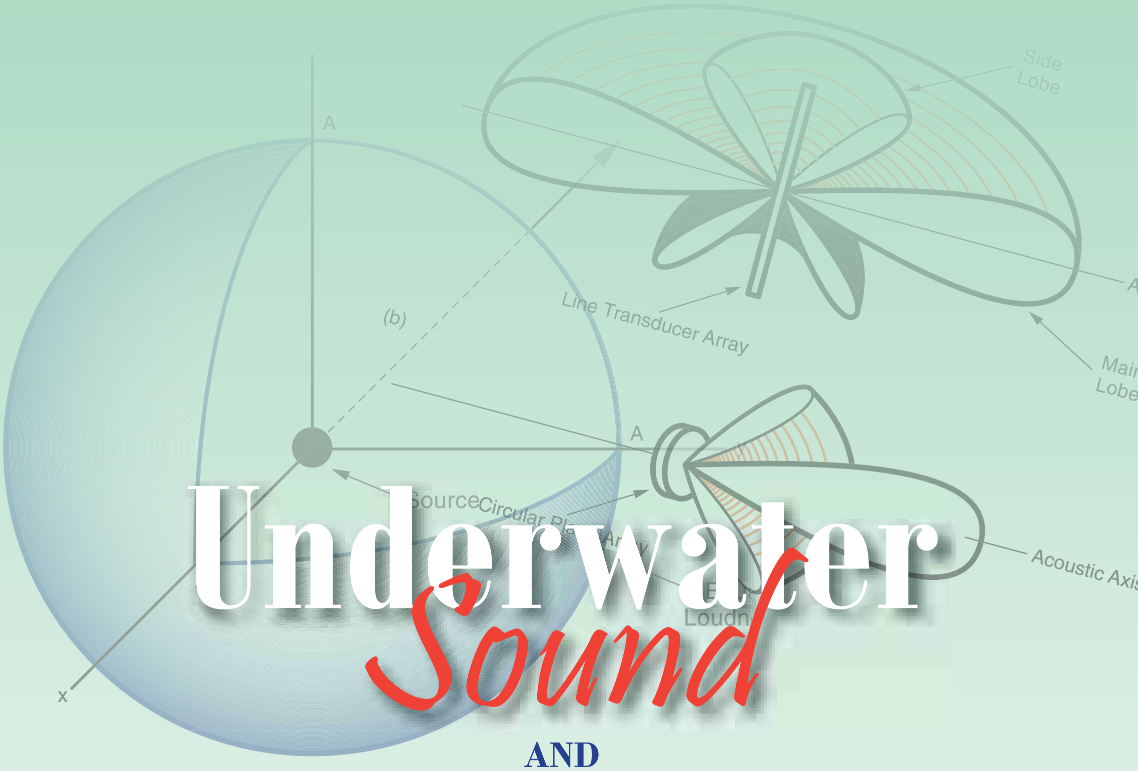

Underwater *Sound*

AND
THE MARINE MAMMAL ACOUSTIC ENVIRONMENT
A Guide to Fundamental Principles

Prepared for the
U. S. Marine Mammal Commission

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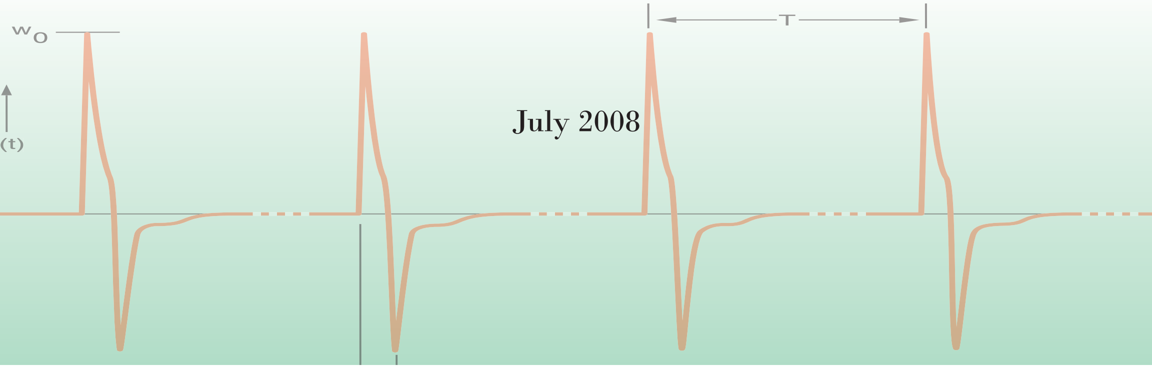

July 2008

UNDERWATER SOUND AND THE MARINE MAMMAL ACOUSTIC ENVIRONMENT

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A NOTE FROM THE COMMISSIONERS

The introduction of human-generated sound into the marine environment began in earnest with the industrial revolution. The potential effects of such sound on marine mammals and ecosystems were not recognized as a concern until the 1970s when studies in the Arctic region indicated that some marine mammal species were responding to activities associated with oil and gas exploration and drilling. Since then, the issue has received increasing attention and been the focus of considerable controversy. The effects of sound and the uncertainty surrounding them are likely to increase in the foreseeable future as human populations grow and human activities in the marine environment increase.

The debate over sound effects has involved persons from various backgrounds and touched on physical and biological subjects that range from relatively straightforward to highly complex. As a result, progress in addressing this potential risk factor has been seriously and frequently confounded by a lack of understanding of sound sources, propagation (or transmission), and reception in the oceans. Assessing and addressing this potential risk factor will require not only rigorous scientific investigation but also an effective working knowledge of sound and its potential effects by sound producers (whether they produce sound intentionally or incidentally), persons responsible for managing sound-producing activities, and persons concerned primarily with their potential effects.

To promote more informed discussion and more effective management of sound-producing activities, the Marine Mammal Commission asked the Acoustical Society of America to prepare a primer on sound in the marine environment. This document is that primer. It was written by David Bradley and Richard Stern and illustrated by Kevin Fox. They have done an outstanding job of explaining complex subjects without using excessively technical language. They worked closely, patiently, and graciously with Commission staff to provide a guide to this subject that will help avoid the confounding effects of misunderstandings regarding sound in the marine environment. We gratefully acknowledge their steadfast efforts to facilitate a more informed discussion of this challenging issue.

PREFACE

This is a primer on the physics of underwater sound as it applies primarily to marine mammals. It was requested by the Marine Mammal Commission to provide a text that will be easily understood by individuals who do not necessarily have a background in science or mathematics but who are familiar with or concerned about issues related to sound and its effect on marine mammals. The material in the book covers both basic and advanced acoustics but at a conceptual level, rather than in a detailed mathematical manner.

The field of acoustics has taken on a new role in today's society. It was not long ago that acoustics was considered a mature science with little yet to be discovered. However, sound and its effects have recently begun to have more of an impact on the world's thinking. Although the physical effects of sound may be subtle, they are complex and can significantly influence the behavior and well-being of living animals. They can potentially lead to behavior modification, tissue damage, injury, and, in the extreme, death.

Some very general characteristics of sounds are that they—

- are easily generated
- travel
- are everywhere
- can be caused by non-living phenomena (rain), biological, non-human sources (e.g., invertebrates, fish, marine mammals), and anthropogenic (human-generated or caused) sources (e.g., shipping, oil and gas production, sonar),
- can do both good and harm
- can cause effects that are costly, both in dollars and impact on the environment of all living creatures
- can be controlled, but mistakes are often irreversible and
- may raise concerns that are both politically and emotionally charged

If the creation of sound and its effects are to be controlled, it must be done with vision, intelligence, knowledge, and sensitivity to all that may be affected.

This primer begins with an explanation of some of the fundamental principles and definitions of acoustics and a description of the ocean's acoustical environment. A guide to the generation and propagation of sound follows. The primer concludes with some observations about human and marine mammal hearing and potential issues. A glossary is also included as a further aid.

The primer was written to prevent conflict among the many stakeholders who need the oceans and are struggling to find equitable solutions that address complex issues. Any misconception as to the meaning of a word or a concept may lead someone down the wrong path. The primer is meant to prevent its readers from accidentally straying.

Anthropogenic sounds (human-generated or caused) can be controlled with laws and technology that are determined by decisions made by those who have been empowered to do so. However, intelligent individuals can make poor and costly decisions if they do not truly understand the physical concepts involved with the issues. We hope that this primer will provide readers who do not necessarily have a background in acoustics with the tools necessary to understand acoustical principles and, on behalf of marine mammal populations, make careful decisions.

CHAPTER 1

FUNDAMENTAL PRINCIPLES AND DEFINITIONS

WHAT IS SOUND?

Sound is a mechanical disturbance that moves through a material. Sound occurs at a place in a material where some mechanical property of the material has changed from the material's average value and changes with time. Figure 1 illustrates a disturbance in air. The disturbance is an increase and decrease in air pressure (a mechanical property of the air) from the air's average pressure value that changes with time. The disturbance is also moving in the air itself. If a person (with an eardrum) is located in the path of the moving disturbance before it actually gets there, the air pressure on both sides of the eardrum is equal, and the eardrum does not move. When the disturbance arrives at the eardrum, and if the air pressure on the outside of the ear has increased above

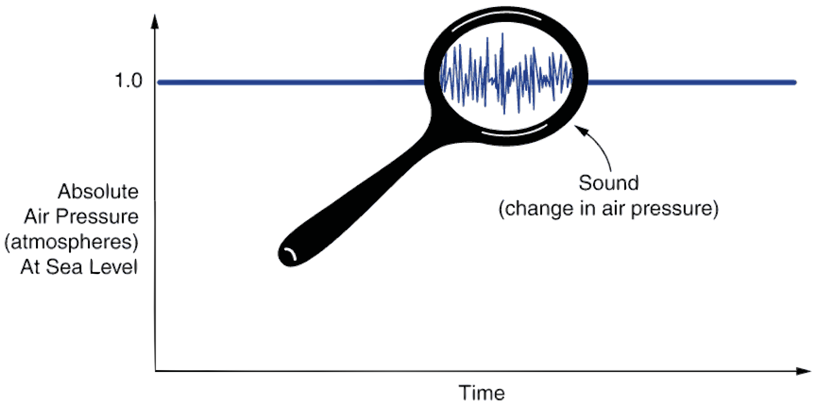


Figure 1. Absolute air pressure at sea level is 1.0 atmosphere. The change in absolute pressure for conversational speech is about ±0.0000002 atmospheres.

the equilibrium value, it pushes the eardrum in. When the air pressure on the outside of the ear decreases below the equilibrium value, the air on the opposite side of the eardrum pushes the eardrum out. The back-and-forth motion of the eardrum is mechanically sent to sensors in the ear where an electrochemical signal is generated and sent to the brain. The person "senses" the movement of the eardrum. The "mechanical disturbance," called sound, is the increase and decrease of air pressure with time as it moves through the air. The person senses only the motion of the eardrum caused by the changes in air pressure. For sound just at the threshold of hearing, the eardrum moves only about one-tenth the diameter of a hydrogen molecule. The sensing of the motion of the eardrum is called hearing. Thus, the answer to the oft-asked question, "If a tree falls in the forest and nothing is there to hear it, does it make a sound?" is "yes." It makes a sound (it creates a disturbance in the air) even though nothing hears it (because there is no eardrum to move).

The example just described for air can be extended to include water. If a pool of still water is examined, the water doesn't seem to be moving at all, yet the individual water molecules are actually moving extremely fast, in every direction randomly, with an average velocity of about zero. (The same thing was actually happening in the air.) If a source of sound is present in the pool, a small volume of the water may be found moving back and forth much like the air disturbance. If a hydrophone (an underwater mechanical sound receiver that detects changes in pressure as a microphone does in air) were placed at that location, the hydrophone would generate electrical signals that indicate the presence of sound. In air or in water, the sound may simultaneously contain both useful information (called a signal) and useless information (as defined by the listener) called noise. A measure of the signal divided by a similar measure of the noise is appropriately called the signal-to-noise ratio and is often used to quantify the quality (or usefulness) of the signal.

Sound can take on an amazing variety of forms—from the pleasant tone of a harp to the roar of a jet engine and from the vocalization of a humpback whale to the blast of an underwater seismic explosion such as often used in oil exploration.

ACOUSTICAL PARAMETERS

When acousticians describe sound in ways that can be quantified, they use terms such as pressure, particle velocity, density, and intensity, usually preceded with the word *acoustic(al)* or *sound*. Every one of these terms describes either a mechanical property of the material through which the sound is traveling or the flow of mechanical energy. The terms used most often throughout this primer are acoustic pressure, acoustic speed (or velocity of sound), and acoustic intensity.

Pressure

At sea level, undisturbed air exerts a steady pressure of about 10,335 kgf/m^2 (14.7 lbsf/in^2, usually written as 14.7 psi because "lbsf/in^2" stands for pounds of force per square inch) that can be measured with an air pressure gauge (such as a barometer). When a sound is created, the measured air pressure at the disturbance will be both different from undisturbed air pressure and changing with time. The change in air pressure due to the presence of the sound is called the acoustic pressure. The disturbance and its movement can also result in a force being applied to the surrounding material (as in the case of the eardrum). If the disturbance applies a force and moves something, the disturbance is doing work and thus contains (and carries) energy. The acoustic pressure is analogous to an extended or compressed spring. It has potential energy and has the ability to do work (that is, to move something).

Particle velocity

Any change in the average mechanical speed of the molecules that make up the disturbance is called the acoustic particle velocity to distinguish it from the absolute speed of any individual molecule or from the speed with which sound travels. The word *particle* is used because the groups of molecules that compose the disturbance behave like packets of particles. The acoustic particle velocity is analogous to a moving mass. It has kinetic energy and can do work. Both the potential energy (from the pressure) and the kinetic energy (from the coordinated movement of the molecules) contribute to the total energy contained in the disturbance.

Density

Looking closely at the region that comprises the disturbance will show that groups of molecules are packed tighter (or looser) than those of the average surrounding region. When this occurs, the density of the group (mass or molecules per unit volume) is said to be higher (or lower) than the average density of the surrounding region.

Intensity

Because energy is carried by the disturbance as it moves through the material, one may ask, "How much energy passes by in a second?" The energy (measured in joules) that passes by in a second is called the power (watts, or joules per second) and that power, spread over a unit area (such as a square meter), is called the acoustic intensity (watts per meter squared). (Note that the definition for acoustic intensity is exactly the same as the definition for electromagnetic intensity such as is used for light, radio signals, and X-rays. It is the total energy that is spread over a unit area, such as a square meter, that passes by every second.)

AMBIENT (BACKGROUND) CONDITIONS

When sound is not present in a local region, the values for acoustic pressure and acoustic intensity in that region are zero. For seawater, the temperature might be 13°C (55°F) and the density would be about 1,026 kilograms per cubic meter (kg/m^3). For air at 20°C (68°F), the density would be 1.21 kg/m^3. However, neither the ocean nor the atmosphere is ever totally quiet. There is always some background sound. For the purposes of this primer, ambient acoustic conditions are considered to be the time-averaged background sound in a local region.

HOW DOES SOUND TRAVEL?

Because sound is a mechanical disturbance, it is necessary that there be some medium or material to be disturbed. That is, sound happens when a material is disturbed and both the disturbance and the energy associated with the disturbance travel through the material. The process of sound travel is referred to as sound propagation whether it occurs in a fluid material (such as air or water) or a solid material (such as steel or the earth). If there is no material to be disturbed (as in outer space), there can be no sound. Sound cannot exist in a vacuum. It is important to realize that only the sound (disturbance) travels, not the material. The material only moves back and forth.

If a disturbance is created (that is, the acoustic pressure or acoustic particle velocity is caused to change at some location), then that disturbance acts on (pushes) the surrounding material and causes it to be disturbed. The surrounding material, in turn, disturbs further surrounding material, and the process continues until the disturbance is so weakened or spread out that it is no longer discernable from the ambient noise. In two dimensions, the process is like waves spreading out from a rock thrown into a still pond. The speed with which the disturbance travels is called the velocity of sound. Again, sound is a moving or traveling phenomenon, not a stationary one. Sound travel (propagation) is discussed in detail in chapter 4.

TIME, SPACE, AND INFORMATION

The parameters described so far are those that characterize the physical properties of sound. However, sound may contain information created by the source of the sound (e.g., speech). Information can also be contained in the behavior and speed of the sound as it travels through a material. To understand how information may be carried by sound, the concepts of period, frequency, wavelength, and phase must be considered. These concepts involve both time and space.

The sine wave

Figure 2 illustrates the use of a sine wave (a mathematical function) to describe the strength of a disturbance at a given location as time passes (perhaps where a hydrophone or microphone is located). Scientists and mathematicians usually evolve theories from models with which they feel most comfortable (and think that they understand), and the use of the sine wave pattern to describe changes in physical and mathematical properties has become favored over other waveform

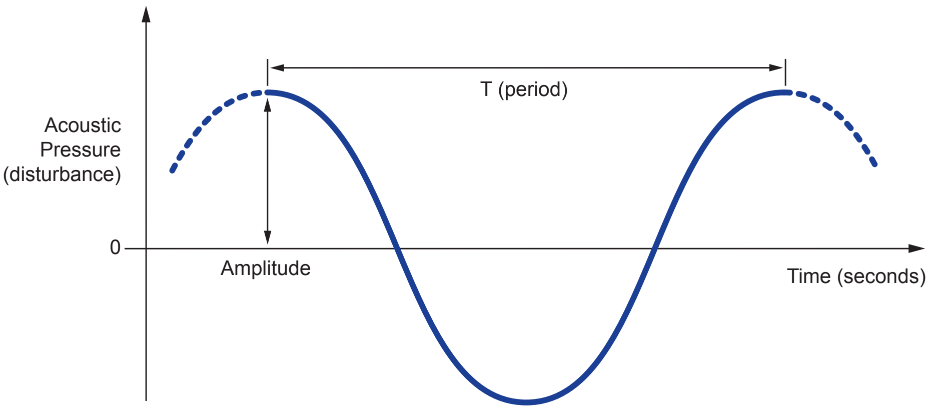


Figure 2. Acoustic pressure (disturbance) measured by a hydrophone in water at one location as a function of time. This particular disturbance varies according to a mathematical function called a "sine wave." The acoustic pressure increases and decreases about the absolute pressure. The ambient background noise is assumed to be zero. The spacing between repeated times is called the period (T). The maximum change is called the amplitude.

models. This is actually not by accident. It is a cyclic waveform (that is, it repeats a pattern over and over again) and can be derived from a circle. It is also taken from nature (e.g., the movement of a pendulum or the ripples produced in a still pool of water by a dropped stone). It is incredibly easy to generate and often hard to eliminate. Most important, sine waves can be combined mathematically to represent other waveforms, including complex waveforms such as human speech, an explosion, a symphony, or the echolocation click of a porpoise or bat.

Natural extensions to the concept of a sine wave are that they may be—

- *continuous* – a virtually never-ending sine wave (see Figure 3a)
- *pulsed* – a single sine wave of short duration or a set of few repeated sine waves of short duration (see Figure 3b)
- *complex* – a sum of sine waves of different frequencies, amplitudes, and phases (see Figure 3c)

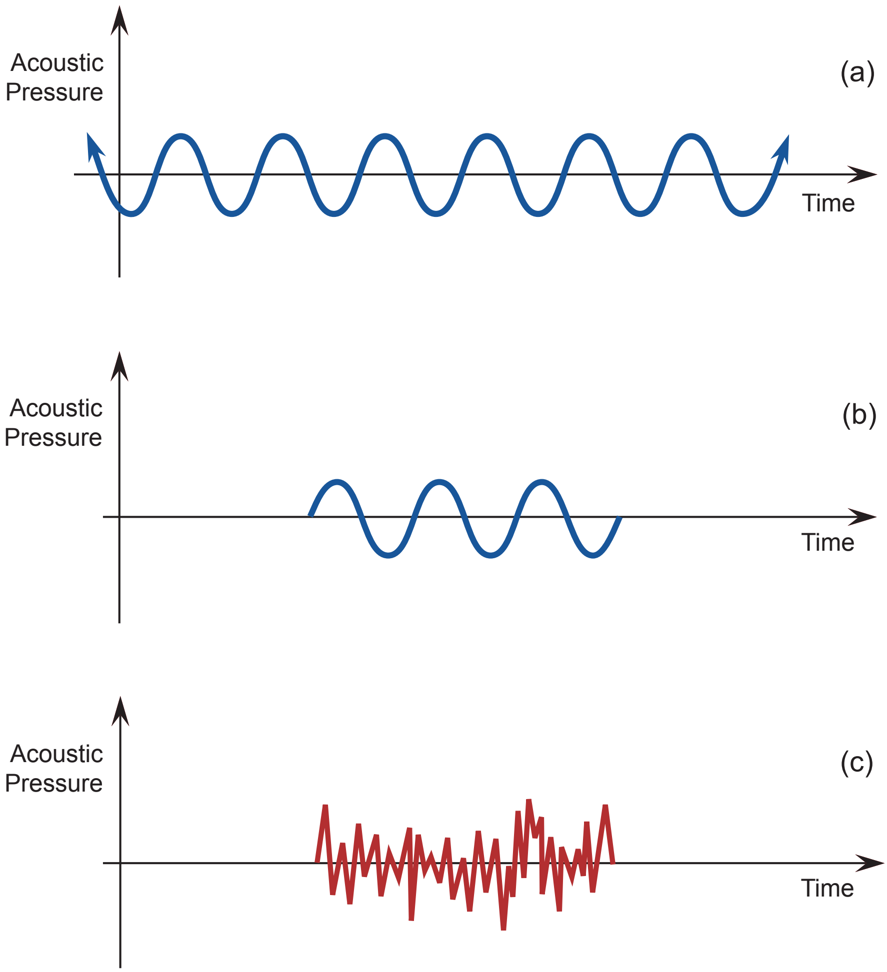


Figure 3. A portion of a continuous sine wave (a), a pulsed sine wave consisting of three periods (b), and a complex wave (perhaps speech) of short duration (c).

Figure 2 shows the acoustic pressure (remember that this is the change in pressure) rising and falling above and below the ambient pressure that is assumed to be zero. The acoustic pressure even at its maximum value is actually very low compared with the absolute pressure measured (for example, with a barometer) without sound. In air under standard conditions (i.e., in a room), the acoustic pressure where sound can barely be heard is less than about one-billionth of the absolute pressure. At its painful loudest, it is still only about one-thousandth of the absolute pressure. The maximum value of the acoustic pressure (or any acoustic parameter) for a sine wave is called the amplitude. The maximum value for a complex wave is often called its amplitude or, more correctly, its peak pressure or peak velocity.

Period and frequency

If we stand in one location with a stopwatch and a sound receiver (called a microphone in air, a hydrophone in water, or a transducer in either material) and measure the smallest increment of time for which the sine wave repeats itself, that time is called the period. The units of period (T) are seconds (s). For example, if the time between repeated waveforms is one-fifth of a second, then the period of the acoustic pressure wave is one-fifth of a second. Frequency (f) is defined as the number of periods per second that occur and its units are called Hertz *(*Hz*)*. Thus the frequency of a sound with a repeated pattern of 5 waves per second is 5 Hz. (Note that frequency is the reciprocal of the period: 1 divided by the period [f = 1/T].)

Wavelength

If, instead of standing in one location and measuring the repetition with a stopwatch, we measure the smallest increment of distance for which the sine wave repeats itself, that distance is defined as the wavelength, λ (the Greek letter, lambda) as shown in Figure 4. (Remember that the sound is traveling so the acoustic pressure varies over and over again in space as well as in time.) The units of wavelength are meters.

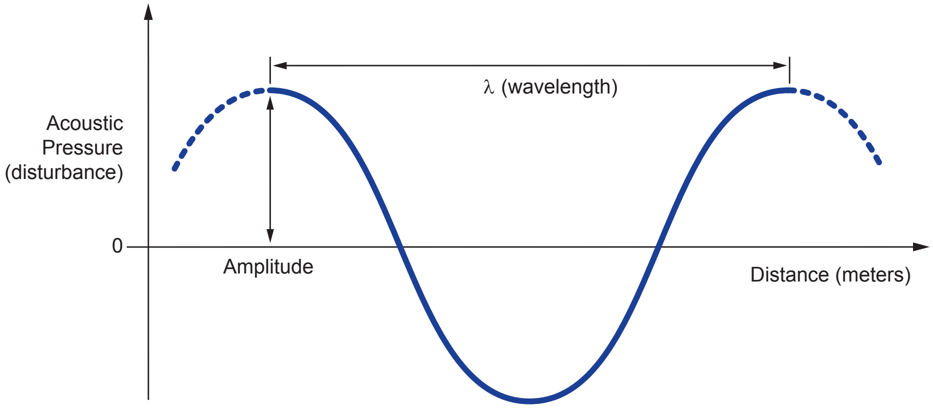


Figure 4. Acoustic pressure (disturbance) measured by a hydrophone in water at an instant of time as a function of distance. The spacing between repeated distances is called the wavelength (λ).

Speed of sound

Using this example, a simple, but important relationship in acoustics can be found. If the period is one-fifth of a second as specified earlier, the distance that the sound travels during each period is the wavelength and therefore the sound travels 5 wavelengths in a second. But this is also the definition of the acoustic velocity or speed of sound (how fast the sound travels in one second). The simple but important relationship is that the frequency, when multiplied by the wavelength, gives the velocity or speed of sound ($f\lambda=c$) where c represents the velocity of sound. The velocity is slower in air (about 340 m per second) than it is in water (about 1,500 m per second). Examples of the magnitude of frequency, wavelength, and period for both air and water are shown in Table 1.

Table 1. Typical values of acoustic parameters in air and water (sound speed in air = 340 m/s, sound speed in water = 1,500 m/s)

Description	Very low	Low	Medium	High	Very high
Frequency (Hz.)	10	100	1,000	10,000	100,000
Period (s)	.1	.01	.001	.0001	.00001
Wavelength (air)	34 m (111 ft)	3.4 m (11.1 ft)	34 cm (13.4 in)	3.4 cm (1.34 in)	.34 cm (0.13 in)
Wavelength (water)	150 m (492 ft)	15 m (49.2 ft)	1.5 m (4.92 ft)	15 cm (5.90 in)	1.5 cm (0.59 in)

Phase

An additional parameter that must be considered when discussing space and time is called phase. This parameter compares the difference in the starting time of two or more identical sine waves and is extremely important. For example, if two identical sound waves (same frequency and amplitude) are added together when both start at the same time in their cycle and at the same place and are traveling in the same direction, they are said to be in phase. They will add constructively and produce a sound that is the sum of the two. If these two waves are added together with one wave beginning exactly halfway through the cycle of the other, they are said to be 180 degrees out of phase. They will also produce a sound that is the sum of the two; however, the addition will be destructive and the signals will be canceled, resulting in no sound. Two acoustic pressure waves are compared in Figure 5. The phase between them is shown as the difference between the two waves at the same point on each wave. Phase is measured in degrees or in radians, where 360 degrees (360^o) equals 2 pi radians (2π radians) for one complete cycle. The size of pi is about 3.14.

DIMENSIONAL UNITS AND THE DECIBEL

Acoustics is both an art and a science. Scientists talk, argue, debate, and sometimes yell at one another about many issues, but they all agree on the units of the various properties of sound. They agree because the units are part of the language of science, a language that demands accurate, consistent, and

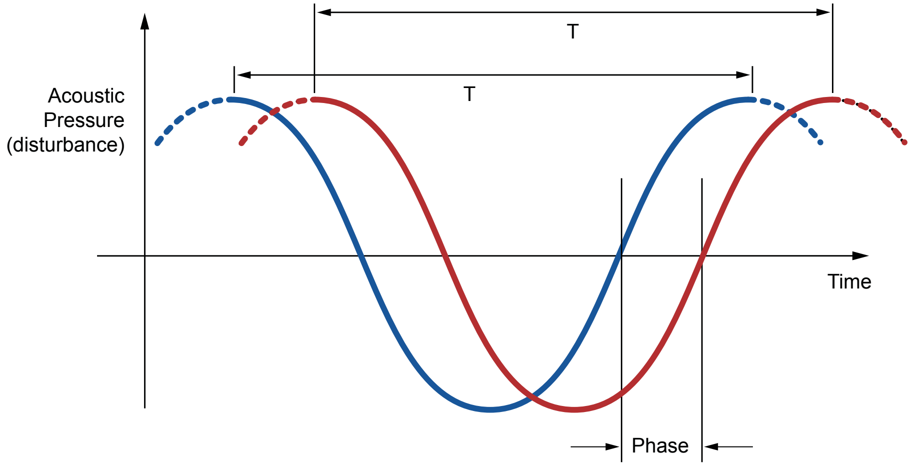


Figure 5. Comparison of the phase of two acoustic pressure waves of equal amplitude and frequency. Each curve can be visualized as "spread-out circles." Each period (T) can then be thought of as containing 360 degrees or 2 π radians (the number of degrees or radians, respectively, in a circle). The time difference between the two waves, called phase, is usually expressed in degrees. In this example, the phase is about 20 percent of the period (about 20 percent of 360 degrees), or 72 degrees. Because the blue curve reached its maximum amplitude first, followed by the red curve a short time later, the phase difference is usually stated as "the blue curve is leading the red curve by 72 degrees."

correct descriptions of the property being discussed. Table 2 summarizes the units used in this book. Its basis is called the MKS (meter, kilogram, second) system. It is how scientists describe units of distance, mass, and time.

Table 2. Dimensional properties and units commonly used in acoustic research

Property	Unit
Length	Meter
Time	Second
Mass	Kilogram
Force	Newton = (Kilogram)(Meter)/(Second)^2
Density	Kilogram/Meter^3
Velocity	Meter/Second
Pressure	Pascal = Newton/Meter^2 = Kilogram/(Meter)(Second)^2
Energy	Joule = (Kilogram)(Meter)^2/(Second)^2
Power	Watts = Joules/Second = (Kilogram)(Meter)^2/(Second)^3
Intensity	Joule/(Second)(Meter)^2 = Watts/(Meter)^2 = Kilogram/(Second)^3

The values of the different parameters found in the study of acoustics vary over a very wide range. For example, audible intensities range from the very quiet values (10^{-12} watts/m^2) to the deafening (10 watts/m^2), a difference of 13 orders of magnitude. Because of this wide range, it is often easier to use logarithms to describe data or values. Table 3 will both refresh one's memory and illustrate the convenience of logarithms. One can quickly see that instead of working with numbers from 0.01 to 10,000 one can work with numbers from –2 to +4 (the value of the exponential [i.e., the superscript]) without loss of information. Logarithms are easy to use, convenient to graph, and match, to a great extent, the way the ear hears.

Table 3. Logarithmic compression of a number. Exponents and logarithms in red may be substituted for the number without loss of information.

Number	Number expressed as a power of 10	Logarithm (base 10)
.01	10^{-2}	-2
.1	10^{-1}	-1
1	10^{0}	0
10	10^{1}	1
100	10^{2}	2
1,000	10^{3}	3
2,000	$10^{3..3}$	3.3
10,000	10^{4}	4

The use of logarithms to describe acoustic properties came into play in the 1920s when routine measurements of acoustic properties became practical. Investigators tried various methods to compress the wide range of acoustic values into a smaller, more convenient range, without loss of information. In 1924 the International Advisory Committee on Long Distance Telephony was organized in Europe and representatives from the United States attended. At those meetings, the term "Bel" (named in honor of Alexander Graham Bell) was suggested as the unit in logarithmic base 10 for expressing power. Scientists in the Bell System had earlier introduced a "sensation" unit that was identified to be one-tenth of a Bel, hence the unit decibel (dB) was introduced (deci = 1/10). Its widespread adoption outside the Bell System can be attributed to the prominence of the Bell System scientists and the convenience of logarithms as a scale compression method.

SOUND PRESSURE AND INTENSITY LEVELS

Scientists often measure physical parameters, such as those used to characterize sound, in absolute values. However, such values often are not particularly intuitive and also are cumbersome to work with mathematically.

To get around those problems, scientists frequently convert or transform their measurements to reference values that are easier to intuit and manipulate. For sound pressure and intensity, the transformation involves dividing the absolute value by a reference value, and then taking the logarithm (base 10) of the result. If the absolute value and the reference value are the same, then the dividend is one and the logarithm of one—the new number—is zero. (Remember from Table 3, 10 raised to the zero power is one.) In effect, this transformation does not change anything except the value that is called zero, but it results in numbers that are easier to think about and manipulate. The new number created by the transformation is referred to as a level, such as sound pressure level or intensity level. For example,

$$\textit{intensity level (dB)} = 10\log_{10}\textit{(sound intensity/reference intensity)}$$

Note the factor (multiplier) of ten in the definition of intensity level. This occurs because the intensity level is given in decibels rather than bels.

Because intensity happens to be proportional to the square of the sound pressure, this equation can also be written as follows:

$$\textit{intensity level (dB)} = 10\log_{10}\textit{(sound pressure}^2\textit{)/reference sound pressure}^2\textit{)}$$

where the constant of proportionality cancels out of the numerator and denominator. Using algebra, this equation can be simply written as

$$\textit{intensity level (dB)} = 20\log_{10}\textit{(sound pressure/reference sound pressure)}$$

The intensity level (dB) and the sound pressure level *(dB)* are defined to have the same value by using appropriate values of reference.

SOUND LEVELS IN AIR VERSUS WATER

Comparing sound pressure levels in air and water can be confusing because different reference pressures are used for the same absolute value of sound pressure. Because the reference value is arbitrary, air acousticians decided that the reference pressure should be about the limit of human hearing for a sound with a frequency of about 1,000 Hz. That limit is about $20\text{x}10^{-6}$ Newtons/m^2. Recall from Table 2 that Newtons are a measure of force, so that the units Newtons/m^2 describe force exerted per area (or pressure). One Newton/m^2 is called a Pascal (Pa) and 10^{-6} Newtons/meter^2 is called a microPascal (μPa).

Unfortunately, the underwater acousticians (who are known to be all wet anyway) had their own idea of a reference. (They actually used three references for a while until they settled on one.) For underwater work, the reference value for acoustic pressure is 1 μPa. The two reference values, $20\text{x}10^{-6}$ Newtons/m^2

for air and 1×10^{-6} Newtons/m^2 for water, have led to misunderstandings and misinterpretations outside the acoustics community.

The difference (of about 26 dB) between the sound pressure levels expressed by an acoustician using an air reference pressure and those expressed by an acoustician using a water reference pressure for the exact same acoustic pressure can be compared by inserting their respective reference pressures in the following equation:

$$\textit{difference}\ (\text{dB}) = 20\log_{10}\ (\textit{air reference pressure/water reference pressure}) = 26\ \text{dB}$$

Thus, care must be taken to interpret correctly the absolute value of acoustic pressure from readings given in decibels. It is of the utmost importance that the reference pressure be stated.

Table 4 provides the reader with a list of some common sounds and the typical sound pressure level that might be read on a sound-level meter (a device used to measure sound pressure level consisting of a microphone, an amplifier, filters designed to match human hearing, and a visual indicator) that has been calibrated to establish 0 dB at 20 μPascals (air reference pressure).

Table 4. Examples of sound-pressure levels in air. (Source: M.C. Liberman, unpublished presentation to the Committee on Potential Impacts of Ambient Noise in the Ocean on Marine Mammals, Ocean Studies Board, National Research Council, Woods Hole Oceanographic Institution, June 2001)

Example	Sound-pressure level (dB re 20 microPascals (air)
3 meters from a jet engine	127
Threshold of pain	117
Rock concert	107
5 meters from an accelerating motorcycle	97
2 meters from a pneumatic hammer	87
Noisy factory	77
Vacuum cleaner	67
Busy traffic	57
2-person conversation	47
Quiet restaurant	37
Residential area at night	27
Empty movie house	17
Rustling of leaves	7
3 meters from a breathing human	-3
Hearing threshold for a person with acute hearing	-13

POINTS TO REMEMBER

Sound is a mechanical disturbance that moves through a solid, liquid, or gas. Sound does not exist in a vacuum. Hearing is sensing the motion of an eardrum or an equivalent organ. Sound may contain information that is useful (a signal) or not useful (noise). The most common parameters that describe sound are acoustic pressure, intensity, and speed. The sine wave is a mathematical function that is commonly used to describe the changes in acoustic parameters. Associated with the sine wave are the concepts of frequency, period, wavelength, and phase. The strength of most acoustic parameters is described by the decibel (dB), a dimensionless unit. Sound pressure levels (in dB) in air versus water must be compared carefully because they are based on different reference levels.

CHAPTER 2

THE OCEAN ENVIRONMENT

GEOGRAPHICAL AND PHYSICAL PROPERTIES

The geographical and physical properties of the ocean have great influence on the generation and propagation of sound in the marine environment. Of the total surface area of the earth (approximately 200 million square miles, or 510 million square kilometers), the oceans and seas make up 70.8 percent and land the remaining 29.2 percent.

Figure 6 provides a view of the earth's surface with the major oceans and seas noted. The figure, a two-dimensional representation of a three-dimensional surface, distorts reality. The average height of all land masses is 840 m (2,757

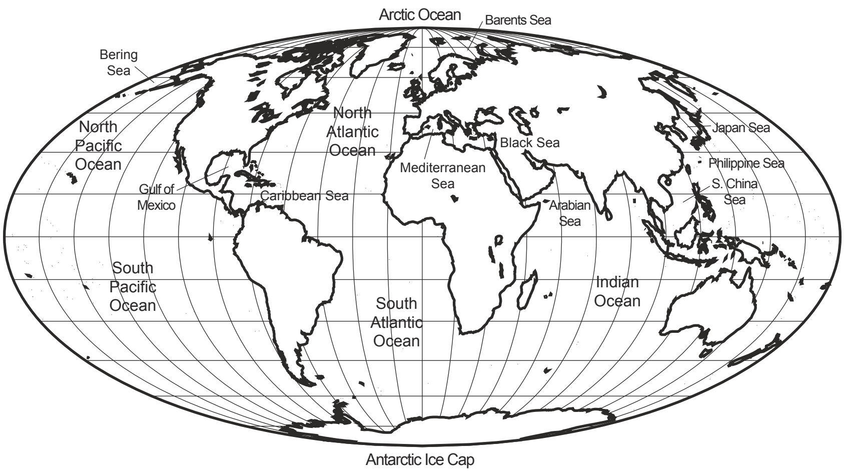


Figure 6. The earth's surface indicating the major oceans and seas. The figure is distorted because it is attempting to display a three-dimensional object on a two-dimensional surface. (Source: Gross and Gross 1996; reprinted by permission of Pearson Education, Inc., see Further Reading)

ft) and the average depth of the oceans and seas is 2,800 m (12,460 ft, or more than two miles). The world's oceans range in temperature from about -4°C (24.8°F) to about 30°C (86°F). The salt content, measured in parts per thousand (ppt), ranges from 33 ppt (3.3 percent) to 38 ppt (3.8 percent). The pressure in the ocean increases approximately 1 atmosphere (1 bar or 14.7 psi) for every 10 m (~33 ft) of depth, leading to a pressure of about 1,100 atmospheres in the deepest locations.

THE OCEAN'S BOUNDARIES

The air–ocean surface interface is influenced largely by the wind and can range from flat (sea state 0) to the mountainous seas caused by severe storms (sea state 6). The surface is extremely dynamic and contributes significantly to the variability of the marine environment. The other interface, the ocean–seafloor, is relatively stable over time. Its movement depends on local water currents and occasional seismic activities. There are exceptions to this such as undersea volcanoes and mud slumps, attributed to the buildup of seafloor material into unstable slopes, that are similar to terrestrial rockslides. The surface interface usually consists of air and water (and, in some places, ice and water); the bottom interface consists of water and materials that range from mud of all viscosities to knife-edged hard coral and volcanic rock. It should be mentioned that there are also internal boundaries within the volume of the ocean that are important to the propagation of sound, such as locations where the temperature or salinity varies abruptly. The ocean's volume over large, deep ocean basins is often called the blue water ocean. A shallow region near the water-land boundary is called a littoral zone (or if close to land, a surf zone). The littoral zone comprises about 15 percent of the oceans and seas. Although marine mammal habitats and environments are not always precisely defined, the littoral zone plays a very important role in the life of many marine mammals. It is where the dynamics of the ocean are accentuated; it is the region where many species of marine mammals are likely to occur; it is where humans and marine mammals are most likely to meet; and it is where the effects of underwater sound have the greatest variations.

EXPECTED VALUES AND VARIATIONS—A CAVEAT

Throughout this primer, acoustical, physical, and other scientific variables will be assigned values and attributes. In general, these values and attributes describe "average" conditions under ordinary circumstances. It is important to understand that our physical planet is a dynamic entity that obeys the laws of causality. The values and attributes given to the variables described here should be considered to be what usually can be expected to be found if the variables were to be measured or described.

VARIATION OF THE SPEED OF SOUND IN THE OCEAN

The velocity of sound is one of the most important physical properties used to characterize the behavior of sound. Even if an “average” ocean is considered (that is, an ocean that reflects typical variations in the speed of sound), a very complex sound speed profile exists that varies with location (latitude and longitude), depth, and time. All three spatial dimensions (latitude, longitude, and depth) as well as the fourth dimension, time, can challenge the oceanographer and acoustician in establishing the speed of sound at a given location in the ocean at a given time. Near the surface, for example, ocean dynamics and solar heating strongly influence temporal and spatial variations of the speed of sound.

The variation of the speed of sound depends on three physical parameters. Temperature is most important, followed by salinity (salt content) and depth (pressure). Table 5 provides a good rule of thumb for calculating the variation for each parameter. Given accurate data describing these three parameters as a function of location and time, the speed of sound can be calculated.

Table 5. Approximate sound speed variations as a function of temperature, salinity, and depth. (Source: Urick 1983; reprinted by permission of The McGraw-Hill Companies; see Further Reading)

Sound speed dependency	Coefficient
Temperature	+ 4.6 m/s per °C (+ 5 ft/s per °F)
Salinity	+ 1.3 m/s per ppt (parts per thousand) (+ 4 ft/s per ppt)
Depth	+ 0.016 m/s per m (+ 0.016 ft/s per ft)

Sound velocity profile

A graph of the speed of sound at various depths in the ocean is called the sound velocity profile (SVP) and the variation of the sound velocity plays a major role in predicting the path that sound takes as it travels through the ocean. Figure 7 is an example of a typical sound velocity profile in the blue water ocean. Near the surface, in the region called the surface layer, there is little change of sound velocity with depth. This is because the ocean water in this region is constantly “mixed” by waves due to the ocean’s surface dynamics. The mixing keeps surface layer water temperatures relatively uniform with depth. A little deeper, in the region called the seasonal thermocline, the temperature may drop quickly to meet the more stable, slowly decreasing temperature of the main thermocline. The sound velocity follows the temperature profile and decreases proportionately and then levels off. Below this depth, the temperature is relatively constant and stable; hence, this region is called the deep isothermal layer, the layer of constant temperature. Within this layer, the salt content is essentially not changing, and the sound velocity follows a steady increase with depth (pressure).

It should be noted that at locations where there are sharp changes in sound velocity profile, there usually are changes in the direction of sound propagation. Changes in water density, for example, where freshwater from a river enters the ocean, produce internal boundaries that may actually reflect the sound.

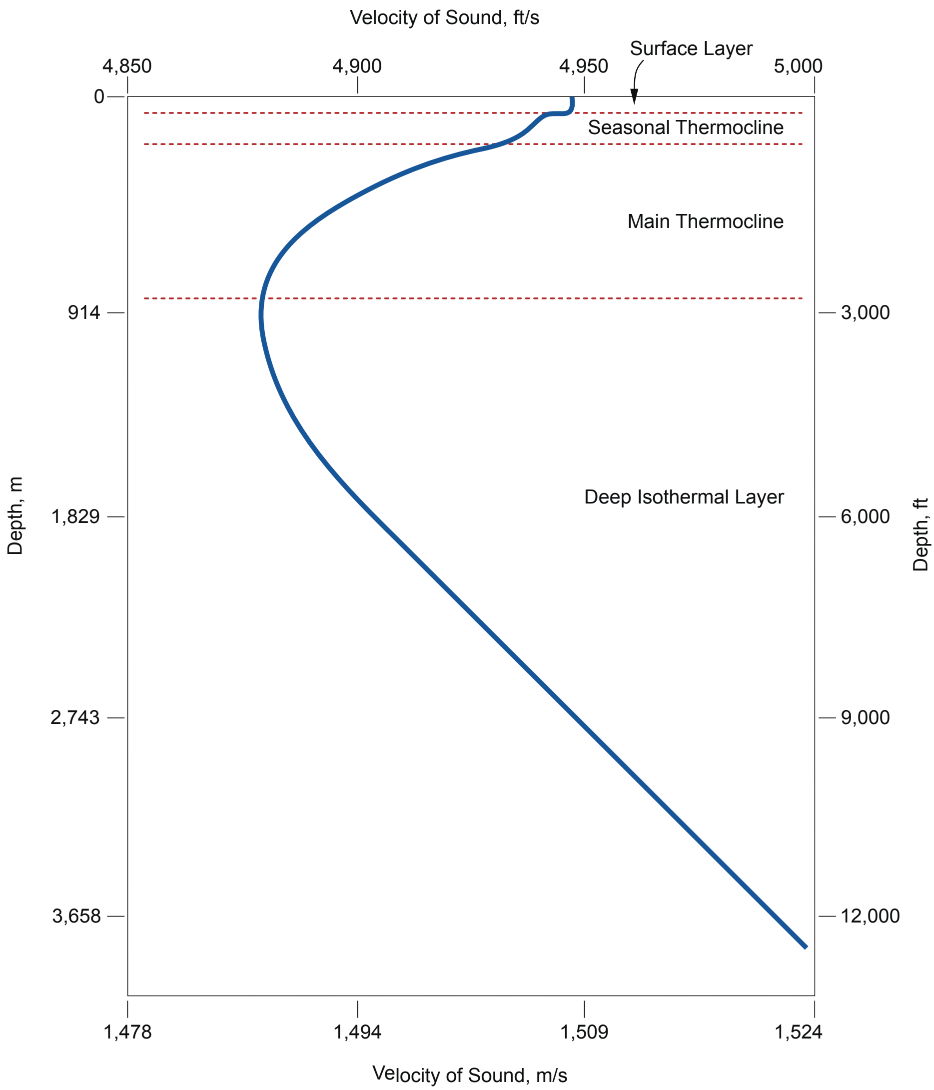


Figure 7. Typical sound velocity profile for the deep ocean. (Source: Urick 1983; reprinted by permission of The McGraw-Hill Companies; see Further Reading)

FREQUENCY SPECTRUM

Suppose that at some location we measured the acoustic pressure by using a hydrophone that converted its mechanical response from a disturbance into an electrical signal whose value was indicated by a properly calibrated meter. This instrument could indicate a number that corresponded to the overall acoustic pressure at the hydrophone. This instrument is called a sound-level meter in Chapter 1. Sound-level meters, although extremely useful, provide only a measure of the overall sound. Most sound-level meters used in air incorporate filters to match human hearing characteristics. Among other characteristics, sounds generally consist of energy at multiple frequencies, and the instrument would be much more useful if it provided the amplitude (or energy) distribution of the sound at every frequency individually. This can be accomplished by placing a variable filter between the hydrophone and the meter that allows only the electrical output of the hydrophone in 1-hertz intervals to reach the meter. A graph of the acoustic pressure in 1-hertz intervals over a range of frequencies is called its spectrum. When the values of the acoustic pressure are compared with a reference value and then converted to decibels, the plot is called its spectrum level. The instrument is called a spectrum analyzer. Often a spectrum analyzer provides too much data for convenient analysis and the output is calibrated to indicate the energy contained in bands of frequencies (usually octaves or one-third octaves). An octave is defined as those frequencies contained between a given frequency and a frequency that is twice as high. For example, middle C on the piano is tuned to about 261.6 Hz. The C above middle C is tuned to twice the frequency of middle C (i.e., about 523.2 Hz). A piano contains eight whole-tones (and twelve half-tones) between the two Cs. Thus the eight whole-tones define an octave. The spectrum analyzer, if set to octave band analysis, will provide a single value that corresponds to the acoustic energy contained in that octave band. The instrument often can be set to provide a measure of the energy in bands that are only one-third of an octave.

NOISE SPECTRUM IN THE OCEAN ENVIRONMENT

The lines or curves shown in Figure 8 (often called the Wenz curves) illustrate some of the noises that marine mammals hear and feel, their source, over what frequency range they occur, and how much noise they contribute to the acoustic environment. Because the sea can be a excellent carrier of sound, and marine mammals live in the sea, they may be exposed to sounds that are generated at great distances as well as locally.

Figure 8 illustrates how noise is distributed with frequency in the ocean. (Noise gets louder at low frequencies.) There may be special frequencies that have exceptionally loud peaks compared with their surrounding frequencies (often called narrowband noise because most of the energy is contained in

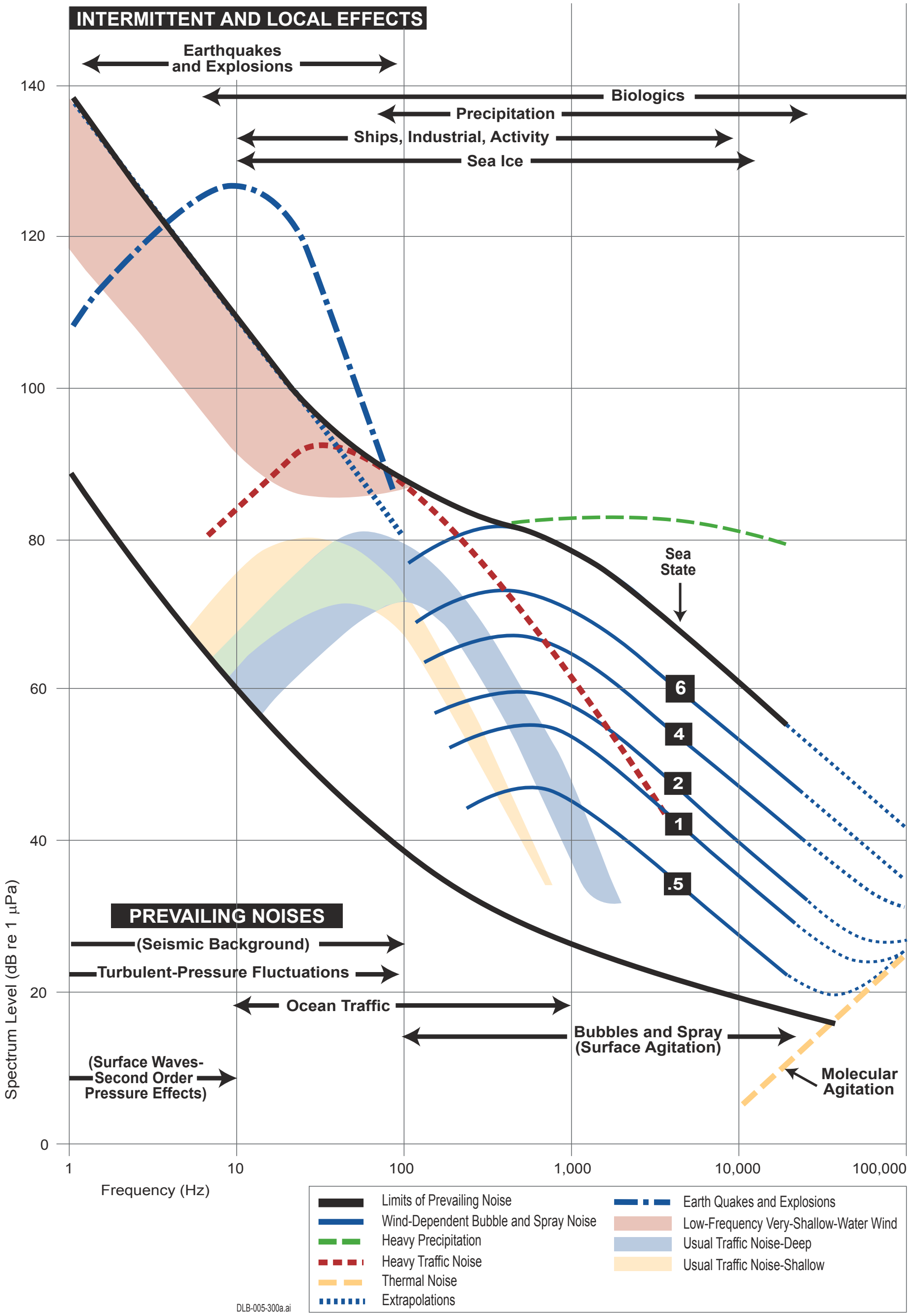


Figure 8. Noise in the ocean extends from less than 1 Hz to more than 100,000 Hz. Values shown are typical spectrum levels and ranges of frequencies for different types of noise. Some of the noises are around most of the time while some occur only intermittently. The oceans are never without noise. (Based on Wenz 1962; reprinted with permission, Journal of the Acoustical Society of America; see Further Reading)

narrow bands of frequencies). When the noise curve is smooth with little or no bumps, it is called broadband noise because the noise is spread over many frequencies. Figure 8 uses 1 μPascal as the reference value, the value for water. The ordinate (vertical axis) is specified as spectrum level (dB re 1 μPascal*)* and the abscissa (horizontal axis) is specified as frequency. Both axes are plotted logarithmically.

Figure 8 is divided into prevailing noises (those noises that are constantly present and that may come from both near and far) and intermittent and local noises. Prevailing noises include contributions from seismic disturbances (earthquakes, volcanoes), turbulent-pressure fluctuations (random motion of the water due to wave movement), ocean traffic (ship movement), surface waves (large-scale raising and lowering of the surface of the ocean due to waves, swells, etc.), and bubbles and spray (surface storms making bubbles and spray that strike the ocean and that increase in intensity with the chaos [i.e., sea state] at the surface). It is interesting that, if all the noise mentioned were gone, there would still be prevailing noise called thermal (or molecular) agitation because water contains molecules that are moving randomly and whose average speed does not always average exactly zero. Notice on Figure 8 that the line labeled molecular agitation prevents the overall spectrum level from getting any lower. On average, humans are not quite capable of hearing molecular agitation.

Intermittent and local noises are sounds that come and go. They are characterized by their time-limited behavior. Intermittent and local noises include contributions from earthquakes and explosions (locally produced), biota (fish, marine mammals, anything that lives in the ocean and makes noise), precipitation (rain, hail), ships, industrial activity (oil drilling, acoustic experiments, sonar), and sea ice (floes striking each other, thermal cracking, etc.).

Figure 8 illustrates that the marine mammal home is never without sound and that it extends from the very lowest frequencies (below 1 Hz) to more than 100,000 Hz. (Some marine mammals generate sound well in excess of 100,000 Hz.) All spectrum levels shown are averages. Note that some portions of the curves have been extrapolated and are not actual measurements.

POINTS TO REMEMBER

The oceans have two interfaces, the air surface and the seafloor. The air-sea surface is dynamic and ever changing. The air-ice surface changes but at a lower rate. The seafloor changes but usually over much longer time scales. The acoustic speed in the ocean varies locally with position (latitude, longitude, and depth) and time. The speed at any point depends on the temperature, the salinity, the depth from the surface at that point, and time. Noise in the ocean may be divided into two categories: prevailing and intermittent noise. The ocean is never without sound that may cover the frequency spectrum from lower than 1 Hz to more than 100,000 Hz.

CHAPTER 3

SOURCES OF SOUND

GENERATING SOUND

Chapter 1 introduced the concept of sound as a mechanical disturbance. We now turn to the subject of the sources of sound and their general characteristics. Consider how we, as humans, sometimes create sounds.

- Impact sounds: the sound of a hammer striking a nail or yelling when a hammer strikes your thumb
- Car sounds: explosions of compressed gas that move pistons repetitively at a precise rate leading to mechanical motor noise, exhaust noise, shifting of gears noise, mechanical linkage noise, and, one hopes, the hiss of tire treads rolling on the road
- Conversational sounds: air flowing over vocal cords that vibrate, with the larynx and mouth shaping the sound into words and sentences
- Musical sounds: strings, reeds, membranes, and resonant pipes that vibrate and are often amplified by electronics and loudspeakers

These are but a few of the vast set of possibilities that contribute to the sounds that surround us—sounds that never seem to cease. Note that every generator of sound moves something (air, metal, liquid, etc.) mechanically. It supplies energy to the medium in which it is embedded and, in most cases, starts the process of sound propagation. If the mechanical disturbance reaches us with sufficient strength, and if it is within the frequency range of our hearing and our hearing processes are not impaired, then our brain tells us that our eardrums are moving and we are hearing a sound.

SCALE

If we think about all the acoustic terms that we have defined, such as particle velocity, acoustic pressure, period, and frequency, all are concerned with a local mechanical movement of a material at a small scale. But the actual sounds and noises with which we are familiar are usually not described at that level. A word, a sentence, the rattling of a garbage can, the sound of an earthquake deep in the ocean or the rain on the surface of the sea heard at a depth of 600 m, all require additional descriptive terms—these require descriptions of a different scale. To describe a sound and its temporal and spatial changes, we must consider

- its duration (seconds, minutes, hours, days, months…)
- its frequency content (narrowband, wideband, changing with time…)
- its amplitude (loud, soft, changing with frequency, and/or time…)
- the spatial extent of its generation (inches, feet, miles, meters, kilometers …)
- the distance between source and receiver (inches, feet, miles, meters, kilometers…)
- the medium that is conveying the sound (air, water, seawater, steel…)

Note that there seem to be extremes for all of these descriptive terms. For example, is an hour long or short? It is short compared with a month but long compared with a second. Often calculations become easier to perform at extremes because it allows a mathematician to simplify an equation. What do acousticians consider long or short, large or small, and near or far?

Long and short times

The time extent of an event that generates sound in the ocean varies greatly. The slow turning of a ship's propeller as the ship moves through the ocean produces a sound that seems to be quite steady. It can be heard for a "long" time. In contrast, an underwater explosion is over very quickly. It can be heard for only a "short" time. However, the question of what constitutes a long or short time in acoustics is not quite as intuitive as it seems. In acoustics, a long time or a short time depends on the period of the sound wave under consideration. The rule of thumb is that a long time is an interval of time that is longer than a few cycles of the sound wave under consideration (i.e., it exists for an interval greater than a few periods). A short time is an interval of time that is less than one cycle of the sound wave (i.e., it is shorter than one period). For example, at a frequency of 100 Hz (100 cycles per second) each cycle takes 0.01 second to complete (one period). A tenth of a second (0.1 second), then, is a long time, and a millisecond (0.001 second) is a short time. The effects of many acoustical processes depend on whether the process takes a long time to complete or a short time to complete compared with a period. Mathematically, it is often easier to calculate a good approximation of an acoustic value when the temporal components that must be considered are either long or short compared with the period of the wave.

Large and small sizes

Just as with the concept of a long or short time, size is relative. This is especially important when generators of sound (sources) are considered. When considering time, the unit of comparison is a period. With size, the unit of comparison is a wavelength. A large generator of sound may be many wavelengths (perhaps many kilometers) in extent (consider the rain or the wind). Generators of sound are considered small when their dimensions are less than a wavelength in size. Small generators radiate sound in every direction. When the dimensions of the generator are large compared with a wavelength, it concentrates the sound into a beam (or many beams) of limited spatial direction. Mathematically, it is often easier to calculate an approximation of an acoustic value when the spatial components that must be considered are large or small compared with the wavelength involved in the process.

Near and far fields

As with time and size, distances in acoustics are relative. Given any source of sound, a rule of thumb that is often used is that the near field (being close to the source) consists of the space closer to the source than approximately three times the source's largest dimension. Conversely, the far field (being away from the source) consists of the space farther than roughly three times the source's largest dimension. The variations of sound (frequency, amplitude, and phase) are usually more complex in the near field of an object than in its far field. Mathematically, it is often easier to calculate an approximation of an acoustic value when the spatial components that must be considered are near to or far from the devices involved in the process.

SOURCES OF SOUND FOUND IN THE SEA

As shown in Figure 8, sounds found in the sea may be categorized as intermittent, local, or prevailing. Using a different set of criteria, sounds can be categorized by their source—natural (including biotic sources [i.e., living sources of sound] and abiotic sources [i.e. non-living sources of sound]) or anthropogenic (human-generated or caused).

Natural, biotic sources

Sounds generated by living, non-human sources (such as fish and marine mammals) usually have the following characteristics:

- They occur over an extremely broad frequency range and/or contain wide spectral content (from the very-low-frequency tonal calls of blue whales to the very-high-frequency clicks of echolocating dolphins).

- They are spatially very limited in extent (compared to a storm front) because they are generated by individual creatures.
- They occur over a short time because they are generated by individual creatures, although a pod of porpoises may "talk" endlessly.

Marine mammals

For pinnipeds (seals, sea lions, and walruses), the voice mechanism is larynx-based sound generation as in humans. For the odontocetes (toothed whales, dolphins, and porpoises), it has been shown fairly conclusively that the sound-generation process is based on high-pressure air being blown over a bone structure, referred to as phonic or "monkey" lips, which enables the animal to recirculate and reuse air without loss to the ocean. This region allows for muscular control of air pressure and frequency. All odontocetes except the sperm whale have two sets of phonic lips symmetrically aligned with the head centerline but of differing size to allow for left-right ambiguity resolution. The location of this region is consistent with "melon" location (for example, the front of a dolphin's head) to allow for spatial signal concentration as well as spatial sound reception resolution. Excellent coupling through the animal's tissue allows the sound to radiate into the ocean efficiently. Mysticetes (baleen whales such as the blue whale and the humpback whale) also use recirculating air for sound generation. Their sound is usually pulsed sound at frequencies well below the frequency that a human can hear. Because of these low frequencies, the sound can travel thousands of miles in the ocean. Because these whales do not possess open ear canals, the bones in their head pick up the sound vibrations and transmit them to an inner ear structure similar to that of humans. The left and right side of the whale's hearing mechanism are isolated from each other by air-filled sinuses that enable the whale to echolocate more accurately.

Marine mammals also create sounds by slapping their body parts together.

It is recommended that the reader enter the search term "marine mammal sounds" into an online search engine such as Google for many pages of references to sources of marine mammal sounds that may be easily heard.

Fish

Fish produce sounds in three ways—by their movement in the water, by using muscles near their swim bladder (relatively low frequencies on the order of hundreds of Hertz), and by rubbing together skeletal parts of their body (relatively high frequencies on the order of thousands of Hertz)

Invertebrates

There are other living sources of sound in the sea such as snapping shrimp that can be quite noisy.

Natural, abiotic sources

Non-living sources of sounds such as rain, seismic disturbances, or underwater volcanoes usually have the following characteristics:

- They occur over a broad frequency range and/or contain wide spectral content.
- They have a wide distribution (tens to hundreds of miles).
- They may be generated over a long time (hours/days).

Notable exceptions: a crack of thunder created during a violent lightning storm, an undersea volcanic vent, or an ice cover (floe) cracking.

Seismic disturbances

As an example of a natural, abiotic source, Figure 9 illustrates the regions of high seismic activity. These must be as frightening to the water life in the regions where they occur as they are to terrestrial life, but unfortunately they are something that must endured if one lives on a relatively young planet.

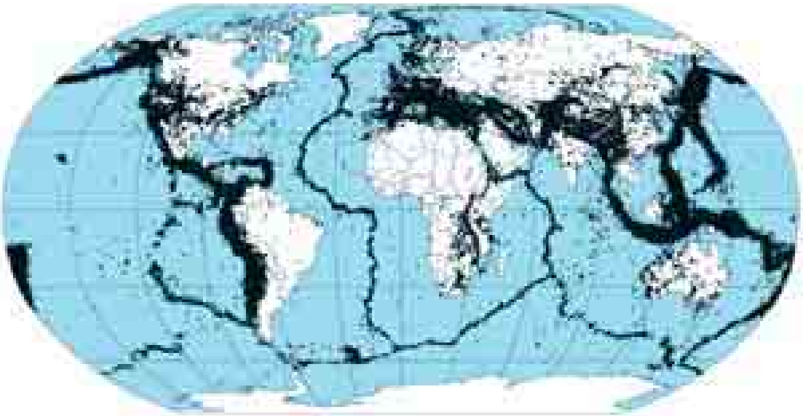


Figure 9: Areas of high seismic activity occurring as a natural phenomenon. (Source:http://core2.gsfc.nasa.gov/dtam/seismic/)

Anthropogenic sources

Anthropogenic sounds (sounds caused and or generated by humans) are multifaceted. Sounds generated directly by humans are much the same as other biological sounds—tonal, short-timed, and, taken one at a time, of limited spatial extent. Sounds caused by humans and their activities are an entirely different matter. The evolution of human presence on the globe and the advent of the Industrial Revolution have resulted in some unique human contributions to the ambient noise of Figure 8.

Large vessels and ports

Humans are terrestrially bound and industrially driven by business-cost minimization. To date, the most efficient means of moving raw material and goods is by ships that are plying the shortest sea routes (the great circle routes). The number of natural deepwater ports on the earth is limited. Resulting sea-lanes between these ports are illustrated in Figure 10. These large vessels contribute to ocean noise on a worldwide basis, but the routes suggest that the noise is not uniformly distributed.

The megaports (roughly, the 20 or so ports throughout the world that handle the most container traffic) are also industrial centers. Each of these centers

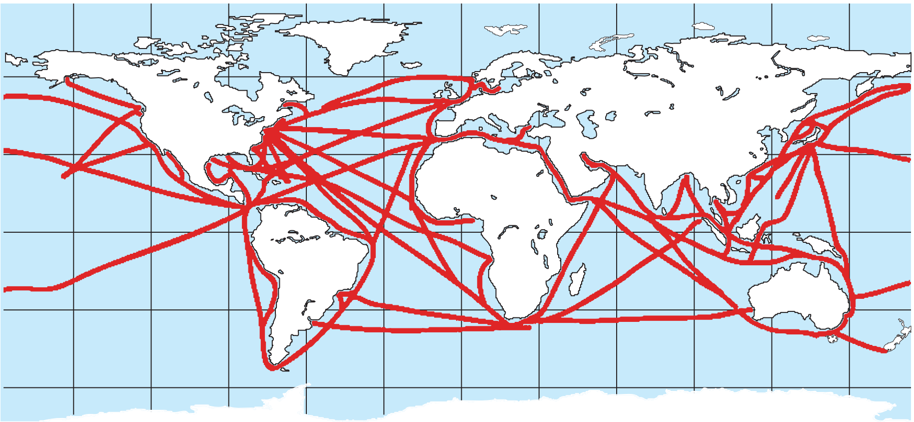


Figure 10. Sea lanes throughout the world. Shipping over these lanes contributes to the ocean noise on a worldwide basis. The low-frequency sounds caused by ships travel great distances and add to the general din of ocean traffic. (Source: Keating 2001)

contributes to the ambient noise shown in Figure 8. Their contribution must be considered both spatially and temporally. Much of the noise that industry generates comes from machinery that creates a combination of both multiple tones and broadband frequency signals. The industrial centers exist at many points scattered over much of the world's coastline, and they are always creating noise. Because marine mammals are relatively coastal in nature, they are closer to ports and noise more than might be expected if their distribution were random in the oceans.

The contribution of shipping noise in the sea-lanes is twofold. Consider the dynamics of a moving freighter. At great distances the freighter is labeled as "Ocean Traffic" under the category of Prevailing Noise as seen in Figure 8. As the ship gets closer, its individual contribution rises above the general din of Ocean Traffic and becomes "Intermittent and Local Traffic" as seen in Figure 11.

But as with all "ships that pass in the night," the sound fades away as does the freighter itself and the sound spectrum returns to that of Figure 8.

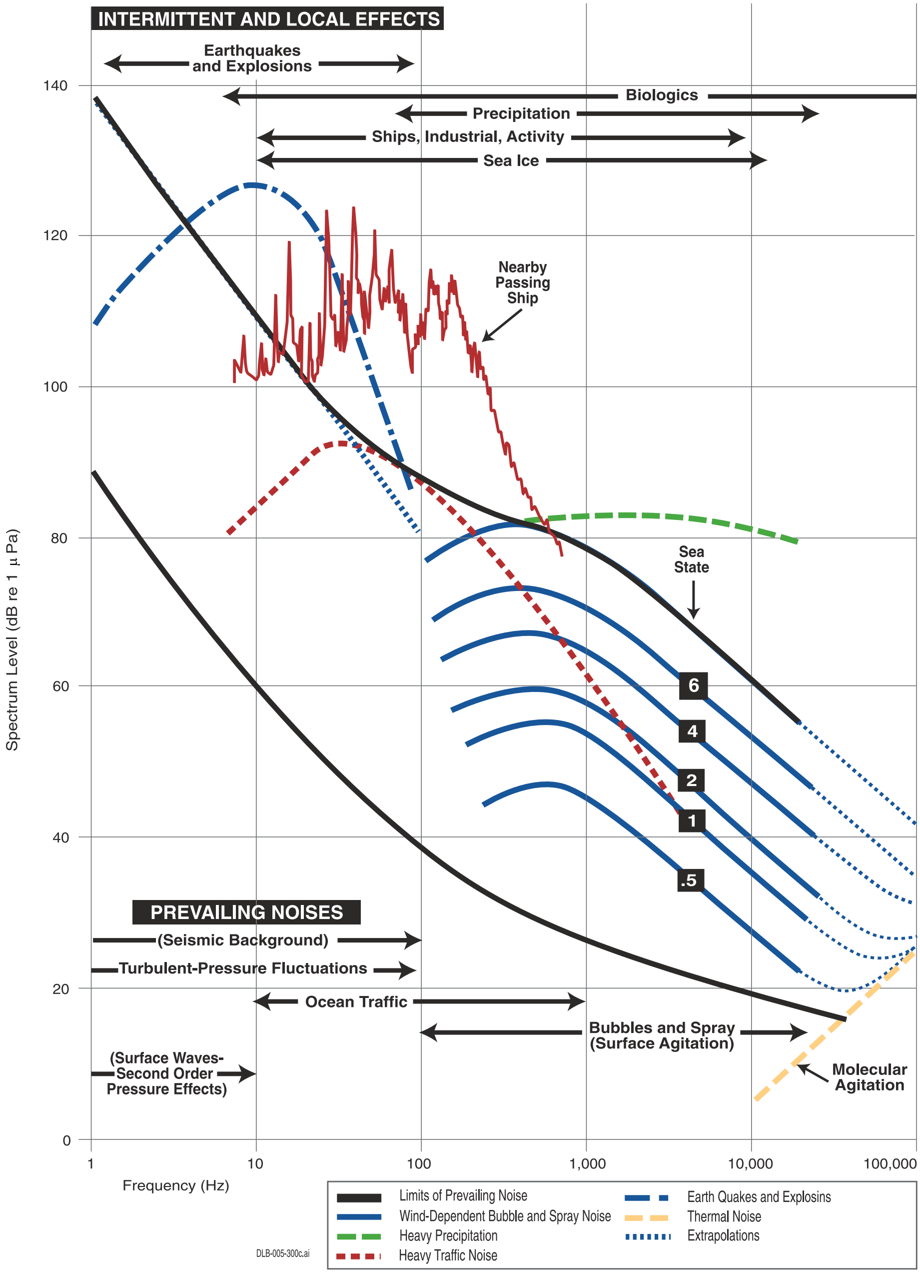


Figure 11. Worldwide shipping contributes continuously to the overall prevailing noise called "Ocean Traffic." However, an individual ship contributes to the local noise at a much higher level as indicated by "Nearby Passing Ship." (Based on Wenz 1962; reprinted with permission, Journal of the Acoustical Society of America; see Further Reading)

Air traffic

As loud as they are, ships are not the only major contributors to noise in the sea. There are others, such as airline traffic, the fishing industry, and offshore petroleum exploration and exploitation. Airline traffic circles the globe and alternates between creating noise on land and noise in the sea as the planes follow their own great circle routes. Because these sources of sound are airborne, traveling at high speeds, and are distant from the sea surface, their contribution is reasonably wide in frequency content and usually short-lived. But there are many planes, and they are quite loud. Their overall contribution is not trivial.

Recently there has been renewed interest in small supersonic aircraft with reduced sonic boom characteristics. If these aircraft proliferate, their contribution to ocean noise may become significant. They "carry" a shock wave of high intensity (the sonic boom) that is moving across the water with a speed greater than the speed of sound. The reaction to this phenomenon by marine mammals has not been determined, but it may be frightening to them.

Fishing industry

Although the fishing industry makes use of smaller craft, there are many of them. They follow the fish, so there is little relief from the noise that they produce. They also add another source of noise, sonar devices, for locating fish. Sonar devices use high-intensity, short tonal bursts (pulses) of sound for their echolocation function. Figure 12 illustrates representative fishing areas.

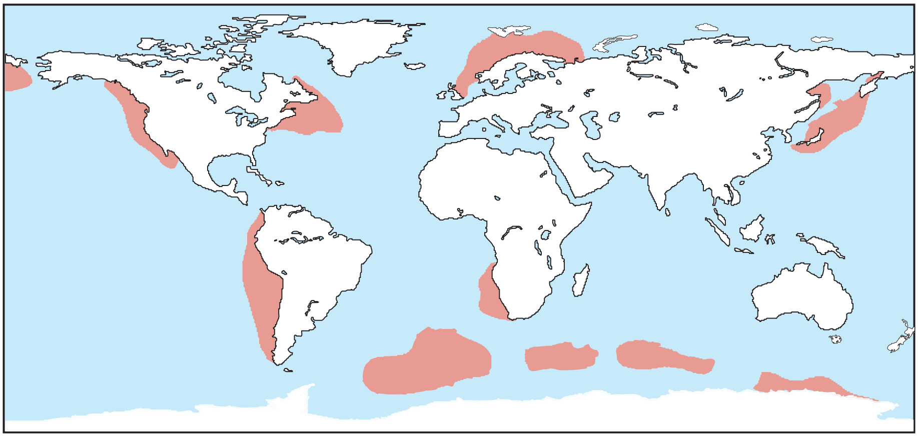


Figure 12. Major fishing areas of the world. (Source: The Sea Around Us database, available at http://seaaroundus.org)

Petroleum exploration

The third major source of sound in the sea comes from offshore petroleum exploration and exploitation (Figure 13). Exploration is episodic and spatially limited, but the acoustic and seismic signals sent out are intense and cover a reasonably broad frequency range because short bursts of sound (firing of airguns) are used (Figure 14). Exploitation is continuous but has been spatially limited to date.

Figure 13. Major petroleum exploration areas of the world.

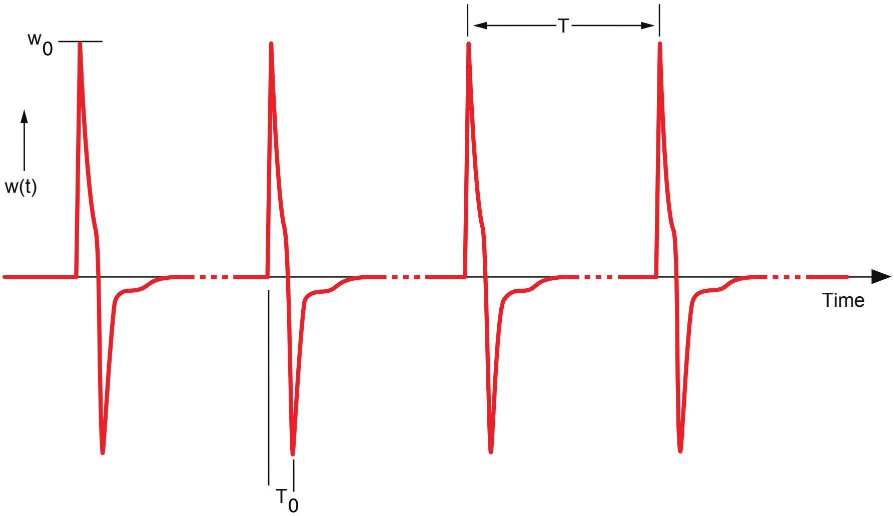


Figure 14. Changes in sound-pressure levels for airgun sources used in seismic exploration. The typical time between explosions (T) is 10–15 seconds, whereas the high levels of sound pressure (T_0) exist for about 5 msecs. The sound-pressure level (W_0) near the explosion can exceed 210–225 dB re 1 μPascal in the horizontal. The sources are typically set to fire at a depth of about six meters. (Source: J. Caldwell, unpublished presentation at 2004 Workshop on Ocean Ambient Noise Budgets, Warwick RI)

Military equipment and operations

The navies of the world have a variety of sonar-based devices, including search sonars, acoustic homing devices for torpedoes, mine-hunting sonars, depth finders, obstacle avoidance sensors, and communication systems. Some sonar devices are classified as active and generate sound as part of their search process. Others are classified as passive and only receive. Sonar frequencies span almost the entire range of interest with respect to marine mammals, as seen in Figure 15. Active sonar systems generally are designed to project their sound beams in limited directions, both horizontally and vertically, because their purpose is to detect and localize potential targets. As discussed earlier, the lower the frequency, the farther the sound travels before losing enough energy to become ineffectual. The lower-frequency military systems are used to detect other vessels—particularly submarines. When their aim is to detect small targets (e.g., fish), the frequency is increased and the special limits just mentioned become even more pronounced.

Operations of military sonar systems often are episodic because they are used for training, experimentation, and systems development or under wartime conditions. They may be globally limited by the requirements of the particular nation that controls them.

Additional military-based sources of sound include test firing of weapons, missile impacts, and explosive testing of ship hulls for damage assessment. In all cases these activities are conducted under tightly controlled circumstances for both safety and security. Typically, they are carried out on well-defined ranges that are in remote locations.

Other significant sources

There are many additional sources of noise in the ocean that are anthropogenic. Some of these are shown in Figure 15 superimposed in the context of Figure 8. The actual list is long and varied. It includes, but is not limited to, high-speed watercraft, coastal development, and scientific experimentation.

POINTS TO REMEMBER

Sound and its spatial and temporal changes are described by duration, frequency content, amplitude, spatial extent of its generation, source and receiver separation, and the medium in which it is propagating. Scales of comparison in acoustics are the period for time, the wavelength for size, and source size for fields. Sound sources may be classified as natural (including biotic and abiotic) and anthropogenic. Humans generally have control over anthropogenic sources only.

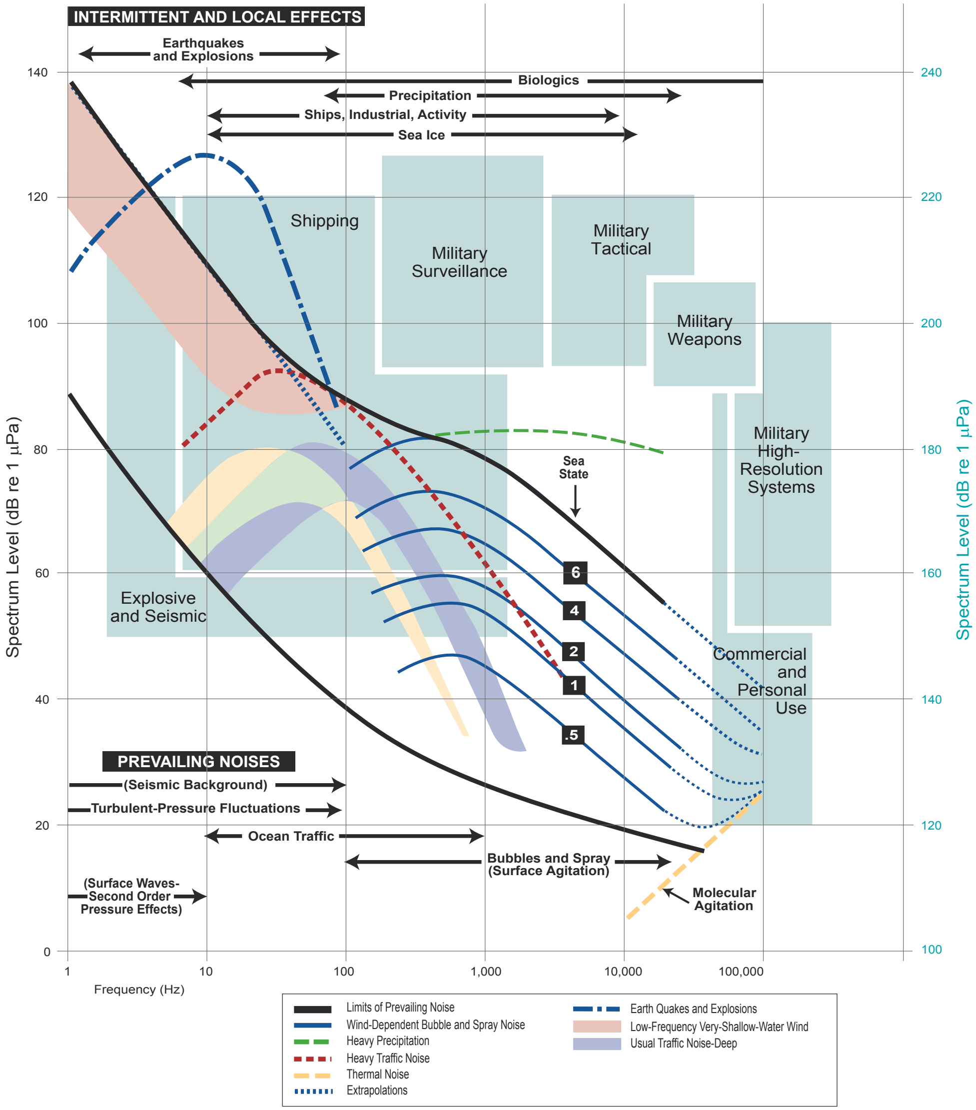


Figure 15. Other sources of noise. Shipping, military, commercial, and personal uses are shown in blue and use the blue spectrum level values on the right axis. These values are 100 dB greater than the values used on the left axis for intermittent, local effects, and prevailing noises. 100 dB corresponds to five orders of magnitude. (Based on Wenz 1962; reprinted with permission, Journal of the Acoustical Society of America; see Further Reading)

CHAPTER 4

SOUND GENERATION, PROPAGATION, AND RECEPTION

The process by which sound is radiated from a source, travels through a fluid such as air or seawater, and is ultimately received and sensed is quite complex. It depends on

- the intensity of the source, the acoustical characteristics of the sound such as frequency content, the information expressed by and within the sound, and the physical dimensions of the source
- the physical and chemical characteristics of the fluid and their spatial and temporal variations. At every point in the fluid, a set of parameters exists that governs which direction the sound will travel as it leaves the point and how it will change in intensity as it travels. Physical characteristics, such as temperature, pressure, sound velocity, fluid velocity, bubble content, surface and bottom interfaces, and chemical characteristics, such as dissolved salts and gases, play major roles
- the sensitivity and signal-processing capabilities of the receiver, its acoustical characteristics, such as frequency response, and the physical dimensions of the receiver

Consider a familiar example in air—a person speaking (the source), and a person listening (the receiver) separated by a short distance. If the speaker is in front of the listener and faces the listener, the speaker's voice might sound loud and clear; if the speaker is in front of the listener but faces away, the sound might be quiet and muffled. Clearly, in this example, the sound leaves the speaker and takes a different path. If there are highly reflective walls nearby, the sound may take multiple paths before it reaches the listener, and the listener may hear many instances (copies) of the sound. Then the sound may be loud but unintelligible. It is also possible that the listener might turn away from the speaker, and again there could be a change in the sound that the listener perceives. In that case, the receiver is changing its spatial characteristics.

Finally, consider the condition when both the speaker and listener are facing each other but are 100 to 200 yards (91 to 182 meters) apart. If there is wind and it is blowing from the speaker to the listener, it is likely that the listener will hear the speaker. If the wind is blowing in the opposite direction (from the listener to the speaker), it is likely that the listener will not hear the speaker. (Note: the explanation of this effect is not that the "wind helps carry the sound.") In this case, however, the characteristics and motion of the medium make the difference. Let us examine in more detail how each of these conditions and many others may affect the generation, propagation, and reception of underwater sound.

SPATIAL CHARACTERISTICS OF SOUND SOURCES

Simple sources

Consider the simplest source of sound, a point source (i.e., a source of sound that radiates its energy equally in all directions [omnidirectional] from a very small region of space). (Remember, the unit of comparison for size in acoustics is the wavelength. A small region, then, is a region whose dimensions are small compared with a wavelength.) If a continuous sound is produced by a point source and allowed to radiate (travel) into a uniform fluid (one whose acoustical characteristics are the same everywhere), and if the sound it produces is measured, a graph of the locations where the sound is equally loud will produce a series of spheres as shown in Figure 16. The acoustic radiation pattern from a point source is described as spherically symmetric. The figure depicts the directivity of the source. At given distance, the sound level is the same, regardless of direction from the source.

Complex sources (arrays)

On the other hand, what if the source is not simple? (Sources seldom are.) Anthropogenic sources are usually designed to satisfy some special directivity requirement connected with an application (for example, sonar may use a "beam of sound" for searching). Anthropogenic sounds are often generated using collections of many point sources, spatially and temporarily distributed, each source radiating sound at a particular frequency, amplitude, phase, and time. The term used for a collection or distribution of point sources (or any group of sources) is an array. Figure 17a shows an example of a line array (a line distribution of point sources radiating at the same time, at the same frequency, and all in phase. Figure 17b shows the output of a baffled, flat, circular panel of point sources (called a circular-plane array). The panel approximates the sound that might be radiated from a sonar system. It has a main "beam of sound" that can be used for locating an object. Note that both the line source and flat panel source have a

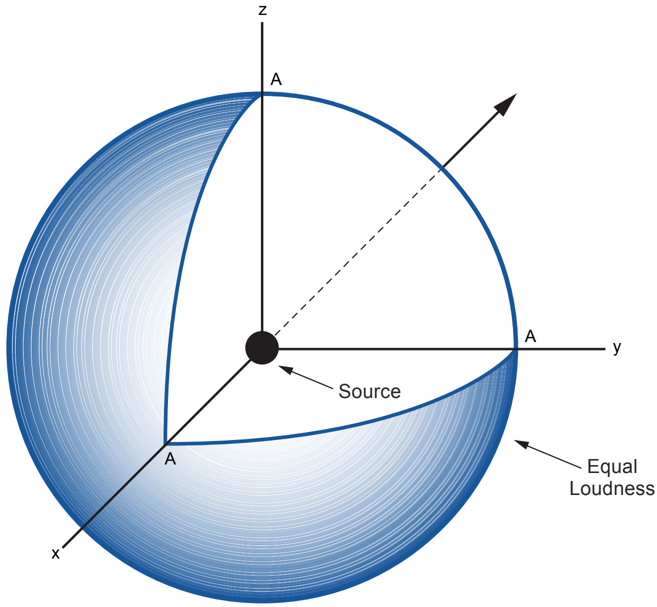


Figure 16. Directivity pattern from a point source. The acoustic radiation is spherically symmetric and decreases with distance from the source.

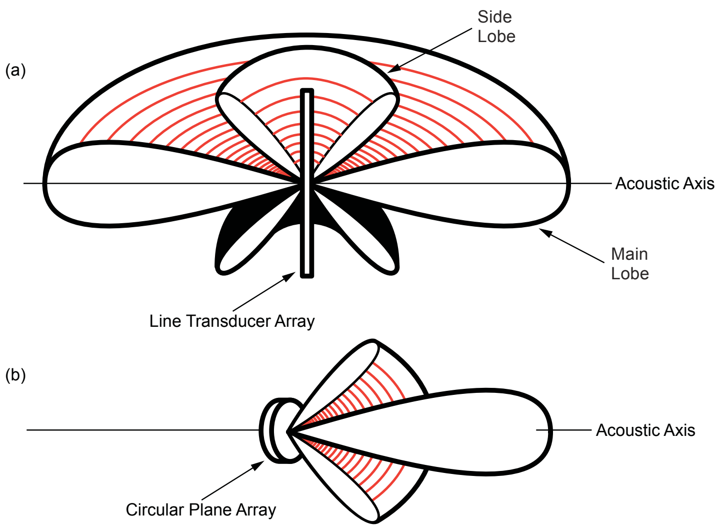


Figure 17. Directivity patterns of two arrays. (a) illustrates a series of point sources in a line. This is typical of a transducer system that might be towed behind a ship searching for submerged objects. It is most sensitive in the direction of its acoustic axis (called the main lobe). This array has a side lobe with less sensitivity and is "looking in a different direction." (b) illustrates a series of point sources arranged to form a flat, circular plate. This array is typical of a sonar system that requires high directivity in a particular direction. Sonar systems are capable of changing the direction of the main lobe electronically (i.e., without changing the direction of the flat, circular plate). They also have the capability of reducing the sensitivity of the side lobes, thereby providing a less-ambiguous search system. (Source: Urick 1983; reprinted by permission of The McGraw-Hill Companies; see Further Reading)

single axis of symmetry as shown in the figure. To describe the loudness of the sound at any point in space, only the distance from the axis of symmetry and one angle must be specified (plus all the information about the sound itself).

THE UNBOUNDED AND IDEAL OCEAN

To understand the effects of the ocean on how sound travels, consider first an ocean that is infinite in extent (no boundaries) and homogeneous (has the same acoustical characteristics everywhere). At first, assume the ocean to be a perfect fluid (i.e., inviscid [without viscosity; i.e., frictionless]) and without any other characteristics that might be detrimental to the acoustic signal.

Geometric spreading

If a burst of sound starts out from a point source in the unbounded and ideal ocean, it spreads in every direction uniformly. However, the burst contains only the limited energy that is given to it when it starts out. As it spreads, that energy is now being distributed over a larger and larger spherical surface, as illustrated in Figure 18. Remember that the intensity of sound is defined as the amount of energy passing per unit time through a unit area. Because the area of the surface of the sphere is proportional to the square of the distance from the source, every time the distance is doubled, the area increases fourfold and the intensity decreases fourfold (same energy, larger area). The term *geometric spreading* is used to describe the decrease in intensity and apparent weakening of the signal due to the spreading of the energy as it gets farther from the source. Even though the intensity decreases, there is no loss in the total energy of the sound. It simply is spread out over more of the ocean. If a marine mammal is receiving the sound, the loss of acoustic energy decreases with the square of the animal's distance from the source.

THE BOUNDED AND REAL OCEAN

Now consider the ocean with boundaries (i.e., a top such as air or ice and a bottom such as sand or rock) as well as properties that weaken the signal as it travels. In the case of the unbounded and ideal ocean, the short burst of sound described earlier approaches a receiver, is heard, and then continues on its way. Thus, a single burst of sound is heard and is forever gone to that receiver. The signal has been weakened due to geometric spreading only. However, the real ocean possesses additional properties that affect the sound—it may be weakened further. It may also be distorted over time and space to the extent that it is no longer recognizable as the same sound. Multiple instances of the sound may be heard or the sound may not be heard at all at a particular location although a short distance away it is perfectly loud and clear. Some of the more important ocean

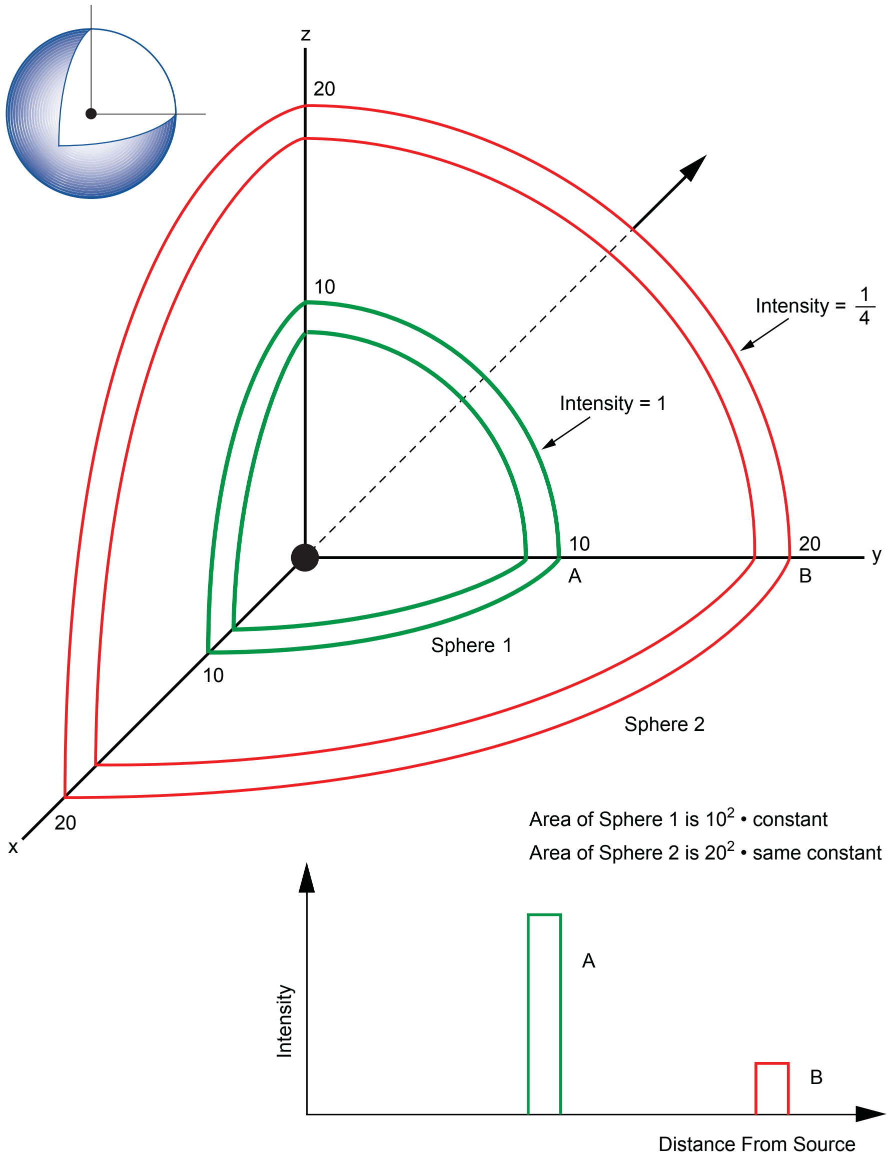


Figure 18. Propagation of a burst of sound. If the sound has an acoustic intensity of "I" at point "A," its acoustic intensity at twice the distance "B" is "I/4", since the energy is spread over four times the area.

properties that affect sound transmission are absorption, reflection, refraction, scattering, and reverberation. Reflection and refraction are extremely important to marine mammals because they change the direction of the path that a sound may be taking. An echolocating marine mammal may think that he or she is heading out to sea if there is no return to its transmitted click whereas refraction due to changes in the sound velocity profile and/or effects caused by internal boundaries can be sending the transmitted click in an entirely different direction.

Absorption

There are two effects that weaken an acoustic signal by taking energy out of the signal (over and above the lossless weakening of geometric spreading) and ultimately converting it into another form of energy (such as heating the ocean). To consider these effects, the ocean may still be assumed to be infinite in extent and homogeneous but not a perfect fluid. It will have viscosity (friction), and it will contain dissolved salts.

Viscosity

First, sound is a mechanical disturbance. The fluid and the molecules that make up the fluid move with respect to each other. If viscosity is present, the molecules associated with the acoustic signal "rub" against each other, creating heat (that is, increased, random, molecular motion that is secondary to the motion that made up the sound signal). Because the energy that is converted to heat is supplied by the motion of the particles, it is lost from the sound and the sound becomes weaker.

Relaxation processes

Second, the fact that seawater contains dissolved salts results in additional loss mechanisms called relaxation processes. Both magnesium sulphate and boron molecules can exist in seawater in two different physical shapes. To convert from one shape to the other requires energy. This energy is supplied by the sound. For boron, the conversion takes place when the sound frequency is low, and for magnesium sulphate, it occurs when the frequency is high. The acoustic pressure causes these molecules or groups of molecules to alternate between the two shapes. As these molecules shift shapes, they take energy from the sound wave (as they change from "shape 1" to "shape 2") and then give it back (as they return to "shape 1"). However, the interval of time that they remain in one shape or the other before they absorb and return the energy (the relaxation time) may bear no relationship to the period of the acoustic signal. Thus, the energy is not necessarily returned at the right time. When this occurs, the energy is being returned incoherently (increasing the background sound in the ocean) and is lost from the acoustic signal, leaving it weakened.

Both processes act independently of each other, but both contribute to the loss of energy from the acoustic signal. In these processes, the area over which the signal is spread remains the same, but the energy in the signal, and therefore the intensity, is decreased. These processes are generically called absorption. The signal is said to undergo attenuation.

Reflection

If boundaries are present ("real," as in the surface of the sea, the seafloor, and submerged objects, or "internal," as in changes in the physical characteristics of the water), they offer opportunities for additional instances of the sound burst to be received. Depending on a variety of factors, there may be many more instances of the sound burst heard from additional reflections. Figure 19a illustrates the ocean, its boundaries, and three paths. Path 1 shows a direct path from the source to the receiver. Path 2 illustrates the path from the source to the receiver and includes a specular (mirror-like) reflection from the sea floor. Path 3 includes a specular reflection from the surface. Because the length of all paths is not the same, Figure 19b illustrates that each instance of the sound burst will reach the receiver at a different time. Considering the attenuation mechanisms described in the previous section (they are both path-

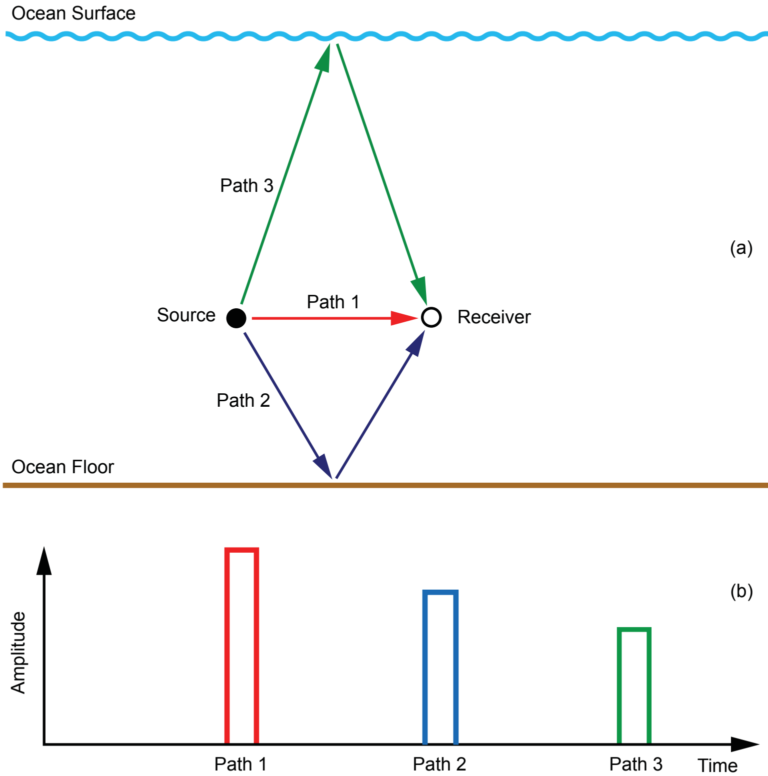


Figure 19. Three paths are taken by the sound as it propagates from the source to the receiver as illustrated in (a). Path 1 is the direct sound with the shortest distance and the shortest time. Path 2 reflects from the ground, travels farther than the direct path, and takes a little longer. Path 3 reflects from the sea surface, travels the farthest, and takes the longest time. The acoustic intensity received depends on the losses due to the path length as well as the amount of energy reflected from each interface. Multiple reflections may also occur as the sound reflects alternately from the bottom and the sea surface.

length dependent), geometric spreading, difference in arrival time, and the fact that the amount of energy reflected at one surface may not be the same as the energy reflected from any other surface (reflections may not be specular), it is unlikely that one instance of the pulse burst will be the same as any other instance. It is also very likely that some instances may actually overlap others and cause both constructive and destructive interference patterns.

Refraction

The speed of sound is not constant with depth and range but depends on the temperature, the pressure, and the salinity of the ocean at every location. If all three of these factors were constant, sound would travel in a straight line. If any (or all of the three) change with position (depth or range), the sound will travel in a curved path. Changes of direction of the sound due to changes of sound velocity are known as refraction. Of the three factors, the largest impact on sound velocity is produced by temperature changes and, as discussed in Chapter 2, when the temperature stabilizes, changes in pressure becomes the dominant influence. A typical sound velocity profile is shown in Figure 7. Figure 20a illustrates an alternate path caused by the curving of the sound, and Figure 20b compares the signal received over both paths emanating from the same source. In this example,

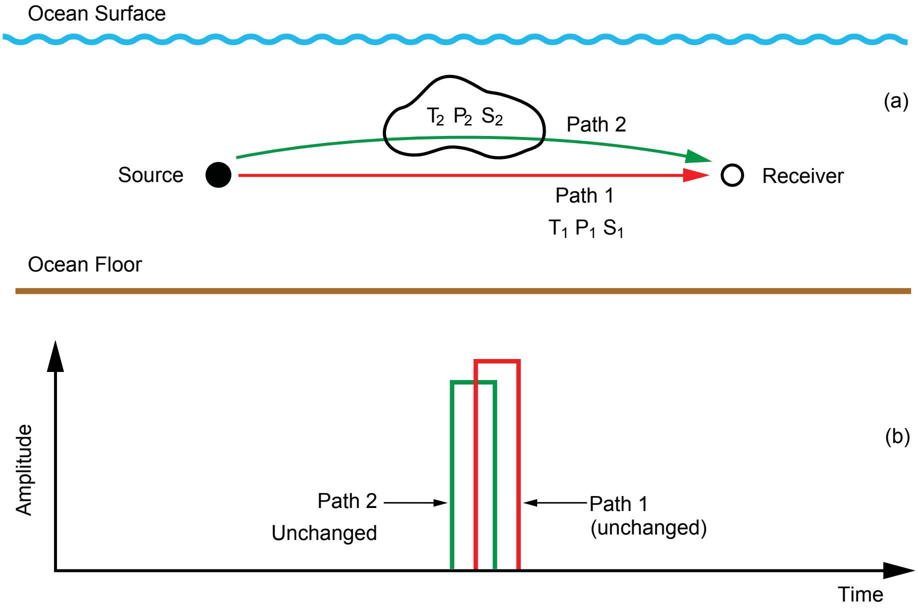


Figure 20. (a) Refraction causes the sound that has started out heading upward to "bend" back down and reach the receiver. This occurs when the velocity of sound in the water decreases with depth. The sound propagating over path 2 travels farther than the direct sound propagating over path 1. (b) However, because the acoustic velocity is faster over path 2, it reaches the receiver before path 1, but the extra distance causes greater losses in intensity. It is both faster and quieter.

it was assumed that the velocity was decreasing with depth. When this occurs, the sound ray, as it is called, curves downward. However, it is traveling in a region where the sound velocity is faster than the direct path velocity, and therefore it reaches the receiver before the signal from the direct path does. It is heard before the direct path signal as shown in Figure 20b. Because sound losses (attenuation) depend on the path length, and the path length for the curved path signal is greater than the path length for the direct path signal, it experiences a greater loss. The result is that it arrives earlier than the direct path signal but is quieter.

The change in the direction of the sound wave with changes in velocity can produce many complex sound paths. It may produce locations in the ocean that a sound ray sent out from a particular transducer cannot penetrate. These are called shadow zones. It may also produce sound channels that can trap the sound and allow a signal to travel thousands of kilometers with little loss in energy.

Scattering

If the ocean boundaries are not smooth but have rough surfaces (and they usually do), then additional complexities are added, as in Figure 21a. When this occurs, scattering or multiple paths with small differences in time or amplitude arrive at the receiver. Figure 21b illustrates the additional received instances of the sound burst. For scattering from the sea surface, a further complexity (variation with time) is added when the surface is in motion due to waves or swells.

Reverberation

Reverberation also distorts the acoustic. When sound strikes a surface at an angle, it becomes “spread out” due to the geometry of the sound and the angle and roughness of the surface. For a burst of sound, the effect increases the received time of the burst. Because the sound heard is similar to that heard in a large room with acoustically reflecting walls, it is called reverberation. The distortion of the original signal is termed surface reverberation when it is an effect caused by the surface. Volume reverberation is additional signal lengthening due to objects (such as fish) that are in the volume of the water itself and scatter the sound.

DEEP WATER (“BLUE WATER”) AND SHALLOW WATER

All the effects described in this chapter can be present in both deep water (blue water) and shallow water (littoral zone). The major impact of shallow water is in the introduction of increased variability. Because the boundaries are closer, the effects occur over shorter distances and shorter times. Other factors may enter into play, such as freshwater runoff (salinity change) close to the shore and strong tidal currents that may change the shape of the seafloor.

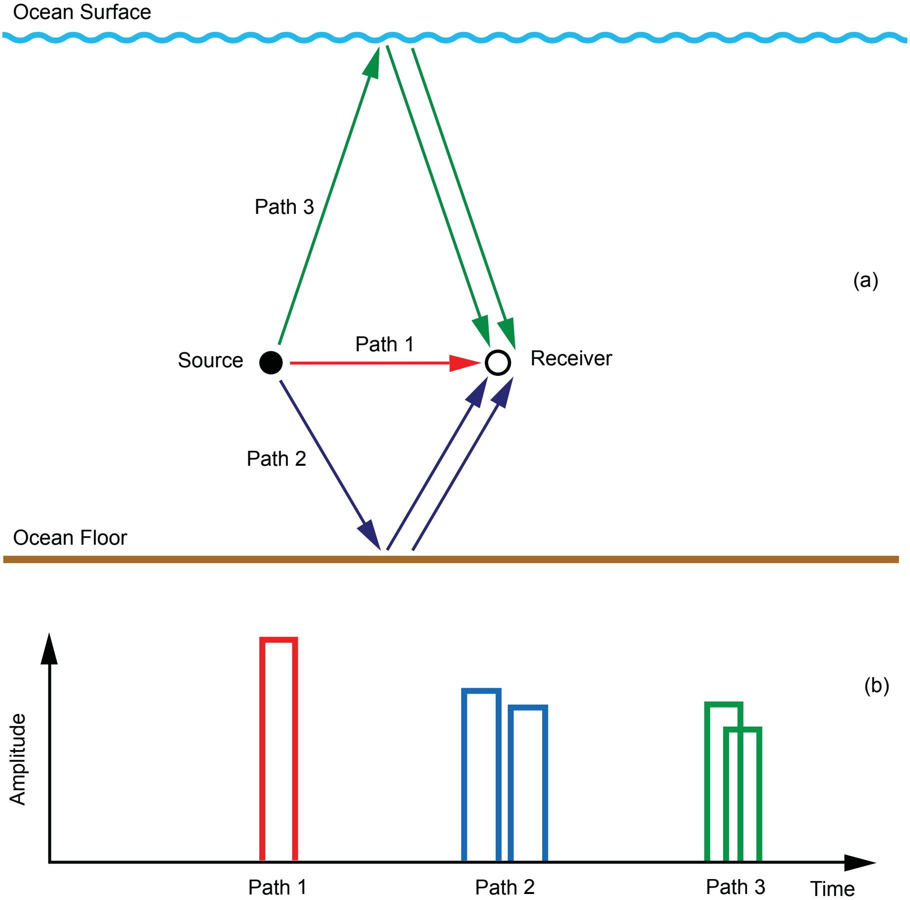


Figure 21. Three paths are taken by the sound as it propagates from the source to the receiver as illustrated in (a). Path 1 is the direct sound with the shortest distance and the shortest time. Path 2 reflects from the ground, travels further than the direct path, and takes a little longer. Because the ocean floor is not mirror-like, the signal reflects (scatters) from many facets of the surface, producing multiple reflections. Path 3 illustrates the same effect from the ocean surface. In this case, the signals overlap each other, causing both constructive and destructive interference.

SPATIAL CHARACTERISTICS OF SOUND RECEIVERS

Sound receivers such as hydrophones and arrays of hydrophones have exactly the same directional characteristics as sound sources and arrays of sound sources. The directivity pattern associated with a given configuration of receivers refers to the sensitivity of the receivers, and the directivity pattern associated with the sources refers to the strength of the sound sources. Again, omnidirectional receivers and beam-forming receivers may be used in acoustic applications. Figure 22a illustrates how a hydrophone may record a sound burst as it starts out, as well as how it sounds after traveling some distance in

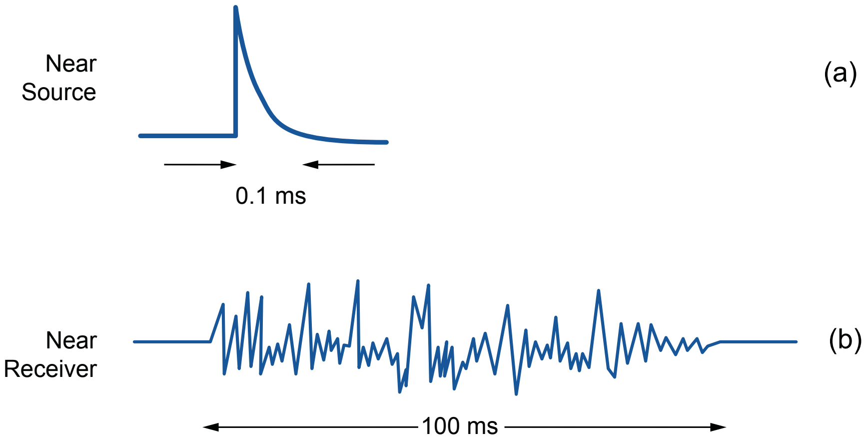


Figure 22. (a) A typical pulse of sound as it leaves the source. For an ideal ocean, the sound detected by a receiver would have the same shape but would be weaker due to geometric spreading. For a real ocean, the pulse may appear as in (b) due to absorption, reflection, refraction, scattering, and reverberation. In addition, there could be many pulses detected arriving at different times. With signal processing, it is sometimes possible to detect the original shape of the signal. (Source: Urick 1983; reprinted by permission of The McGraw-Hill Companies; see Further Reading)

the ideal ocean. Figure 22b illustrates how the same signal may be received after traveling in a real ocean. A simple signal may become so distorted that it is impossible to interpret without a detailed knowledge of the environment through which the signal has traveled, usually accompanied by extensive signal processing.

POINTS TO REMEMBER

Sound sources may be simple (point sources) or complex (arrays of point sources). Propagation of sound is influenced by geometric spreading, absorption from viscosity and relaxation processes, reflection, refraction, scattering, and reverberation. These effects usually distort the sound severely as it propagates through the ocean. Effects such as reflection and refraction can lead an echolocating marine mammal astray and may be a possible cause of stranding.

CHAPTER 5

HEARING SOUND: HUMANS AND MARINE ANIMALS

TRANSDUCTION

Transduction is defined as the process of converting energy from one form to another. Both the generation of sound and hearing are transduction processes. For example, a signal generator and amplifier transform electrical energy into mechanical energy (sound). For hearing, mechanical energy (sound) enters the ear (the transducer) and is converted to electrochemical signals (electrical energy) that correspond to the mechanical energy. Figure 23 illustrates the mechanical to electrical energy conversion that the ear performs. There are many texts and technical articles reporting on studies, medical records, and measurements of both human and other mammalian ears. In its simplest form (see Figure 24), the ear can be described as a three-section processor. The outer ear and ear canal serve as a sound-gathering device that channels the acoustic energy (the sound wave that enters the ear canal) to the eardrum and sets it in vibratory motion. The eardrum, in turn, is mechanically connected to a series of three bones that act as a leverage system. The combination of eardrum and bones (one of which, the stapes, is the smallest bone in the human

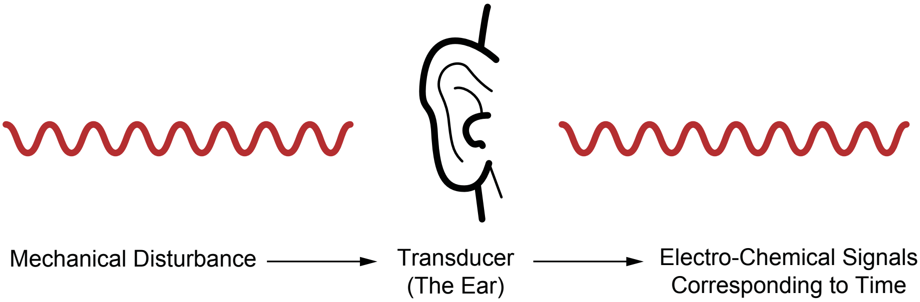


Figure 23. The transduction process. Mechanical energy is converted into electrochemical energy.

body) converts the energy of the sound wave in air extremely efficiently into the fluid-filled inner ear, the cochlea. The inner ear is the section of the ear in which the actual transduction occurs (that is, mechanical energy of vibration is converted to electrochemical energy and sent to the brain to be processed, analyzed, and "interpreted"). The inner ear is an elegant structure that is simple to describe physically but extremely complex in function. The cochlea contains a membrane that is set into flexural motion by the movement of the fluid, much as a flag moves in a breeze. Part of the membrane contains tiny hairs that are flexed by the movement of the membrane. These hair cells (called cilia) convert the mechanical energy of sound into electrochemical energy by exciting the auditory nerve that carries the information to the brain. The process of transduction in the inner ear continues to be the subject of scientific and medical debate as to exactly how the system works.

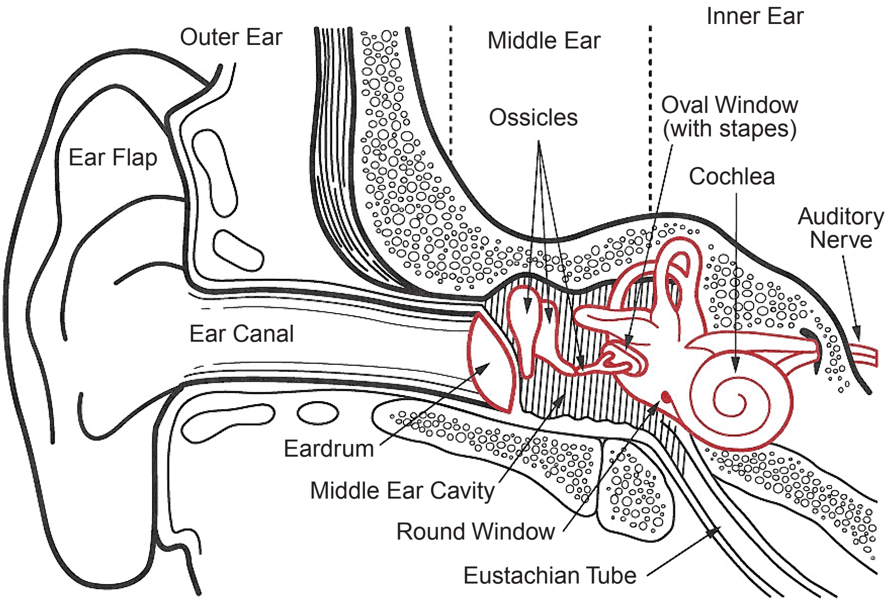


Figure 24. Simplified diagram of the human ear. Airborne sound is gathered by the ear flap and travels down the ear canal. This mechanical disturbance reaches the eardrum, setting it into motion. The motion is picked up by the ossicles and transmitted to the oval window of the cochlea. Fluid in the inside of the cochlea is set into mechanical motion by the vibration of the oval window, and the fluid vibrates the basilar membrane (not shown) that runs the length of the cochlea. The basilar membrane changes the mechanical energy of the fluid into electrochemical energy that is sent to the brain by the auditory nerve.

HUMANS

Those who speak, listen (excluding, of course, teenagers), or, more correctly stated, those who can generate sound usually can hear. The graph used to quantify the ability to "just hear" a sound is called an audiogram. The data indicate the threshold of hearing at different frequencies. Figure 25 illustrates a typical audiogram for a human in air. However, it uses scales of sound pressure levels that have been adjusted for underwater conditions (reference pressure equals 1 μPa) on the left side of the audiogram (left ordinate) and for air (reference pressure equals 20 μPa) on the right side of the audiogram (right ordinate). The "U-shaped" curve is the threshold of hearing for humans in air and is the averaged result of thousands of measurements. The graph also contains the sound pressure levels and frequency range typically used for conversational speech. Hearing "threshold" simply means that at a particular frequency sounds that have a higher sound-pressure level than the curve will be heard by a person with "normal" hearing, but sounds that are below the curve will not be heard.

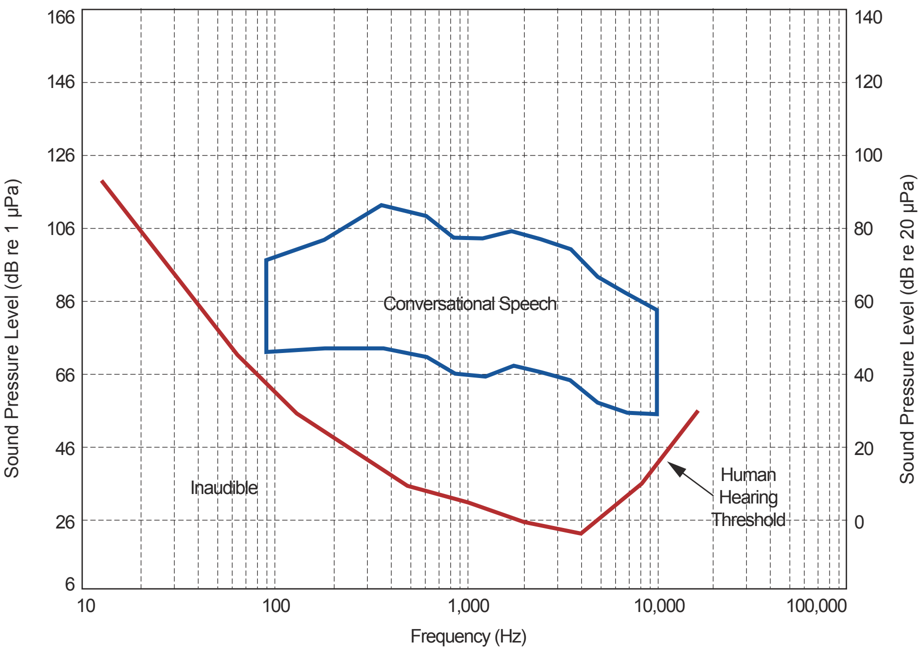


Figure 25. Typical human audiogram illustrating the threshold of hearing. Sounds above the threshold will be heard, but sounds below will not. The range of conversational speech has been included. It covers the same frequencies to which a human is most sensitive. The values of the sound-pressure level on the left axis correspond to the underwater reference, while the values on the right axis correspond to the air reference. The sound is the same, but the readings on the sound-level meters are different. (Source: M.C. Liberman, unpublished presentation to the Committee on Potential Impacts of Ambient Noise in the Ocean on Marine Mammals, Ocean Studies Board, National Research Council, Woods Hole Oceanographic Institution, June 2001)

For example, if a sound of frequency 1,000 Hz has a sound pressure level of 26 dB (re 1 μPa [i.e., as measured in water]), a typical person will not hear it. Note how a human's threshold of hearing is frequency-dependent. Sounds below 100 Hz will not be heard unless the sound is very loud (about 60 dB re 1 μPa). At higher frequencies such as 10,000 Hz, a human will only hear sounds that are greater than about 41 dB (re 1 μPa). The audiogram shows that human hearing is most sensitive at about 4,000 Hz. For humans, the area described as conversational speech is centered where human hearing is most sensitive.

MARINE MAMMALS

Turning now to marine mammals, we consider pinnipeds (e.g., seals and sea lions) that must function both in the water and on land and cetaceans that function only in the water, except for breathing. Pinnipeds essentially have the same hearing mechanism as humans and other terrestrial mammals except for the size or extent of their external ears (or earflaps) and the size of their ear canals. Some pinnipeds can close their ear canals.

In contrast to humans and pinnipeds, cetaceans "collect" sound energy through their lower jaw and send it to their middle ear and inner ear. Usually their ear canals are blocked and are not part of the hearing process. Again, in contrast to humans and pinnipeds, the hearing mechanisms of cetaceans are not contained within their skull. Outside of size, the cochleae of cetaceans function in the same manner as those of humans and pinnipeds.

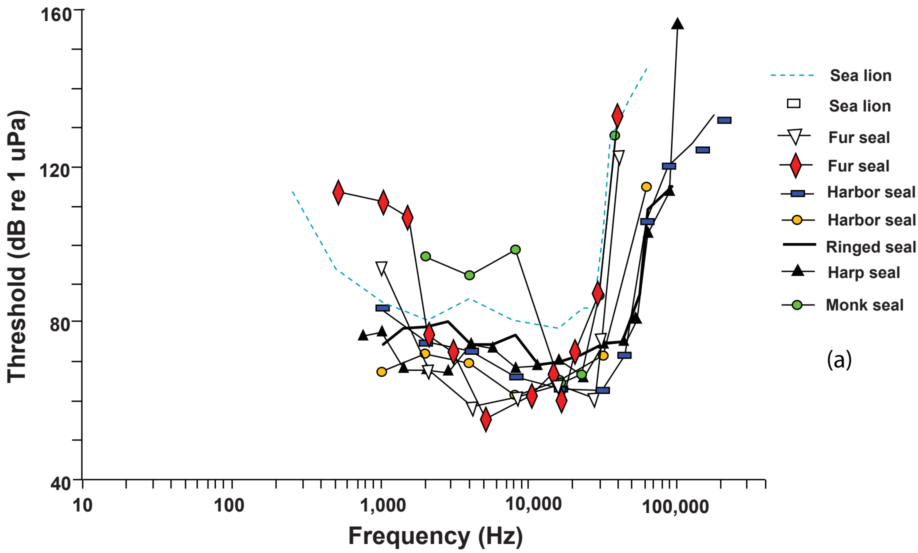
Sound levels

Figure 26 illustrates the underwater audiograms for (a) pinnipeds and (b) cetaceans, specifically odontecetes or toothed whales. The most striking characteristic of marine mammals' audiograms is that, in general, they are very similar to those of humans, noting the obvious frequency shifts.

It is important to understand that there are fundamental and quite important differences between species (and within species) regarding relative sensitivity to sound pressure and particle motion. For this reason, there is truly no clear and simple answer as to the meaningful difference between exposures in air and water. The most meaningful comparative metric for evaluating the respective loudness of a sound to a marine mammal is the extent to which it is known or estimated to exceed their hearing sensitivity in the same medium (called noise sensation level).

POINTS TO REMEMBER

Transduction in humans and marine mammals is not very different.



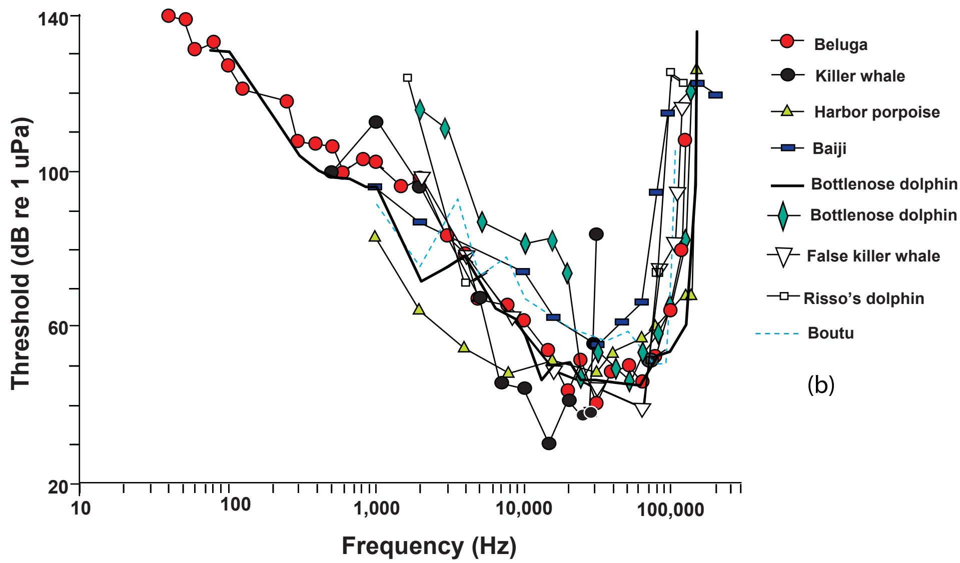


Figure 26. Audiogram for (a) pinnipeds (e.g., seals and sea lions) and (b) odontocetes (e.g., toothed whales). Note that these mammals are most sensitive at frequencies that are higher than the frequencies at which humans are most sensitive (4,000 Hz). (Source: Reynolds and Rommel 1999)

CHAPTER 6

SOUND AND MARINE MAMMALS—FINAL THOUGHTS

HEARING-CENTRIC SENSINGS

Humans are primarily land-based and vision-centric. That is, they use vision as their primary sensor with hearing as a secondary sensor, as are smell, taste, and other senses. In contrast, marine mammals are at home in the ocean where light transmission is greatly limited. They must depend on sound to assess the environment beyond their limited vision. As with terrestrial environments, the oceans are never without sound.

In the oceans, marine mammals must find food, locate mates and rear young, navigate, and avoid predators. Hearing serves the purposes of communication (social behavior, which includes maintaining group cohesion), navigation and exploration (sensing the environment), echolocation (foraging and detection of prey), and survival (detection of predators)—all of which are critical to life for the mammal. As can be seen in Figure 26, the frequencies and thresholds of hearing are quite varied, which should not be a surprise, because every species has its unique social circumstance, habitat and food requirements, and predators.

Similarly, each mammal species has unique vocalizations, calls, whistles, clicks, tones, and other sounds that are used to communicate, navigate, explore, hunt, track, and converge on prey. It is not common for marine mammals to vocalize when they are the hunted. More typically, the marine mammal's behavior is to be stealthy or to avoid a predator. Because hearing and vocalization or the production of sounds have different functions for marine mammals (and other species), it is reasonable to expect that their hearing range is greater than their vocalization range. Consider, for example, that humans can hear well beyond the frequencies that they produce. A harbor seal may not be able to reproduce the sounds of a killer whale, but it certainly behooves the harbor seal to be able to hear the killer whale.

POTENTIAL THREATS TO MARINE MAMMAL SURVIVAL

Because marine mammals are hearing-centric, the potential effects of either new, different, or loud noises are of critical importance to them. Their acoustic environment influences all of the biologically significant things they do; if it changes, it is reasonable to expect that their behavior will change. Like humans, marine mammal species also exhibit individual variations by gender, age, health condition, experience, social structure, sensitivity to habitat, population size, and a number of other factors.

Humans, like marine mammals, live in a very noisy environment. Everyone shares a myriad of "home" sounds, many of which are "tuned out." Humans may become desensitized to some noises and ignore them to the point that they may claim that they do not even hear them, but they are surrounded by noise. Moreover, they might even feel comfortable with them; it "sounds like home." Yet there are stress-related diseases and disorders that occur as a result of the presence of noise. For example, extremely loud noises are present in automobiles and aircraft that are too low in pitch to be detected by humans and may be ignored by instruments designed to measure sound as heard by a human. However, these low-pitched sounds (called infrasonics or infrasound) are not ignored by the body and may easily cause malaise to travelers. It is important to point out that in the ocean, low-pitched sounds may travel very far from their source without significant loss of energy and may provide both a hazard and increased stress for marine mammals. Even sounds that go unheard by marine mammals may harm them if those sounds affect the normal functioning of their tissues and organs.

If a human has the opportunity to spend time in a well-designed anechoic room—a room that is isolated from all external sounds (sounds created outside the room) and has special sound-absorbing walls that do not permit echoes within the room—it usually will not be long before sensory deprivation takes its toll and begins to have a strong psychological impact. Unfamiliar sounds and sights tend to make one feel insecure. Attention is drawn to a noise that has not been heard before. Worry starts when a car makes "strange noises." One also becomes alerted when a noise stops. It is often a change in sound that may draw one's attention and that represents a potential threat. For marine mammals as well as for humans, noise—its presence, its absence, and its change—may cause both physiological stress and changes in behavior.

Because marine mammals are exposed to a variety of sounds, they may experience a variety of adverse and/or damaging consequences. Masking is defined as the condition whereby the presence of one sound (pure tone, narrowband or broadband) increases the threshold of hearing for a second sound (i.e., reduces the mammal's ability to hear a second sound). It is especially important when the masking sound is about the same frequency as the sounds of interest. For example, in humans, a low-frequency tone that is pure and steady will decrease the ear's ability to hear sounds of similar and slightly higher frequency. If the masking sound is pulsed, its effect on the threshold of hearing of other sounds is time dependent. A masking sound that prevents a marine mammal from hearing an important sound has the capability of threatening its survival simply by occurring at the wrong place and at the wrong time. Damage can range from a temporary threshold shift (TTS), (temporarily raising a marine mammal's threshold of hearing) to a permanent threshold shift (PTS), (permanently raising a mammal's threshold of hearing). For a hearing-centric marine mammal, a PTS may spell its demise. TTS and PTS depend on the level of the sound, its duration, and the mammal.

Large amplitudes as well as other acoustic effects, can cause bodily harm, including tissue damage, bleeding, organ injury, and death (either directly by the sound or indirectly by the response from the mammal). Secondarily, but also important, may be the effects of the sound on the environment that the marine mammal requires to survive. Loss of prey and increased exposure to predators, for example, may result from sound-related threats. Note that these effects can be both short term and long term. Moreover, they can be additive (i.e., independent, so that their total effect can be estimated by adding their individual effects), synergistic (i.e., interacting in a manner that increases the total effect to larger than the sum of individual effects), or countervailing (i.e., interacting in a manner so that the total effect is less than the sum of individual effects).

MEASUREMENTS AND OBSERVATIONS

The ability to observe marine mammals in the oceanic environment is technically limited to date and is further complicated by our primitive knowledge of their living dynamics. Humans can describe their reaction to a new sound. The reaction of a marine mammal must be inferred by a large and inevitably non-uniform set of observations. However, there are indicators that can be measured and/or observed. For individual mammals, changes in behavior, growth, health and condition, habitat-use patterns (including range), reproductive value, and survival may result from exposure to anthropogenic sounds. For populations, changes in abundance and trends, average health and condition, reproductive and survival rates, age structure, habitat-use patterns, distribution, and migration may result from such exposure. In turn, population-level effects may adversely and significantly alter important characteristics of marine ecosystems (e.g., biodiversity, trophic relations). Understanding such effects is a considerable scientific challenge. Progress is being made, but our current understanding of them remains rudimentary in many respects.

POINTS TO REMEMBER

Measurement of the effects of anthropogenic noise in the ocean on marine mammals must be considered a long-term investment in interdisciplinary research among ocean acousticians, marine biologists, and oceanographers. Given the diversity of the species and their biological, physical, and acoustic environments, properly quantifying these effects will require a commitment to continued, well-directed, long- and short-term research. The results will provide a basis for successful management of any potential effects on marine mammals and marine ecosystems. The research cannot be solely observation-driven but must include physics-based models of the functions critical to mammal life—communication, navigation, foraging, and predator population, among others.

ACKNOWLEDGEMENTS

Writing a primer about a complex subject is much more difficult than writing a journal article about it. Equations, acronyms, information, and concepts learned over a lifetime keep getting in the way. What should be covered and what should not be covered is easy but attempting to explain the material in a simple way without leaving a reader with a false image is a skill that is not easily acquired. We owe much to the late Kevin Fox for his ability to create the graphics that were used in the primer. We were fortunate to have the guidance, advice, and dedication of Timothy J. Ragen, Executive Director of the Marine Mammal Commission, throughout the process. His keen perception and knowledge of marine mammals made the primer possible, and we owe him a deep debt of gratitude.

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GLOSSARY

Absorption – the loss of energy from an acoustic signal due to a conversion of a portion of its energy to an acoustically, non-contributing energy, such as heat

Ambient acoustic sound – time-averaged background sound in a local region

Amplitude – the maximum value of a periodic wave such as a sine wave (For waves more complex than a sine wave, other definitions may be used.)

Analyzer, spectrum – an instrument designed to measure the spectrum level of a source

Anechoic room – a room that is both isolated from external noises and has highly absorbent walls; thus, neither outside noises nor echoes can be heard in the room

Array – a coupled, combination of generators of sound or receivers of sound

Array, circular-plane – a coupled, combination of generators of sound or receivers of sound that have been constructed as a flat, circular panel

Array, line – a coupled, combination of generators of sound or receivers of sound that have been constructed in a single line

Array, towed – a coupled, combination of generators of sound or receivers of sound (or both) that is towed behind a ship or boat

Attenuation – the loss of acoustical energy as it propagates

Audiogram – a graph of the threshold of hearing as a function of frequency

Blue water ocean – the ocean's volume over large, deep ocean basins

Cetaceans – the scientific term used to describe the family of all whales, dolphins, and porpoises

Decibel – one/tenth of the logarithm (to the base 10) of a dimensionless number (For acoustics, the dimensionless number is usually the ratio of the absolute value of an acoustic quantity such as acoustic pressure or intensity to an established reference value.)

Density – material per unit volume

Directivity – a three-dimensional plot of the level of sound generated by a source or the sensitivity of a receiving system as a function of direction

Energy, kinetic – the time-averaged energy contained in the acoustic particle velocity component of disturbance

Energy, potential – the time-averaged energy contained in the acoustic pressure component of disturbance

Energy, total – the time-averaged sum of the potential energy and the kinetic energy

Field, far – the space around a source greater than approximately three times the source's largest dimension

Field, near – the space around a source less than approximately three times the source's largest dimension

Frequency – the number of periods that occur in a second

Geometric spreading – describes the decrease in intensity and apparent weakening of an acoustic signal due to the spatial spreading of a finite amount of energy as it gets farther from a source

Hearing – sensing the motion of the eardrum or its equivalent

Hearing-centric – use hearing as their primary sensor

Homogeneous, acoustically – has the same acoustical characteristics everywhere

Hydrophone – an underwater mechanical sensor that detects pressure changes

Infrasonics – sounds whose frequencies are below the limit of human hearing range

Instances – a copy

Intensity, acoustic – the total acoustic energy that passes by a location in a second over a unit area

Inviscid – without viscosity (friction)

Isothermal layer, deep – the deeper regions of the world's oceans where the temperature is constant and the sound velocity increases with depth

Isotropic, acoustically – acoustical characteristics do not depend on the direction of sound travel (i.e., the sound travels equally in all directions)

Level, intensity – the decibel value of the actual intensity divided by a reference intensity

Level, sound pressure – the decibel value of the actual sound pressure divided by a reference sound pressure (The reference sound pressure for water measurements is not the same as the reference sound pressure for air measurements.)

Level, spectrum – the acoustic pressure in 1-Hz intervals divided by a reference level and converted to decibels

Littoral zone – shallow regions near the water-land boundary of the ocean

Masking – the condition whereby the presence of one sound (pure tone, narrowband or broadband) increases the threshold of hearing for a second sound

Meter, sound-level – an instrument used to measure sound pressure level (Most sound- level meters used to measure the sound level in air incorporate filters designed to match human hearing.)

Microphone – an air mechanical sensor that may detect either pressure changes or particle velocity changes

Molecular agitation (or thermal agitation) – noise produced directly by the motion of water or air molecules whose average speed does not average to zero

Noise – useless information

Noise, broadband – noise level is relatively smooth, with noise spread over many frequencies

Noise, narrowband – noise contained in narrow bands of frequencies, usually surrounded by lower levels of noise

Ocean traffic – noise produced by ship and boat movement

Particle velocity, acoustic – the change in the average mechanical speed of the molecules that make up a disturbance

Pattern, acoustic radiation – a three-dimensional plot of the level of sound generated as a function of direction

Period – the smallest increment of time for which a signal repeats itself

Phase – the difference in the start time of two identical sine waves

Pinnipeds – seals, sea lions, and walruses that function on land and in water and that use flippers for movement both on land, on ice, and in the water

Power, acoustic – the total acoustic energy that passes by a location in a second

Pressure, acoustic – the change in the absolute pressure due to the presence of sound

Propagation, sound – the process of sound travel

Reflection – the change in direction of a sound wave as it strikes an interface

Reflection, specular – a mirror-like reflection

Refraction – a change in the direction of a sound wave due to changes in sound velocity in a material

Relaxation process – an absorption process whereby energy is converted from an acoustic signal and returned to it at a later time, often incoherently

Relaxation time – the time interval in a relaxation process between the conversion of the acoustic energy and the “attempted” return of the energy to the acoustic signal

Reverberation – the temporal or spatial “spreading out” of a signal as it travels in the ocean due to a variety of causes

Reverberation, surface – reverberation caused by surface reflection effects

Reverberation, volume – reverberation caused by objects in the path of the signal, such as fish

Scattering – incoherent reflection of an acoustic signal from an interface

Sea state (0–6) – a measure of the variability of the air-ocean surface interface (sea state 0 signifies a "flat" surface; sea state 6 signifies mountainous seas caused by severe storms.)

Seismic disturbances – noise produced by earthquakes and volcanoes

Shadow zone – locations in the ocean where sound does not seem to penetrate due to the locations of the source, the receiver, and the sound velocity profiles in the region between the two

Signal – useful information

Signal-to-noise ratio – the signal divided by the noise (dimensionless), used to quantify the quality of the signal

Sine wave – a cyclic waveform derived from a mathematical function

Sine wave, complex – a sum of sine waves of different frequencies, amplitudes, and phases

Sine wave, continuous – a virtually never-ending string of sine waves

Sine wave, pulsed – a single sine wave of short duration or a continuous set of a few repeated sine waves of short duration

Sonar – an instrument used to search acoustically for an underwater object

Sonar, active – an instrument that both generates sound and receives sound while searching for an underwater object

Sonar, passive – an instrument that only receives sound while searching for an underwater object

Sound – a mechanical disturbance that moves through a material

Sound channel – a condition caused by the sound velocity profiles between a source and a receiver that "trap" the sound energy and allow it to travel over basin-scale distances

Sound ray – the appearance of sound as it travels over large distances

Sound velocity profile – graph of the speed of sound in the ocean as a function of depth

Source – a generator of sound energy

Source, anthropogenic – a source of sound generated or caused by a human, such as in speaking or operating a sonar device

Source, biological – a source of sound generated by non-human, living organisms, such as fish or marine mammals

Source, non-living – a source of sound generated by non-living phenomena, such as rain, volcanoes, or earthquakes

Source, omni-directional – a generator of sound that radiates sound energy in all directions equally

Source, point or small – a generator of sound that is small compared with the wavelength under consideration

Spectrum – a graph of the acoustic pressure in 1-hertz intervals

Surf zone – shallow regions close to the land at water-land boundary of the oceans

Surface layer – the layer of ocean near the surface, usually with little variation in sound velocity

Surface waves – large-scale raising and lowering of the ocean surface due to waves and swells, resulting in generation of acoustical noise in the ocean

Thermal agitation (or molecular agitation) – noise produced directly by the motion of water molecules whose average speed does not average to zero

Thermocline, main – the region of the ocean where the sound velocity essentially follows the temperature profile until the temperature levels off

Thermocline, seasonal – a thin ocean layer with highly variable sound velocity above the main thermocline

Threshold of hearing – the particular frequency at which a sound is barely able to be heard

Threshold shift, permanent – permanent decrease in hearing sensitivity due to some cause

Threshold shift, temporary – temporary decrease in hearing sensitivity due to some cause

Time, long – in acoustics, an interval of time longer than a few periods of the sound wave under consideration

Time, short – in acoustics, an interval of time shorter than one period of the sound wave under consideration

Transducer – a microphone or hydrophone

Transduction – the process of converting energy from one form to another

Turbulent-pressure fluctuations – usually referred to as noise produced by random motion of the water due to wave movement

Velocity, sound – the speed with which a disturbance travels in a material

Viscosity – friction

Vision-centric – using vision as a primary sensor

Wavelength – the smallest increment of distance for which the sine wave repeats itself

BIOGRAPHIES OF AUTHORS

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Dr. David L. Bradley is a senior scientist in the Applied Research Laboratory at Pennsylvania State University and head of the lab's Acoustics Division and the Environmental Acoustics Department. He received his B.S. degree in physics from Michigan Technological University, an M.S. in physics from Michigan State University, and a Ph.D. in mechanical engineering (applied physics/underwater acoustics) from Catholic University. Dr. Bradley has been active in establishing the Applied Research Laboratory as a leader in autonomous underwater vehicle technology for marine science. In addition, he has become an expert in understanding the oceanic limits on high-frequency coherence and the development of hydrodynamic surface ship wake models and their use in calculating the acoustic field within a turbulent wake structure. Prior to coming to Pennsylvania State University, Dr. Bradley was member of the staff at various U.S. Navy facilities, including the Naval Ordnance Laboratory, the Naval Ocean Research and Development Activity, the Office of Naval Research, and the Naval Research Laboratory. He later became director of NATO's Undersea Research Centre, La Spezia, Italy, before coming to Pennsylvania State University. Dr. Bradley is a Fellow of the Acoustical Society of America and a former member of its Executive Council. He is active in the State College Chapter of the Acoustical Society of America and is a member of the American Geophysical Union. He has authored or co-authored more than 60 publications.

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Dr. Richard Stern has a research rank of senior scientist in the Applied Research Laboratory at Pennsylvania State University. He also has an academic rank of professor of acoustics in the graduate program in acoustics, College of Engineering, Pennsylvania State University. Within the laboratory, he is the head of the Research and Academic Programs Office, which administers the Division of Acoustics and the Division of Information Sciences and Technology. Before coming to Pennsylvania State University in 1984, Dr. Stern was a professor of engineering and applied science for 18 years at the University of California, Los Angeles, where he and his students investigated issues in physical acoustics, medical acoustics, and underwater acoustics. Dr. Stern is a co-editor for Academic Press (Elsevier) on its Applications of Modern Acoustics series and co-edited the Handbook of Elastic Properties of Solids, Liquids, and Gases. Dr. Stern is a fellow of the Acoustical Society of America and a past president (2002–2003) of the society. He is also the editor of the society's publication Acoustics Today. He has been a member of the American Institute of Physics Governing Board and currently serves on its Publishing Policy Committee.

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