underwater sound equipment. For the first time, in 1918, echoes were received from a submarine, occasionally at distances as great as 1,500 meters. Parallel

British investigations with quartz projectors were conducted by a group under R. W. Boyle. The word "asdic" was coined at the time to refer to their then highly secret experiments.* World War I came to a close, however, before underwater echo ranging could make any contribution to meet the German U-boat threat.

In the meantime, extensive use had been made of Leonardo's air tube for passive listening, improved by the use of two tubes to take advantage of the binaural directional sense of a human observer. The MV device consisted (5) of a pair of line arrays of 12 air tubes each, mounted along the bottom of a ship on the port and starboard sides and steered with a special compensator. Surprising precision was achieved in determining the bearing of a noisy target; an untrained observer could find the bearing of a distant target to an accuracy of ½°. Another development of the time (5) was a neutrally buoyant, flexible line array of 12 hydrophones called the "eel," which could easily be fitted to any ship and could be towed astern away from the noisy vessel on which it was mounted. All in all, some three thousand escort craft were fitted with listening devices of various kinds in World War I. By operating in groups of two or three and using cross bearings, they could obtain a "fix" on a suspected submarine contact.

The years of peace following World War I saw a steady, though extremely slow, advance in applying underwater sound to practical needs. Depth sounding by ships under way was soon developed, and by 1925, fathometers, a word coined by the Submarine Signal Company for their own equipment, were available commercially in both the United States and Great Britain. The search for a practical means of echo ranging on submarine targets was conducted in the United States by a handful of men under H. C. Hayes at the Naval Research Laboratory. The problem of finding a suitable sound projector in echo ranging was solved by resorting to magnetostrictive projectors for generating the required amount of acoustic power. Also, synthetic crystals of Rochelle salt began to replace scarce natural quartz as the basic piezoelectric material for piezoelectric transducers. During the interwar period sonar received a great practical impetus from advances in electronics, which made possible vast new domains of amplifying, processing, and displaying sonar information to an observer.

Ultrasonic frequencies, that is, frequencies beyond the region of sensitivity of the unaided human ear, came to be used for both listening and echo ranging and enabled an increased directionality to be obtained with projectors and hydrophones of modest size. A number of small, but vital, components of sonar systems were added during this period, notably the development by the British of the range recorder for echo-ranging sonars to provide a "memory"

* According to A. B. Wood (4), the word "asdic" was originally an acronym for "*A*nti-*S*ubmarine *D*ivision—*ics*" from the name of the group which did the work. The suffix had the same significance as it does in the words "physics," "acoustics," etc. For many years thereafter, the word "asdic" was used by the British to refer to echo ranging and echo-ranging sonar systems generally.

of past events and the streamlined dome to protect the transducer on a moving ship from the noisy, turbulent environment of water flow past a moving vessel. By 1935, several fairly adequate sonar systems had been developed, and by 1938, with the imminence of World War II, quantity production of sonar sets started in the United States. By the time the war began, a large number of American ships were equipped for both underwater listening and echo ranging. The standard echo-ranging sonar set for surface ships was the QC equipment. The operator searched in bearing with it by turning a handwheel and listening for an echo with headphones or loudspeaker. If an echo was obtained, its range was noted by the flash of a rotating light or from the range recorder. Submarines were fitted with JP listening sets, consisting of a rotatable horizontal line hydrophone, an amplifier, a selectable bandpass filter, and a pair of headphones. The cost of this equipment with spares was $5,000! With such primitive sonar sets, the Battle of the Atlantic against the German U-boat was engaged and, eventually, won.

But from a scientific standpoint, perhaps the most notable accomplishment of the years between World War I and World War II was the obtaining of an understanding of the vagaries of sound propagation in the sea. Early shipboard echo-ranging sets installed in the late twenties and early thirties were mysteriously unreliable in performance. Good echoes were often obtained in the morning, but poor echoes, or none at all, were obtained in the afternoon. When it became clear that the sonar operators themselves were not to blame and that the echoes were actually weaker in the afternoon, the cause began to be sought in the transmission characteristics of the seawater medium. Only with the use of special temperature-measuring equipment did it become evident that slight thermal gradients, hitherto unsuspected, were capable of refracting sound deep into the depths of the sea and could cause the target to lie in what is now known as a "shadow zone." The effect was called by E. B. Stephenson the "afternoon effect." As a means to indicate temperature gradients in the upper few hundred feet of the sea, A. F. Spilhaus built the first bathythermograph in 1937; by the start of World War II, every naval vessel engaged in antisubmarine work was equipped with the device. During this period also, a clear understanding was gained of absorption of sound in the sea, and remarkably accurate values of absorption coefficients were determined at the ultrasonic frequencies 20 to 30 kHz then of interest. These and other achievements of the interwar period are described in a paper by Klein (6).

On both sides of the Atlantic, as in World War I, the World War II period was marked by feverish activity in underwater sound. In the United States, a large group of scientists organized by the National Defense Research Committee (NDRC) began investigations of all phases of the subject.* Most of our present concepts as well as practical applications had their origins in this period. The acoustic homing torpedo, the modern acoustic mine, and scanning

* At the end of the war the findings of that part of NDRC engaged in underwater sound were summarized in an admirable series of some 22 reports called the *NDRC Division 6 Summary Technical Reports*.

sonar sets were wartime developments. Methods for quick calibration of projectors and hydrophones began to be used, and an understanding of the many factors affecting sonar performance that are now summarized in the sonar equations was gained. Factors such as target strength, the noise output of various classes of ships at different speeds and frequencies, reverberation in the sea, and the recognition of underwater sound by the human ear were all first understood in a quantitative way during the years of World War II. Indeed, in retrospect, there is little of our fund of underwater acoustic knowledge that cannot be traced, in its rudiments, to the discoveries of the wartime period.

The Germans must be given credit for a number of unique accomplishments. One was the development of Alberich, a nonreflecting coating for submarines. It consisted of a perforated sheet of rubber cemented to the hull of a submarine and covered by a solid, thin sheet of rubber to keep water out of the air-filled perforations. This coating was effective only over a limited range of depth and frequency, and could not be kept bonded to the hull for long periods under operating conditions. Another innovation was the use of flush-mounted arrays for listening aboard surface ships. An array of this kind—given the designation GHG for *grüppen-hört-gerät* or "array listening equipment"—was installed on the cruiser "Prinz Eugen" and used with some success (7).

According to Batchelder (8), the word "sonar" was coined late in the war as a counterpart of the then-glamorous word "radar" and came into use later only after having been dignified as an acronym for *so*und *na*vigation and *r*anging!

1.2 Postwar Developments

The years since World War II have seen some remarkable advances in the exploitation of underwater sound, for both military and nonmilitary purposes. On the military side, *active sonars* have grown larger and more powerful and operate at frequencies several octaves lower than in World War II. As a result, active sonar ranges are today far greater than they were during the hectic days of the war. Similarly, *passive sonars* have tended toward lower frequencies in order to take advantage of the tonal or line components in the low-frequency submarine noise spectrum.

Passive sonar arrays containing many hydrophones have been placed on the deep ocean floor to take advantage of the quiet environment and good propagation conditions existing at such low frequencies. At the same time, however, the submarine targets of passive sonars have become quieter, and have become far more difficult targets for detection than they once were. The developments of complex signal processing, in both time and space, that the emergence of digital computers has made possible have enabled much more information to be used for whatever function the sonar is called upon to perform. Finally, research in sound propagation in the sea has led to the exploitation of propagation paths not even dreamed of in earlier years; an example is the discovery