

# CHAPTER I

## OCEAN ACOUSTICS

### 1.1 GENERAL INTRODUCTION

Acoustics is the science of sound including its production, transmission and effects. In present usage, the term sound applies not only to the phenomenon in air responsible for sensation of hearing but also whatever else is governed by analogous physical principles. Thus, disturbances with frequencies too low (infrasound) and too high (ultra sound) to be heard by a normal person are also regarded as sound. One may speak of underwater sound, sound in solids, or structure borne sound. In Acoustics the propagating wave is mechanical rather than electromagnetic as in optics.

The broad scope of acoustics as an area of interest and endeavor can be recognized to a variety of reasons. First, there is the ubiquitous nature of mechanical radiation, generated by natural causes and human activity. Then, there is the existence of the sensation of hearing, of the human vocal ability, of communication via sound, along with the variety of psychological influences sound has on those who hear it. Such areas as speech, music, sound recording and reproduction, telephony, sound reinforcement, audiology, architectural acoustics, and noise control have strong association with sensation of hearing. That sound is a means of transmitting information, irrespective of our natural ability to hear, is also a significant factor, especially in underwater acoustics. A variety of applications, in basic research and technology, exploit the fact that the transmission of sound is affected by, and consequently gives information concerning, the medium through which it passes and intervening bodies and inhomogenities. The physical effect of sound on substances and bodies with which it interacts presents other areas of concern.

The scope of acoustics has ever been increasing. Following is the list of some traditional areas of application in acoustics: Seismic waves, underwater sound, atmospheric sound, bioacoustics, hearing, psychoacoustics, communication, musical scales & instruments, room & theatre acoustics, noise, shock & vibration, electro acoustics, and Sonic & ultra sonic engineering. In modern days the domain of acoustics has broadened to include areas like oceanography, electrical & chemical, mechanical, architectural, visual arts, music, speech, psychology, physiology, medicine, earth & atmospheric sciences, etc. With the advancement of computers the branch of acoustics has become easier and more applicable to broader areas. One such area is of computational ocean acoustics which is dealt with in this text.

## **1.2 OCEAN ACOUSTICS**

Oceans are a vast, complex, optically opaque but acoustically transparent world which is only thinly sampled by today's limited science and technology. Underwater sound is used as the premier tool to determine the detailed characteristics of physical and biological bodies and processes in the ocean. The distributions within the sea of the physical variables affect the transmission of sound. The wide range of acoustic frequencies and wavelengths, together with the diverse oceanographic phenomena that occur over full spectra of space and time scales, thus give rise to a number of interesting effects and opportunities. Because of its great practical importance, especially to naval submarine operations, ocean acoustics research has been driven by applications more than other branches of ocean science.

The intensity and phase of sound field generated by an acoustic source in the ocean can be deduced, in principle, by solving either the wave equation or the Helmholtz equation

in the case of a harmonic acoustic source. However, this procedure is generally difficult to implement due to the complexity of the ocean-acoustic environment: the sound speed profile is usually non-uniform in depth and / or range, giving rise to waveguide, focusing and shadowing effects; the sea surface is rough and time dependent; the ocean floor is typically a very complex, rough boundary which may be inclined to the horizontal; and the bottom may be an elastic medium, capable of supporting shear along the ocean or bottom boundary. To compound the problem, various ocean processes, including internal waves and small-scale turbulence, introduce small fluctuations in the sound speed, which are responsible for significant acoustic fluctuations over long transmission paths.

Analytical solutions of the governing differential equations in underwater acoustics are not always feasible and can only be obtained if the physical boundaries can be described simply in mathematical terms. This is rarely the case in engineering and so it is generally necessary to employ approximate numerical methods. A variety of numerical techniques has been developed for estimating sound fields in the ocean but no single method is capable of handling all possible environmental conditions, frequencies and transmission ranges of interest in the applications (Buckingham, 1992). Even so, many of the existing ocean-acoustic propagation models are highly sophisticated and may take several hours to run on the fastest available supercomputer. A completely general model is unlikely to be developed in the foreseeable future. These acoustical models are derived from the basic equations of conservation of mass and momentum for the fluid continuum.

Several different types of solution for the sound field in the ocean have evolved over the past fifty years: ray tracing provides a very graphic picture of the field; normal mode techniques are a natural alternative to rays, and coupled-mode models have been

developed that are accurate but computationally intensive; the parabolic-equation is an approximation to the wave equation that has been solved using explicit and implicit finite difference schemes; Green's function solutions (Fast Field Programs) are essentially exact but are restricted to horizontally stratified media; and finite element methods, which are very versatile, are computationally demanding and require further development before becoming widely available.

### 1.3 OCEAN ACOUSTICS ENVIRONMENT

#### 1.3.1 SOUND SPEED

The most important parameter that affects the propagation of acoustic waves within ocean is the speed of sound ( $c$ ) which has a nominal value of 1500 m/s. Density variations also influence acoustic propagation, but these are negligibly small over the entire oceanic water column. The speed of sound in the ocean is an increasing function of temperature, salinity and pressure (or depth). A simple empirical expression for the sound speed (m/s) in terms of these quantities is due to Mackenzie (1981) and is as follows:

$$c(T, s, z) = 1448.96 + 4.591T - 0.591T^2 - 0.05304T^3 + 2.374 \times 10^{-4}T^4 + 1.34(s - 35) \\ + 0.0163z + 1.675 \times 10^{-7}z^2 - 0.01025T(s - 35) - 7.319 \times 10^{-13}Tz^3 \quad (1.1)$$

where  $T$  is temperature in degree celsius,  $s$  is the salinity in parts per thousand, and  $z$  is the depth in meters. Eqn. (1.1) is valid for all depths up to 8000 m, for temperatures between  $-2^\circ\text{C}$  and  $30^\circ\text{C}$ , and for salinities between 25 and 40 ppt. It may be noted that ideal waveguide models for which exact solutions are available cannot account for sound speed variation shown in Eqs. (1.1). If the variation of sound speed profile is independent of range, the ocean is said to be horizontally stratified. Several of the numerical ocean-acoustic propagation models assume horizontal stratification, the advantage, from the

point of view of the computation, being that the solution field separates into range and depth components, which simplifies the calculation of the field considerably. The speed of sound in the ocean shows only small departures (of order 1 %) from 1500 m/s, but nevertheless its effect on sound propagation on the ocean is profound. In the deep ocean, the sound speed profile acts as an acoustic waveguide, supporting propagation to long ranges with little attenuation.

### 1.3.2 SOUND SPEED PROFILE

Seasonal and diurnal changes affect the oceanographic parameters in the upper ocean. In addition all of those parameters are functions of geography. A typical sound speed profile

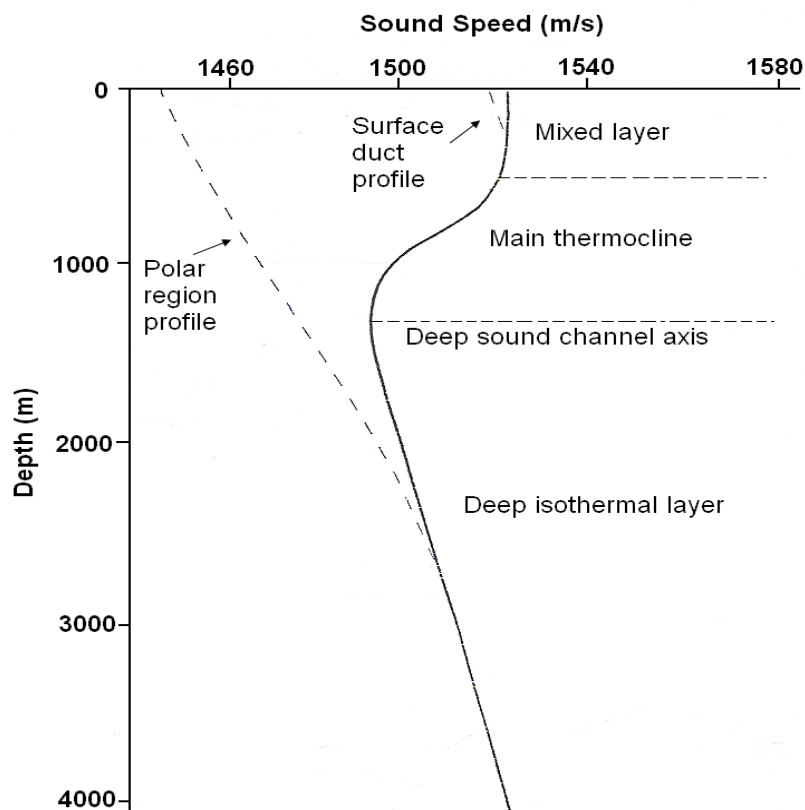


Fig 1.1 Generic sound speed profile

indicating greatest variability near the surface as a function of season and time of the day. In a warm season or warmer part of the day the temperature increases near the sea

surface and hence the sound speed increases towards the sea surface. This near surface heating (or subsequent cooling) has a profound effect on surface ship sonar. Thus the diurnal heating causes poorer sonar performance in the afternoon and this phenomenon known as afternoon effect.

In non polar regions, the oceanographic properties of the water near the surface result from mixing due to wind and wave activity at the air sea interface. This near surface mixed layer has a constant temperature (except in calm, warm surface conditions as described above). Hence, in this isothermal mixed layer we have a sound speed profile which increases with depth because of the pressure gradient effect. This is the surface duct region and its existence depends on the near surface oceanographic condition. Note that, the more restless the upper layer is, the deeper the mixed layer and less likely will there be any departure from the mixed layer part of the profile depicted. Hence, an atmospheric storm passing over a region mixes the near surface waters so that a surface duct is created or an existing one deepened or enhanced.

Bellow the mixed layer is the thermocline layer where the temperature decreases with depth and therefore the sound speed also decreases with depth. Bellow the thermocline, the temperature is constant ( $2^{\circ}\text{c}$  – thermodynamics property of salt water at high pressure) and sound speed increases due to increasing of the pressure or depth. Therefore, between the deep isothermal region and the mixed layer we must have a minimum sound speed which is often referred to as the axis of deep sound channel. However, in polar region the water is coldest near the surface and hence the minimum sound speed is at the ocean- air (or ice) interface.

In continental shelf regions (Shallow water) with water depth of the order of a few hun-

dred meters, only the upper part of the sound speed profile in Fig 1.1 is relevant. Thus upper region is dependent on season and time of the day, which in turn affects sound propagation in water column.

Generally we consider the sea surface is a simple horizontal boundary and a nearly perfect reflector and on the other hand the sea floor is a lossy boundary with strongly varying topography across wave basins. Both boundaries have small scale roughness associated with them which causes scattering and attenuation of sound. The sea bed is in general quit flat, even close to sea mounts, ridges and the continental slops with a slope seldomly exceeding  $10^\circ$ .The importance of treating the ocean bottom accurately in the numerical models depends on the factors such as source receiver separation, source frequency and ocean depth. The bottom interaction is in general unimportant for large range, high frequency and deep water due to the upward refracting sound speed profile. On the other hand a correct treatment of the bottom as a visco-elastic medium is crucial for a short range low frequency and shallow water propagation.

## 1.4 SOUND PROPAGATION IN OCEAN

### 1.4.1 SNELL'S LAW

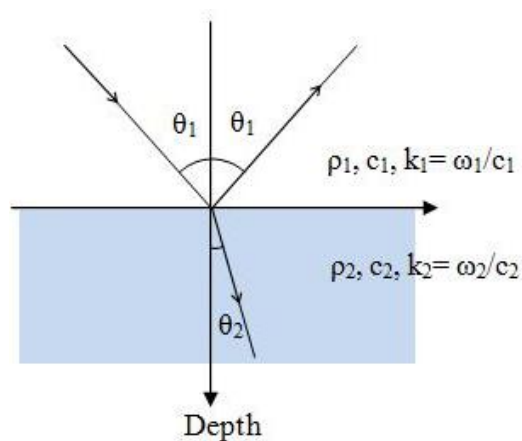


Fig 1.2 Snell's law (sound path)

Fig 1.2 is a schematic of the basic type of propagation in the ocean resulting from the sound speed profile (see Fig 1.1). The sound path can be understood from Snell's law.

$$\text{Snell's law: } \frac{\sin \theta_1}{c_1} = \frac{\sin \theta_2}{c_2}. \quad (1.2)$$

From Snell's law we can conclude that sound bends towards the region of low velocity and bends away from the region of high velocity.

The other forms of the Snell's law is  $(\cos \theta_1)/c_1 = (\cos \theta_2)/c_2$ , where  $\theta_i, i = 1, 2$  are the angle with the horizontal.

#### 1.4.2 CHARACTERISTIC PROPAGATION PATH

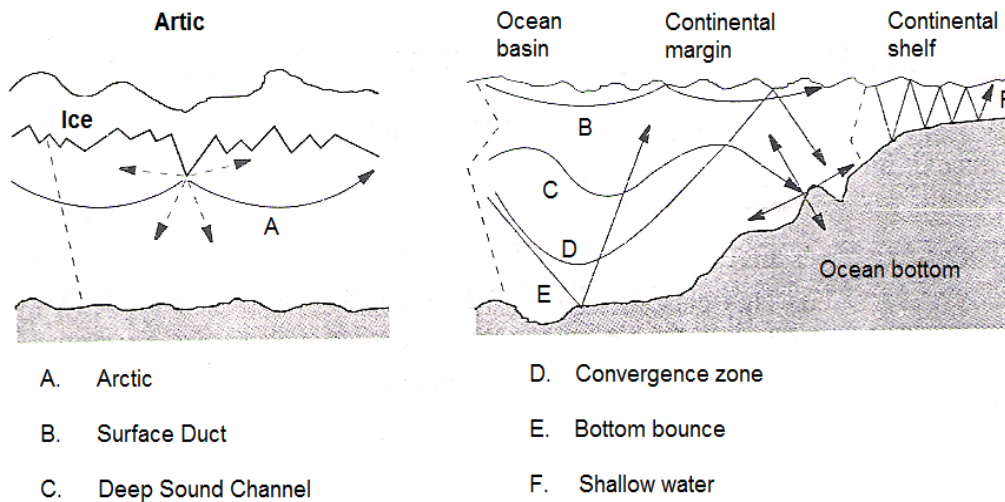


Fig 1.3 Characterization of paths

Paths A and B corresponds to surface duct propagation where the minimum sound speed is at the ocean surface or beneath the ice cover for Arctic case.

Path C depicted by a ray leaving a deeper source at a shallow horizontal angle propagates in the deep sound channel whose axis is at the shown sound speed minimum. For mid latitude sound in the deep channel can propagate long distance without interacting with



lossy boundaries, low frequency propagation via this path has been observed to distances of thousand of km.

Path D, which is at slightly steeper angle than those associated with path C is convergence propagation, a spatially periodic ( $\sim 35 - 70$  km) refocusing phenomenon producing zones of high intensity near the surface because of upward refracting nature of the deep sound speed profile.

Note that there may be exists such depth in the deep isothermal layer at which the sound speed is same as the surface, this depth is called Critical depth and is the lower limit of the deep sound channel.

A receiver bellows this critical depth will only receive sound from distant shallow sources via surface interacting paths. A positive critical depth or depth excess specifies that the environment supports that the long distance propagation without bottom interaction, where as negative critical depth implies that the sea floor is the lower boundary of the deep sound channel.

The bottom bounce path E is also a periodic phenomenon but with shorter cycle distance and a shorter total propagation distance because of loses when sound is reflected from the ocean bottom.

The path F depicts the propagation in shallow water region. Here, sound is channeled in a waveguide bounded above by the ocean surface and bellow by the ocean bottom. Because of the existence of negative critical depth environment exhibit much of the sound propagation physics descriptive of shallow water environments.

Therefore for our convenience we can alternatively classifies the ray paths in the ocean which is briefly introduced.

Type of Rays:

1. Rays propagating via refracted path only is called Refracted & Refracted (RR rays) :

Path C.

2. Rays bouncing off at sea surface and called Refracted & Surface–reflected (RSL rays): Path A, B and D.

3. Rays bouncing off the sea floor and called Refracted & Bottom–reflected (RBR rays): Path E.

4. Rays reflected off both the sea surface and the sea floor and called Surface–reflected & Bottom–reflected (SRBR rays): Path F.

Clearly SRBR paths are the most lossy since they are subject to all of the lose mechanism present in the ocean waveguide. On the other hand RR path only affected by the attenuation and scattering within the water column (no boundary loses).

### **1.4.3 DEEP WATER**

The principal characteristics of deep water propagation is the existence of an upward refracting sound speed profile which permits long range propagation without significant of bottom interaction. Hence, the important ray path is Refracted & Refracted (RR) or Refracted & Surface-reflected (RSB). Typical deep water environment are found in all ocean at depths exceeding 2000 m.

CONVERGENCE-ZONE PROPAGATION: The acoustic field pattern shown in Fig 1.4 is definitely one of the most interesting features of propagation in the deep ocean. This pattern referred to as a convergence zone (CZ) propagation because the sound emitted from a near surface sources forms a downward directed beam which after following a deep refracted path in the ocean reappears near the surface to create a zone of high sound

intensity (convergence of focusing) at a distance of tens of kms from the source. The phenomenon is repetitive in range, with the distance between the high intensity regions called Convergence-zone range. The importance of convergence-zone propagation stems from the fact that it allows for long-range transmission of acoustic signals of high-intensity and low-distortion.

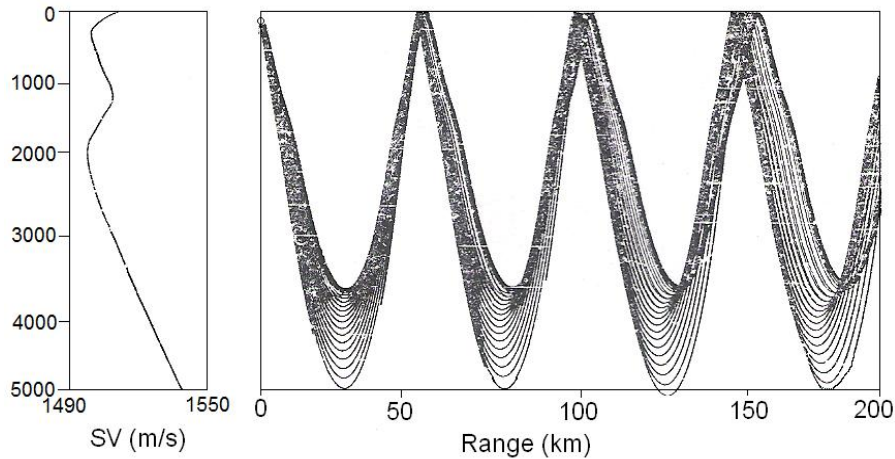


Fig 1.4 Convergence zone propagation

A necessary condition for the existence of deep refracted paths in the ocean is that the sound speed near the bottom exceeds that at the source. This condition is easily verified by the Snell's law. Thus the launch angle for a ray grazing the bottom is given by  $\cos \theta_0 = c_0/c_b$ ,  $c_0, c_b$  are the sound speed at the source and the bottom. Clearly if  $c_b \geq c_0$  then the ray exits. The requirement of "depth-excess" in the profile means that CZ propagation for shallow sources is possible only for water depth exceeding about 3500 m in Atlantic and 2000 m in Mediterranean.

The necessary condition for Convergence- zone propagation:

1. Sound speed near sources is must less than the sound speed at the bottom, i.e their exits positive depth excess.

2. Source must be near to the surface so that the up and down going rays generate a well-collimated beam in the downward direction.
3. To avoid ducting near the surface (mixed modes of propagation) the source must be in a region of decreasing sounds peed with depth.

To this end we introduce a liberalized version of the real sound speed profiles with the sound speeds at the interfaces and the sound speed gradients denoted by  $c_i$  and  $g_i$ .

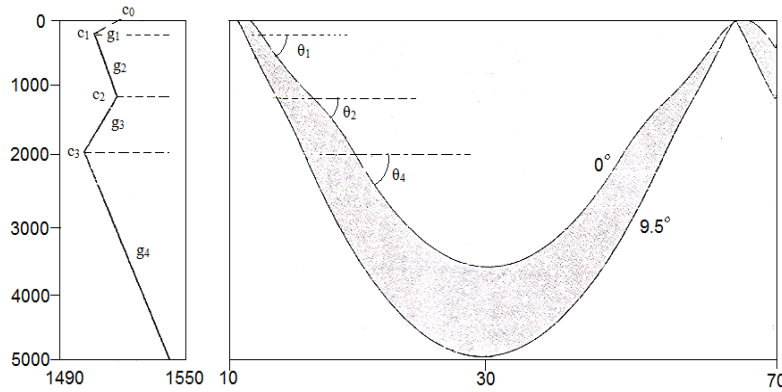


Fig 1.5 CZ paths for liberalized version of sound speed profile

$$\text{The range } R_{\text{CZ}} = 2c_0 \left[ \frac{\sin \theta_1}{|g_1|} + \frac{\sin \theta_1 - \sin \theta_2}{|g_2|} + \frac{\sin \theta_3 - \sin \theta_2}{|g_3|} + \frac{\sin \theta_4}{|g_4|} \right], \theta_i = \cos^{-1} \frac{c_i}{c_0}. \quad (1.3)$$

**DEEP SOUND CHANNEL PROPAGATION:** Propagation in the deep sound channel, also referred to as the SOFAR channel. This internal sound channel allows for sound transmission entirely via refracted paths, which means that a portion of the acoustic power radiated by the source in the channel propagates to long ranges without encountering reflection losses at the sea surface and the sea floor. Because of the low transmission loss of acoustic signals from small explosive charges in the deep sound channel have been recorded over distance of thousand kilometers in some case even half way around the world.

The deep sound channel is not equally effective as a waveguide at all latitude. As the sound channel axis (minimum sound speed) varies in depth from 1000 m at mid latitudes to the ocean surface in polar regions.

A necessary condition for the existence of the low loss refracted path is that the sound speed axis is below the sea surface since otherwise the propagation becomes entirely surface-interacting and lossy. Moreover, the portion of the source power trapped in the waveguide is directly proportional to the aperture of ray angles propagating as internally refracted rays.

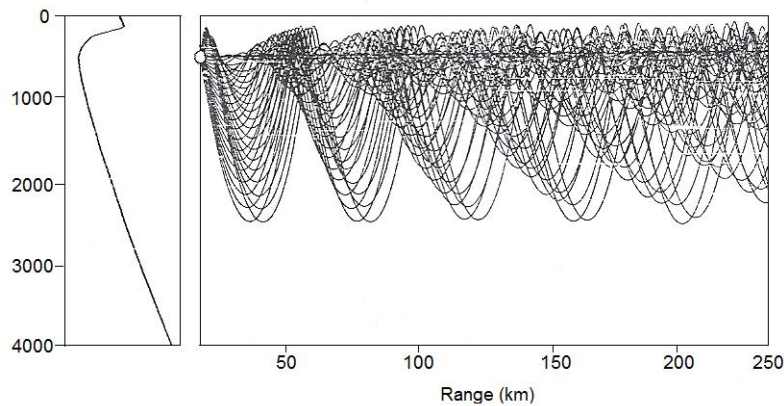


Fig 1.6 Deep sound channel propagation

For a source the aperture is straight forwardly determined from Snell law as  $\theta_{\max} = \cos^{-1}(c_0/c_{\max})$ ,  $c_0$  is the sound speed at the channel axis (min. sound speed) and  $c_{\max}$  is the maximum sound speed between the channel axis and the sea surface (normally at the bottom of the mixed layer). Consequently, the deep sound channel is most effective as a waveguide at mid to moderately high latitudes, where also the major part of the long range transmission experiments have been performed.

**SURFACE DUCT PROPAGATION:** In temperate, windy regions of the world's oceans the temperature profile regularly shows the presence of an isothermal layer just

beneath the sea surface. This layer of isothermal water is maintained by turbulent wind mixing, extending deeper after a heavy storm and becoming shallower again during a period of light winds. There is also seasonal dependence of the mixed layer depth. Absolutely the isothermal mixed layer acts as a waveguide because of the slight increase in sound speed with depth (0.016 m/s/m) caused by hydrostatic pressure. The result is that a portion of the acoustic energy emitted by a source placed in the mixed layer will be trapped in the surface duct. For a source depth near about 40 m depth, the ray diagram shows that the energy emitted with a cone of  $\pm 3^\circ$  is trapped in the duct, whereas the steeper rays leave the duct and propagate via deep refracted path. The result is that a shadow zone is formed, limited above by the lower boundary of the surface duct and to the left by the ray leaving the source at an angle slightly steeper than the critical angle for trapping within the duct. The surface duct is not very stable feature since a heating of upper layers, for example just by  $1^\circ\text{C}$  increases the sound speed by 3 m/s, thus transforming the duct into non guiding iso-speed surface layer.

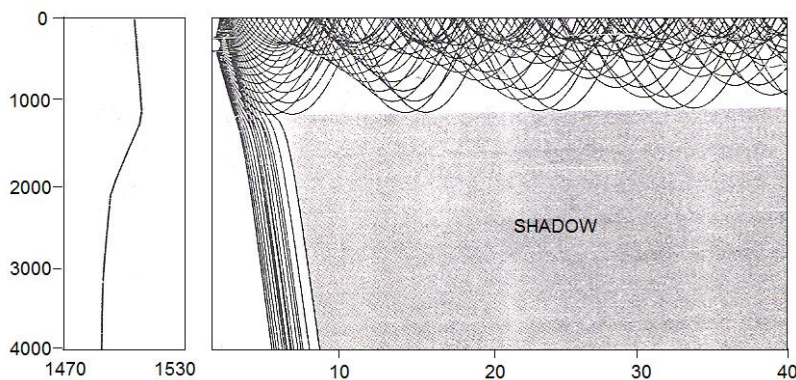


Fig 1.7 Surface duct propagation

Here we are given an approximate formula for the cut off frequency below which no energy can propagate in the surface duct. For an isothermal layer of depth  $D$  in meters the cut off frequency ( $f_0$ ) in Hz given by

$$f_0 = \frac{1500}{0.008D^{3/2}} \quad (1.4)$$

For example, a 150 m deep surface duct, the cut off frequency is 100 Hz. In general surface duct ( $D < 50$  m) is most common but they are effective waveguide only at high frequency where scattering losses are significant. The deeper ducts ( $D > 100$  m) are effective waveguide down to much lower frequencies but they are less frequently.

**ARCTIC PROPAGATION:** Propagation in arctic ocean is characterized by an upward refracting profile over the entire water depth causing energy to undergo repeated refractions at the underside of the ice. The sound speed profile can be often be approximated by two linear segments with a step gradient in the upper 200 m creating a strong surface duct followed by standard hydrostatic pressure gradient (0.016 m/s/m) below.

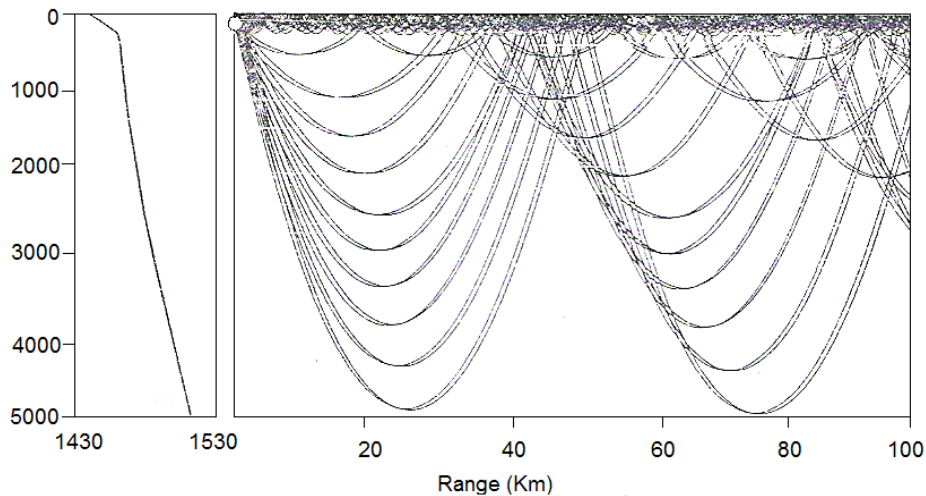


Fig 1.8 Arctic propagation

The ray diagram shows that the energy is partly channeled beneath the ice cover with the 200 m deep surface duct and partly follows deeper refracted path. However, all rays within a cone of  $\pm 17^\circ$  propagate along ranges without bottom interaction.

At low frequency sound is not trapped effectively in arctic sound channel. We can provide a simple estimate of the optimum frequency of propagation by recalling that the radiation pattern from a point source near a boundary is a series of Lloyd-mirror beams, which at high frequency are refracted within the water and for low frequency beams become steeper and bottom interacting.

Assuming that the optimum frequency coincides with the situation where the lower most Lloyd mirror beams just grazes the sea floor we have

$$f_{\text{opt}} = \frac{c_0}{4z_s \sin \theta_c} \text{ and } \theta_c = \cos^{-1} \frac{c_0}{c_{\text{max}}}, \quad (1.5)$$

Where  $c_0$ ,  $c_{\text{max}}$  is the sound speed at source, the sea floor and  $z_s$  is the source depth. With this definition of the optimum frequency all energy path for  $f < f_{\text{opt}}$  are bottom interacting and hence lossy. On the other hand for  $f > f_{\text{opt}}$  the lowermost Lloyd mirror beam just grazes the bottom and consequently one low loss refracted path exit.

Note that, the optimum frequency is primarily dependent on the source depth and the water depth (through  $\theta_c$ ). Thus a shallower source or small water depth both result in a higher optimum frequency.

**SHALLOW WATER PROPAGATION:** The principal characteristic of shallow water propagation is that the sound speed profile is downward refracting or nearly constant over depth, meaning that long-range propagation takes place exclusively via bottom interacting paths. The important ray paths are either refracted bottom reflected or surface reflected bottom reflected. Typical shallow water environments are found on the continental shelf for water depths down to 200 m. In shallow water, the surface volume and the bottom properties are all important and also the oceanographic parameter had a certain role to play in shallow acoustic propagation.



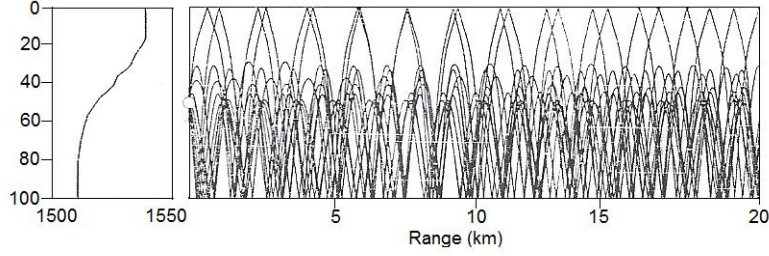


Fig 1.9 Shallow water propagation

A common feature of all acoustic ducts is the existence of a low frequency cut-off. Hence there is a critical frequency below which the shallow water channel ceases to act as a waveguide, causing energy radiated by the source to propagate directly into the bottom.

This cut of frequency can be calculated by the following formula

$$f_0 = \frac{c_w}{4D\sqrt{1-(c_w/c_b)^2}} \quad (1.6)$$

The expression is exact only for homogeneous water column depth  $D$  and the sound speed  $c_w$  overlying a homogeneous bottom of sound speed  $c_b$ . For rigid bottom that is  $c_b \rightarrow \infty$ , the cut off frequency occurs at  $D = \lambda/4$  where  $\lambda$  is the acoustic wave length.

## 1.5 SOURCES AND RECEIVERS

We are interested in modeling sound phenomenon generated by a source and received by a hydrophone. A brief description of such devices is presented here avoiding any detail for completeness and reference.

A transducer converts some type of energy into sound (sound or projector) or converts sound to some form of energy (receiver), usually electric. In underwater acoustics, piezoelectric and magnetostrictive transducers are used. The piezoelectric effect is a result of coupling between mechanical strain and electric field in certain crystals such as quartz, and certain composite materials such as lead zirconate titanate (PZT). Thus, such materials will exhibit a potential difference between the various faces of the crystal when

undergoing mechanical strain, and vice versa. Note that there is an electrostrictive effect which is common to all dielectrics but is much smaller than the piezoelectric effect: an electric field mechanically deforms the dielectric by inducing the dipole moments. Magnetostriction is the change in dimensions of a ferromagnetic material when it is placed in a magnetic field and the change in magnetization when the material dimensions change due to an external force.

Some other transduction mechanisms employed are electrodynamics where, for example, sound pressure causes a coil to move through a magnetic field thereby generating an output voltage. This electromagnetic principle is the same principle used in electric generators. Electric motors and sound sources utilize the reverse effect.

Parametric elements or finite-amplitude sources are sound projectors which are excited by two high amplitude primary frequencies. The non-linearity of the medium results in the formation of sum and difference-frequency waves and their harmonics in the region in front of the projector. In practice, the primary frequencies are high so that all but the difference-frequency waves are attenuated after a short distance. Hence, the projector behaves like a low frequency end fire array with exponential shading. The main disadvantage of parametric sources is that they have low efficiency.

The parametric receiver also exists. It uses a high frequency “pump” transmitter whose acoustic wave interacts with the signal to be detected. The output of the receiver is the sum and difference frequencies; the pump frequency is removed by a filter. The parametric receiver also behaves like an end fire array. Explosive and air gun sources are high energy wideband types of sources.. Electric discharge and laser sources are also being used.

## 1.6 RELAVANT UNITS ( DECIBELS)

The decibel (dB) is the dominant unit in under water acoustics and denotes a ratio of intensities (not pressures) expressed in terms of a logarithmic (base 10) scale. Two intensities  $I_1$  and  $I_2$  have a ratio  $I_1/I_2$  in decibels of  $10 \log_{10}(I_1/I_2)$  dB. Absolute intensities can therefore be expressed by using reference intensity. The presently accepted reference intensity is the intensity of a plane wave having a root mean squared (rms) pressure equal to  $10^{-6}$  Pascal (= N/m<sup>2</sup>) or a micro-Pascal ( $\mu$ Pa). Therefore taking 1  $\mu$ Pa as the reference sound pressure level, a sound wave having an intensity of, say, one million times that of a plane wave of rms pressure 1  $\mu$ Pa has a level of  $10 \log_{10} 10^6 = 60$  dB re 1  $\mu$ Pa. Pressure ( $p$ ) ratios are expressed in dB re 1  $\mu$ Pa by taking  $10 \log_{10}(p_1/p_2)$  where it is understood that the reference originates from the intensity of a plane wave of pressure equal to 1  $\mu$ Pa.

The average intensity  $I$  of a plane wave with rms pressure  $p$  in a medium of density  $\rho$  and sound speed  $c$  is  $I = p^2 / \rho c$ . In seawater,  $\rho c$  is  $1.5 \times 10^6$  Kg/ m<sup>2</sup>s, so that a plane wave of rms pressure 1  $\mu$ Pa has an intensity of  $I = (10^{-6})^2 / 1.5 \times 10^6 = 0.67 \times 10^{-18}$  W/m<sup>2</sup> i.e. 0 dB re 1  $\mu$ Pa as Decibel scales are also used to quantify sound pressure levels.

## 1.7 TRANSMISSION LOSS

An acoustic signal traveling through the ocean becomes distorted due to multi path effects and weakened due to various loss mechanisms. The standard measure in underwater acoustics of the change in signal strength with range is transmission loss defined as the ratio in decibels between the acoustic intensity  $I(r, z)$  at a field point and the intensity  $I_0$  at 1-m distance from the source, i.e.

$$TL = -10 \log_{10} \frac{I(r, z)}{I_0} \quad (1.7)$$

$$TL = -20 \log_{10} \left| \frac{p(r, z)}{p_0} \right| [\text{dB re 1m}] \quad (1.8)$$

Here we have made use of the fact that the intensity in a plane wave is proportional to the square of the pressure amplitude. Transmission loss may be considered to be the sum of a loss due to geometrical spreading and a loss due to attenuation. The spreading loss is simply a measure of signal weakening as it propagates outward from the source.

## 1.8 VOLUME ATTENUATION

### 1.8.1 ATTENUATION OF PLANE WAVES

Plane wave attenuation  $\alpha$ , which is a quantity defined from decay-law-type equation as,

$$\frac{dA}{dx} = -\alpha A \text{ that is } A = A_0 e^{-\alpha x} \quad (1.9)$$

where  $A_0$  is the rms amplitude at  $x=0$ . The unit of  $\alpha$  is nepers/m with  $x$  in meters. For example, a plane wave in free space with sound speed  $c$ , angular frequency  $\omega$ , and hence wave number  $k = \omega/c$ , that undergoes attenuation has the form

$$e^{ikx - \alpha x} = e^{ikx(1+i\delta)} \quad (1.10)$$

where  $\delta$  is called the loss tangent. The plane wave attenuation  $\alpha'$  is often expressed as a loss in decibels per unit distance,

$$\text{Loss} = -20 \log_{10} \frac{A}{A_0} \cong 8.686 \alpha x \text{ i.e. } \alpha' = 8.686 \alpha \quad (1.11)$$

where  $\alpha'$  is in dB/m (if  $x$  is in meters) and should be multiplied by 1000 to be in units of dB/km. When sound propagates in sea water part of the acoustic energy is continuously absorbed, i.e., the energy is transformed into heat. Moreover, sound is scattered by different kinds of inhomogenities, also resulting in a decay of sound intensity with range.

As a rule, it is not possible in real ocean experiments to distinguish between absorption and scattering effects; they both contribute to sound attenuation in sea water. An empirical formula for frequency dependence of the attenuation is,

$$\alpha' = 3.3 \times 10^{-3} + \frac{0.11f^2}{1+f^2} + \frac{44f}{4100+f} + 3.0 \times 10^{-4} f^2 \left[ \frac{dB}{km} \right] \quad (1.12)$$

where  $f$  denotes frequency in Hertz (Hz).

### 1.8.2 ATTENUATION IN SEA WATER

When sound propagate in the ocean, part of the acoustic energy is continuously absorbed, i.e. the sound energy transformed into heat. Moreover sound is scattered by different kinds of inhomogeneties also resulting in a decay of sound intensity with range. As a rule it is not possible in real ocean experiments to distinguish between absorption and scattering effects, they both contribute to sound attenuation in sea water.

The frequency dependence of attenuation can be roughly divided into four regimes of different physical origin as displayed in the figure.

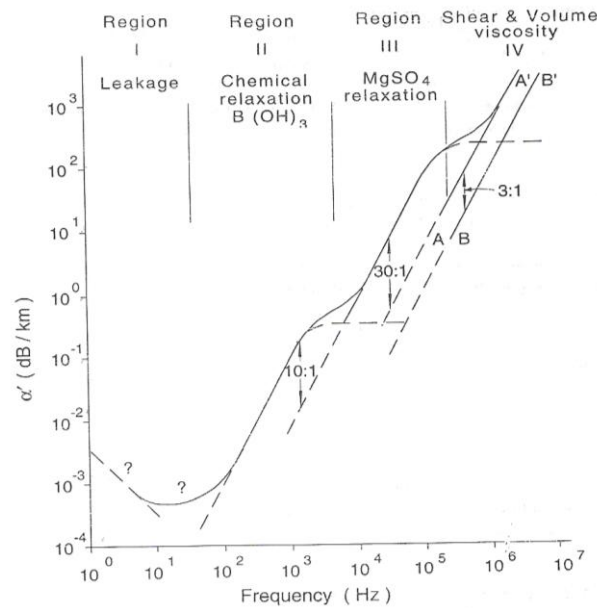


Fig 1.10 Regions of dominant process of attenuation of sound in sea water

A simplified expression for the frequency dependence ( $f$  in kHz) of the attenuation with the four terms sequentially associated with regions I to IV.

$$\alpha' \approx 3.3 \times 10^{-3} + \frac{0.11 f^2}{1 + f^2} + \frac{44 f^2}{4100 + f^2} + 3.0 \times 10^{-4} f^2 \text{ [db/km]} \quad (1.13)$$

The above expression applies for a temperature of 4°C, a salinity of 35 ppt, a pH of 8.0 and a depth of about 1000 m where most of the measurements on which it is based were made.

Even though the attenuation of sound in sea water has some dependence on temperature salinity and acidity and the above formula is sufficiently accurate for the most problem in ocean acoustics.

## **1.9 SURFACE, BOTTOM AND VOLUME SCATTERING**

Scattering is a mechanism for loss interference and fluctuation. A rough sea surface and sea floor causes attenuation of the mean acoustic field propagating in the wave guide. The attenuation increases with frequency. The field scattered away from the specular direction and in particular the backscattered field (called reverberation) acts as interference for active sonar system. Because the ocean sea surface moves, it will also generate acoustic fluctuations. Bottom roughness can also generate fluctuations when the sound source or receiver is moving. The importance of boundary roughness depends on the sound speed profile which determines the degree of interaction of sound with the rough boundaries.

## **1.10 BOTTOM LOSS**

When sound interacts with the seafloor, the structure of the ocean bottom becomes important. Ocean bottom sediments are often modeled as fluids which mean that they support only one type of sound wave – a compressional wave. This is often a good

approximation since the rigidity (and hence the shear speed) of the sediment is usually considerably less than that of solid, such as rock. In case, which applies to the ocean basement, the medium must be modeled as elastic, which means it supports both compressional and shear waves. In reality, the media are viscoelastic, meaning that they are also lossy.

A geoacoustic model is defined as a model of the sea floor with emphasis on measured, extrapolated and predicted values of those materials properties which are important for the modeling of sound transmission. In general a geoacoustic model details the true thickness and properties of sediment and rock layers within the sea bed to a depth termed the effective penetration depth. Thus at high frequencies, details of the bottom composition are required only in the upper few meters or ten meters of sediments whereas at very low frequency (<10 Hz) information must be provide on the whole sediment columns and on properties of underlying rocks.

#### SOME OBSERVATIONS:

1. Lower porosity results in a higher density and higher velocity.
2. The shear speed in sediments are quite low but increase rapidly with depth  $\bar{z}$  bellow the water-bottom interface.
3. Wave attenuation  $\alpha$  are generally in units of dB per wavelength indicating that the attenuation increases linearly with frequency.

#### **1.11 AMBIENT NOISE**

In under water acoustics, ambient noise becomes an issue when it makes a signal of interest. Ocean acoustic signal processing is essentially a procedure for extracting a signal embedded in noise. The noise is irrelevant if the signal is very strong. However the

more interesting case is the marginal situation of low signal to noise ratio ( $S/N < 1$ ). Here, we would like to exploit the difference in the physical properties of the signal of interest and the noise to be neglected.

For instance, omnidirectional noise can be reduced by directional receiver with narrow “look directions” (beams) while directional noise can be avoided by not looking in the direction of the noise.

The more general case of achieving “noise gain” , i.e enhancement of signal to noise ratio, is somehow factor into the design of a receiving system knowledge of the general distribution of the ambient noise, including its coherence properties.

There are two types of noise: manmade and natural. The man made noise primarily consists of shipping noise, through noise from offshore rigs is becoming more prevalent.

In general natural noise dominates at low frequencies ( $< 10$  Hz) and at high frequencies ( $> 300$  Hz) while shipping noise dominants in the intermediate regions from 10 to 300 Hz. The higher frequency wind noise is usually parameterized according to sea state or wind force.