Prologue: Active and passive sensing in the sea

An innocent person, fully informed by the news media about the fantastic successes of radar and other electromagnetic frequencies in studies of the universe, can be excused for asking "Why should one use sound to probe or communicate in the sea? Why not use light or radar?"

In fact, sound has overwhelming advantages, compared to light or radar, as a tool for active or passive studies and for communication within the ocean. The great advantages of acoustics compared to electromagnetics at sea, depend on two crucial characteristics of all waves:

(*a*) the wavelength needed to "see" a body by its backscatter or radiation;
(*b*) the wave attenuation (decrease with propagation distance) at "usable" frequencies.

First, the effect of wavelength on wave backscatter.

In the nineteenth century Lord Rayleigh proved that, if a simple spherical body is to be sensed by an observer, the wavelength of the sound or light that is used as an active probe should be less than the circumference of the sphere. In fact, if the wavelength is larger than the circumference, the cross-section of the object appears to be very much *smaller* than it actually is. The reduction is inversely proportional to the fourth power of the wavelength. That is, if the wavelength is twice the circumference, the backscattered sound intensity (which one needs to identify an object) is approximately one-sixteenth as great as when the wavelength is equal to, or less than, the circumference!

A strong argument against the use of light or radar for detection or communication under the ocean surface is quite simple. Wavelengths of visible light range from 0.4 to 0.8 microns (slightly less in water). This means that ocean particles with circumference greater than about one micron will scatter light very effectively. In fact, it is well known that light beams are greatly attenuated by scatter from the large amount of minute suspended particles in the sea. In most oceans, one must get very close to take a photograph of an object. Skin divers talk about a typical maximum range of about 2 meters (6 feet) and point out that side lighting and strobe lighting is generally essential. It has been said that the opacity of the water in the English Channel is so great that, regardless of the illumination, a diver is unable to see his fingers at the end of his outstretched arm! Submersible vehicles that travel to great depths suffer from the same limitation. In conclusion, the extraordinarily large scatter of short optical and radar wavelengths, accompanied by the enormous absorption of all electromagnetic waves due to the electrical conductivity of salt water, combine to make light and radar almost unusable except for very short distances in the ocean.

Active sensing by light or sound

Let us summarize *active* detection of bodies at sea.

To see and describe an object *optically*, one can use the visual part of the electromagnetic spectrum from blue to red light (frequency ratio, two to one). Unfortunately, the typical ocean range for visible light is only a few meters.

Because of its very much smaller attenuation in the sea, a far greater span of *acoustic* frequencies can be employed productively. The more than 1000 to one frequency ratio for active uses of sounds includes *fractions of a kilohertz* (mid-keyboard of the piano) which are effective in the study of large scale ocean motions (eddies) kilometers in extent, *kilohertz* sounds (near the upper limit of human hearing) common for active sonar detection by submarines, *tens of kilohertz* frequencies for acoustical fish finders, *hundreds of kilohertz* sounds to measure ocean particle motions and search for buried objects, and *thousands of kilohertz* (megahertz) sonars for remote, acoustical, non-destructive, *in situ* "counting" of 0.1 mm diameter zooplankton!

These acoustical studies can be accomplished at acoustic intensities that are not harmful to marine life. In fact, almost all ocean acoustical research is performed at sound levels that are barely detectable above the ambient noise in the sea.

The superiority of active acoustical probing compared to optical photography can be comprehended in a practical case by considering the detail in the "acoustical image" of a 57 m long shipwreck, sunk in turbid water of depth 38 m. The photo below was produced by using *acoustical* backscatter of a 500 kHz side-scan sonar at a range of 75 meters. The *optical* visibility was only about one or two meters at the time of this test! Note the missing stern section, the three large hatches designed for convenient handling of timber, and the crater due to sediment erosion.

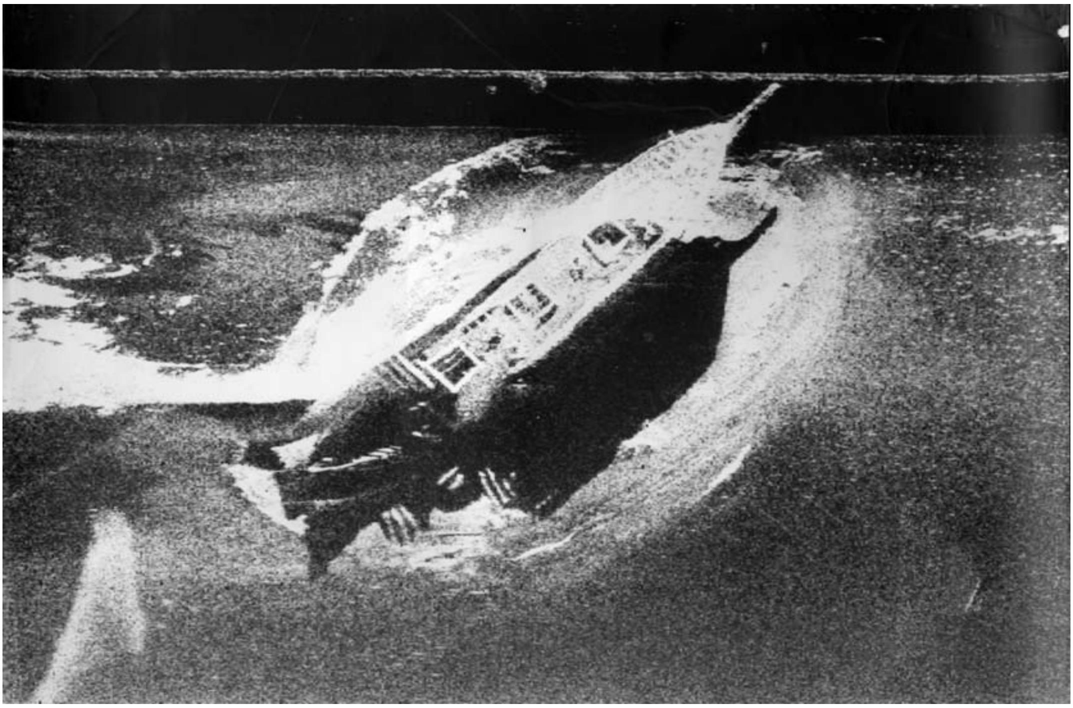

Photo courtesy of EDGE TECH, Milford, Massachusetts.

Passive sensing by light or sound

Finally, consider *passive* detection in the sea. Marine biologists have studied several species, such as some jellyfish, which make their presence known by emitting light. But one must be within a few meters of the animals to observe them.

On the other hand, some "sound" (defined here for the frequency range from a fraction of a hertz to several megahertz) is emitted by all whales, many species of fish and plankton, all oceanographic and meteorological phenomena, and all man-made vehicles. This makes it possible to detect, identify, and study these sources by simply listening. Recent passive underwater sound research includes: low frequency detection of secret underwater explosions and microseisms at distances over 10 000 kilometers; eavesdropping on voices of the great whales hundreds of kilometers away; and measuring the amount and detailed characteristics of mid-ocean rainfall by remote satellite transmission of the sounds of the raindrop impacts and the ringing microbubbles created by the splash.

Part I
Fundamentals

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Chapter 1
Sound propagation in a simplified sea

Summary

Sound is a mechanical disturbance that travels through a fluid. The sound wave can be a short-duration pulse or a continuous wave oscillation (CW) that is usually, for simplicity, sinusoidal. Because most detectors of ocean sounds are pressure sensitive devices, the propagating disturbance is most often identified as a time-varying incremental pressure, i.e., an *acoustic pressure*. Sometimes the description is in terms of the incremental density, the incremental temperature, the material displacement from equilibrium, or the transient particle velocity of the sound.

In this chapter we assume that the medium is *homogeneous* (same physical properties at all points) and *isotropic* (same propagation properties in all directions). We also assume that there is no sound *absorption* (no sound energy conversion to heat) and no *dispersion* (no dependence of sound speed on sound frequency). And we assume that the acoustic pressure increment is very, very small compared to the ambient pressure (no finite amplitude, non-linear effects).

Several wave phenomena that occur in the sea will be discussed here. When sound encounters an obstacle, it is *scattered*; part of the scattered energy bends around the obstacle (this is called *diffraction*) and part is backscattered toward the source; when it is incident on a boundary surface where it meets a different density or different sound speed, some *reflection* occurs, accompanied by some *refraction* (i.e., transmission at an angle different from the incident angle). When a sound wave meets another sound wave, the two pressures may add constructively or destructively, and *interference* ensues.

We seek to exploit the capabilities of underwater sound to discover more about the world's oceans and its inhabitants. This is done by interpreting the behavior of several descriptors of sound such as its pressure amplitude, particle velocity, density, intensity, radiated power, and propagation speed, all of which are introduced in this chapter. Also in this chapter, we study the effect of the ocean on sounds, including the basic behaviors such as: "reflection" from ocean surfaces; "refraction" of sound rays (the bending caused mostly by the spatial variation of the water temperature and salinity); "interference," (the superposition of sounds from different sources, or sounds that have traveled different paths from the same source). These same phenomena may be known from one's study of optics, but the omnipresent effects are crucially important to understand and interpret sounds in the sea.

Various simplifying approximations are developed at this time to derive the sound propagation equations that describe the effects of the ocean surface, volume, and bottom. We discuss waves in plane, cylindrical, and spherical coordinate systems, which will be needed to express the propagation at sea simply and appropriately to the sources and the environment.

Contents

1.1 Sound speed in water

Knowing the sound speed in water is critical to ocean communication and much of biological and geophysical ocean research. The earliest measurement was by Colladon and Sturm (1827) in the fresh water of Lake Geneva, Switzerland (Fig. 1.1). A value of 1435 m/s was found, but it was soon realized that the speed in saline water is somewhat greater than this and that, in general, the temperature of the water is an even more important parameter than salinity.

* This section contains some advanced analytical material.

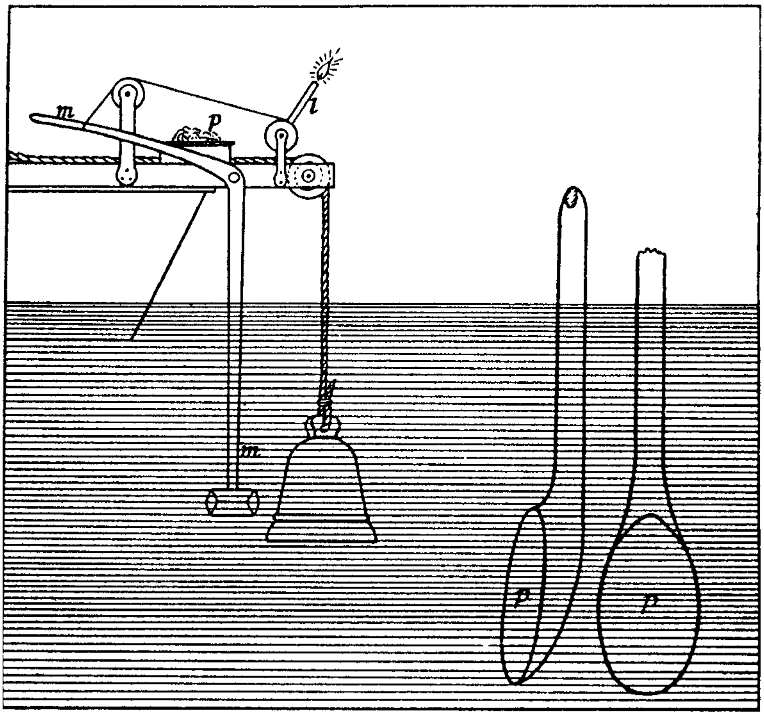

Fig. 1.1. Colladon and Sturm's apparatus for measuring the speed of sound in water. A bell suspended from a boat was struck under water by means of a lever *m*, which at the same moment caused the candle *l* to ignite powder *p* and set off a flash of light. An observer in a second boat used a listening tube to measure the time elapsed between the flash of light and the sound of the bell. The excellent results were published in both the French and German technical literature. (*Annales de Chimie et de la Physique* 36, [2], 236 [1827] and Poggendorff's *Annalen der Physik und Chemie* **12**, 171 [1828].)

Numerous laboratory and field measurements have now shown that the sound speed increases in a complicated way with increasing temperature, hydrostatic pressure, and the amount of dissolved salts in the water. A very simple formula for the speed in m/s, accurate to 0.1 m/s, but good only to 1 kilometer depth, was given by Medwin (1975),

$$\begin{aligned} c = {} & 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 \\ & + (1.34 - 0.010T)(S - 35) + 0.016z \end{aligned} \tag{1.1}$$

In (1.1), temperature T is in degrees centigrade, salinity S is in parts per thousand of dissolved weight of salts, and the depth z is in meters. A better, longer, but still simple expression (Mackenzie, 1981) is in Chapter 2. The best equation (Del Grosso, 1974) involves some 19 terms containing coefficients with 12 significant figures.

Portable sound "velocimeters," which measure the time of travel of a megahertz pulse, have an accuracy of 0.1 m/s in non-bubbly water. But everpresent microbubbles, which are not considered in any of the sound speed equations above, can cause the actual speed of propagation at frequencies below about 100 kHz to be different from the velocimeter readings by tens of meters/s, particularly near the ocean surface, see Chapter 6.

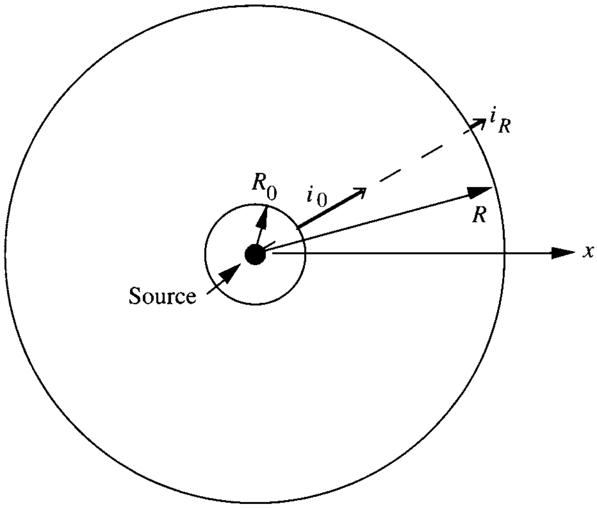

Fig. 1.2. Spherical spreading of a pulse wave front. The instantaneous intensity is i_0 at the radius R_0 and later is i_R at the radius R.

1.2 Pulse wave propagation

1.2.1 Intensity of a diverging compressional pulse

In a medium that is homogeneous and isotropic, a tiny sphere expands suddenly and uniformly and creates an adjacent region of slightly higher density and pressure. This higher density region is called a *condensation*. Assume that it has a thickness *dr*. The condensation "impulse" or "pulse," will move outward as a spherical wave shell and will pass a reference point during time δt. It is called a *longitudinal wave* because the displacements in the medium are along the direction of wave propagation. As it propagates, the energy of the impulse is spread over new spherical shells of ever larger radius, at ever lower acoustic pressure. By conservation of energy, the energy in the expanding wave front is constant in a lossless medium.

The *acoustic intensity is the fluctuating energy per unit time that passes through a unit area*. The total energy of the pulse is the integral of the intensity over time and over the spherical surface that it passes through. Figure 1.2 shows the expanding wave front at two radii. Applying the conservation of energy, the energy that passes through the sphere of radius R_0 is the same as the energy passing through the sphere of radius R. Conservation of energy gives the sound intensity relationship, where i_0 and i_R are the intensities at R_0 and R,

$$4\pi i_R R^2(\delta t) = 4\pi i_0 R_0^2(\delta t) \tag{1.2}$$

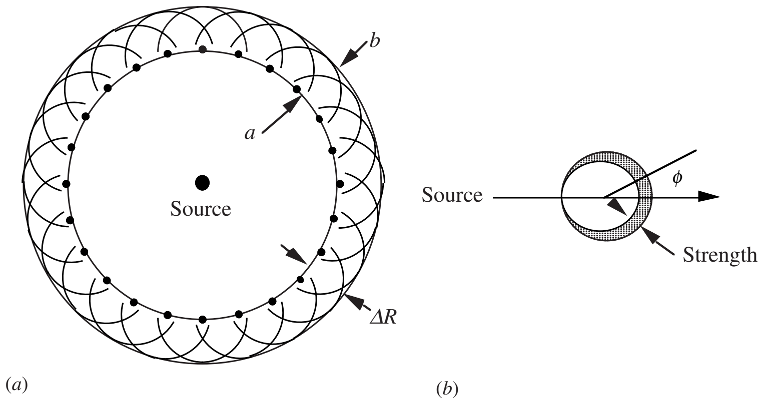

Fig. 1.3. Huygens wavelet construction for a pulse. (*a*) Points on a previous pulse wave front at "*a*" are the sources of wavelets whose envelope becomes the new wave front, "*b*." The wave front thereby moves from *a* to *b*. (*b*) The dependence of wavelet strength on propagation *direction*, is shown by shadowing. The analytical description of the dependence on ϕ, (1.4) is called the Stokes obliquity factor.

Solving for the intensity at R, one gets

$$i_R = \frac{i_0 R_0^2}{R^2} \tag{1.3}$$

The sound intensity decreases as $1/R^2$ due to spherical spreading. Later, in Section 1.5.3 "Near field and far field approximations," we will show that the sound intensity is proportional to the square of the sound pressure. Therefore, sound pressure decreases as $1/R$ in a spherically diverging wave. We would have had the same result if the sphere at the origin had imploded instead of exploded. Then a *rarefaction* pulse, a propagating region of density less than the ambient value, would have been created.

1.3 Pulse wave reflection, refraction, and diffraction

A useful qualitative description of wave propagation was first given by Christian Huygens, Dutch physicist–astronomer (1629–1695). Huygens proposed that each point on an advancing wave front can be considered as a source of secondary waves which move outward as spherical wavelets in a homogeneous, isotropic medium. The outer surface that envelops all these wavelets constitutes the new wave front (Fig. 1.3).

The sources used in underwater sound measurements are sometimes condensation pulses, for example the shock wave from an explosion. The application of Huygens' Principle to an idealized pulse wave front is particularly simple and physically direct.

Baker and Copson (1950) provided a secure mathematical basis for Huygens' Principle. The concept is extensively used in optics, as well as acoustics. e.g., see A.D. Pierce (1981).