

Investigation of underwater sound wave propagation characteristics for channel modelling

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Abstract

Unlike terrestrial communication which is based on radio communication principle, sound is the means of communication in underwater. This is because sea water conducts electricity pretty well, and anything that conducts electricity will absorb the electromagnetic energy of the radar and not allow it to penetrate. The dielectric constant of water is not good for RF propagation. However water is good for propagating sound wave though it propagates much slower than the RF waves. The distance that sound waves (which is a pressure waves) travel is vastly longer than Radio Waves in water. In underwater medium the propagation of sound is effected by characteristics such as velocity of sound wave, sound pressure and sound power, transmission loss of sound in underwater environment, sound absorption in sea water, viscosity, ionic relaxation and scattering. Sound waves while propagating underwater they get attenuated due to cylindrical and spherical spreading of the energy. In this paper, sound wave propagation characteristics are analyzed.

Keywords: Acoustic; Propagation Characteristics; Underwater.

1. Introduction

The underwater world covers 70% of our planet and hence, the possible use of this medium for the purpose of communication is a major issue for consideration. Traditionally, underwater has provided voice and low speed telegraphy capability. Now that we are in the global information age, underwater communication has caught on rapidly and much advancement has been made in this field. Communication using sound waves has been the primary means of underwater communications, mainly due to non propagation of EM waves in the underwater environment. It provides vital means of communication between ships, ships and submarines and also with AUV for their control and data transfer. In recent years, the specific issue of data communication has become an extremely important aspect of underwater communications. The characteristics of the underwater medium have proved to be the chief limiting factor in achieving the high rate data communication. The principal limitations that constrain the throughput and the error rate performance in the underwater channel are those of time-varying multipath and Doppler spreads [1].

In underwater scenario, this task becomes more complicated due to the channel that is offered by underwater environment. The first reason is that the speed of sound is very low in water i.e. approximately 1,500 meters per second, and the second reason is fanning out of the sound waves underwater which reach at the receiver after the main signal has arrived, which creates the fading of the signals at the receiver. This necessitates the additional processing in order to mitigate the errors those creep in because of this multipath phenomenon [2]. The use of Radio Frequencies (RF) has been highly restricted for communicating in the underwater scenario due to the fast attenuation of EM Waves in the underwater environment. So it is very essential to understand the characteristics of sound in underwater environment. In the subsequent para-

graphs investigation of underwater sound wave propagation characteristics are presented with necessary results.

2. Sound propagation in underwater medium

The basic theory of acoustics involves the study of vibration, waves and their propagation. If the direction of particle vibration is the same as the direction of wave propagation, then the wave is called a longitudinal wave. If the direction of particle vibration is perpendicular to the direction of wave propagation, then the wave is called a transversal wave. When a sound wave propagates in sea water, the structure of the water medium is changed, resulting in the spread of sound energy. The sensing of an underwater receiver for sound pressure is based on this sound pressure change. In the wave propagation process, particles in the sea water do not move from one place to another, but only vibrate around some fixed point. The acceleration speed of a particle is always proportional to the distance from a fixed point. This kind of motion is called resonance motion. It is the simplest form of periodic motion. The expression of a one-dimensional differential equation of resonance motion is

$$\frac{d^2x}{dt^2} + w^2x = 0$$

The solution of this equation is

$$x(t) = A \sin(\omega t) + B \cos(\omega t)$$

Where A, B are arbitrary constants and $\omega = 2\pi f$ is the cycle frequency with unit rad/s, and the unit of f is Hz [3].

2.1. Velocity of sound wave

Sound travels more slowly in fresh water than in sea water. The speed of sound is determined by the water's bulk modulus and mass density. The bulk modulus is affected by temperature, dissolved impurities (usually salinity), and pressure. The density effect is small. The speed of sound (in feet per second) is approximately:

$$4388 + (11.25 \times \text{temperature (in } ^\circ\text{F)}) + (0.0182 \times \text{depth (in feet)}) + \text{salinity (in parts-per-thousand)}$$

This empirically derived approximation equation is reasonably accurate for normal temperatures, concentrations of salinity and the range of most ocean depths. Ocean temperature varies with depth, but at between 30 and 100 meters there is often a marked change, called the thermocline, dividing the warmer surface water from the cold, still waters that make up the rest of the ocean. The acoustic devices may not produce the desired result as the sound originating on one side of the thermocline tends to be bent, or refracted, through the thermocline. The thermocline may be present in shallower coastal waters. However, wave action will often mix the water column and eliminate the thermocline. Water pressure also affects sound propagation: higher pressure increases the sound speed, which causes the sound waves to refract away from the area of higher sound speed [4]. The mathematical model of refraction is called Snell's law.

The propagation velocity c of sound in the sea can be derived from the following adiabatic equation

$$c = \left(\frac{\partial p}{\partial \rho} \right) = \frac{1}{\rho K_a}$$

where, p is the sound pressure, ρ is the density of water, and K_a is the adiabatic compression coefficient. In sea water, since pK_a is a function of temperature, salinity and pressure, the sound speed in sea water is also a function of temperature, salinity and pressure, but temperature is the dominant factor. In fresh water, the empirical formula for calculating sound speed is generally

$$c = 1410 + 4.21t - 0.037t^2 + 0.018d \text{ (m/s)}$$

Where, t is the temperature of sea water in $^\circ\text{C}$; d is the depth (m). $c \approx 1,500$ m/s, for $t = 20^\circ\text{C}$. The empirical formula for calculating sound speed in sea water is given by

$$c = 1410 + 4.21t - 0.037t^2 + 1.1S + 0.018d \text{ (m/s)}$$

Where S is the salinity (%). $C \approx 1,500$ m/s when $t = 14^\circ\text{C}$, $S = 34.5$, $d = 15\text{m}$.

Because the propagation characteristics of sound in the sea strongly depend on the sound speed, it is very important to understand the distribution of sound speed for any specific area. The relation between sound speed and depth is called the sound speed profile (SSP). The SSP is related to the latitude, season, and day/night [5].

2.2. Sound pressure and sound power

"Sound power" and "Sound pressure" are two distinct and commonly confused characteristics of sound. Sound power or acoustic power is a measure of the total sound power emitted by a source in all directions in watts (joules per second) per unit time. Sound power levels are connected to the sound source and are independent of distance. Sound power levels are indicated in decibel as follows

$$L_w = 10 \log_{10} \frac{I}{I_0}$$

Where sound power I_0 is chosen to be a reference sound power, define it as 0 dB, and then any other sound power I has the dB value of $20 \log I/I_0$ dB with respect to reference level.

Sound pressure is a pressure disturbance in the air whose intensity is influenced not only by the strength of the source, but also by the surroundings and the distance from the source to the receiver and diminishes as a result of intervening obstacles and barriers, air absorption, wind and other factors. Sound pressure levels quantify in decibels and the intensity of given sound sources are indicated in decibels [6].

$$\text{Sound pressure level (SPL)} \quad L_p = 10 \log_{10} \frac{P}{P_0}$$

Where sound pressure P_0 is chosen to be a reference sound pressure, define it as 0 dB, and then any other sound pressure P has the dB value of $20 \log P/P_0$ dB.

A frequently used method of estimating the sound power level at a source L_w is to measure the sound pressure level L_p at some distance, and solve for L_w . If the source is in free space

$$L_w = L_p - 10 \log_{10} \left(\frac{1}{4\pi r^2} \right)$$

Or if the source is on the floor or on a wall, such that it radiates into a half sphere.

$$L_w = L_p - 10 \log_{10} \left(\frac{2}{4\pi r^2} \right)$$

2.3. Transmission loss of sound in underwater

Transmission Loss is the parameter that compares the amount of intensity of the signal at a specific range from the source to the source intensity at one yard. The equation for this would be:

$$TL = 10 \log \frac{I(1yd)}{I(r)}$$

In sonar equations, transmission loss TL is an important parameter in sonar design because the performance of a sonar system depends only on the transmission loss. When a sound wave propagates in an ocean environment, the sound intensity will gradually decrease with travel distance, because of the following reasons:

- i) The geometrical spread of the wave front, spherical or cylindrical spreading,
- ii) The loss of the sound wave at the sea surface and the sea floor,
- iii) Sound absorption,
- iv) Sound reflection.

2.3.1. Spreading and cylindrical losses

Sound waves while propagating underwater they get attenuated due to cylindrical and spherical spreading of the energy. Cylindrical spreading presents underwater only when the sea surface and the sea floor are flat. However spherical spreading presents underwater in all kinds of sea environment [7]. The transmission loss increases linearly in both spherical and cylindrical spreading and the transmission loss due to spherical spreading is twice the transmission loss due to cylindrical spreading.

Spreading Loss

Let's assume a point source which emits a signal in all directions (that is in three dimensions). The source would produce wave fronts that were spheres that would grow in size as the wave propagates away from the source as shown in Fig 1.

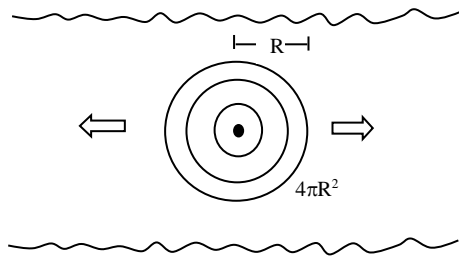


Fig. 1:Spherical Spread.

$$TL = 20 \log r$$

The above equation is for transmission loss only due to spherical spreading. In this case, from 1 m to 100 m, the intensity of the sound wave will attenuate by 40 dB. Spherical spreading is the most dominant factor in the transmission loss portion of the passive sonar equation. As the range increases the transmission loss increases linearly as shown in Fig 2 and the corresponding values are given in Table 1.

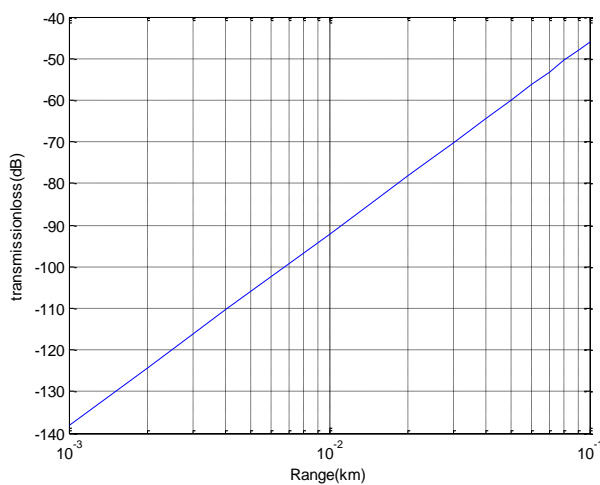


Fig. 2:Typical Transmission Loss Curve of Band Limited Signal.

Table 1:Range Prediction by Calculation of Transmission Loss for Spherical Spread

Range(m)	Transmission loss(dB)
1	-138.1
5	-105.9
10	-92.1
20	-78.2
50	-59.9
70	-53.1
100	-46.0

2.3.2. Cylindrical spreading

In the propagation of a sound wave, if the sea surface and sea floor are relatively flat, sound reflection and absorption are negligible, so the spread of a sound wave can be considered as cylindrical (Fig. 3). The transmission loss is proportional to the distance R [8]. As the range increases the transmission loss increases linearly as shown in Fig 4 and the corresponding values are given in Table 2. The transmission loss due to cylindrical spreading is half of the spherical spreading.

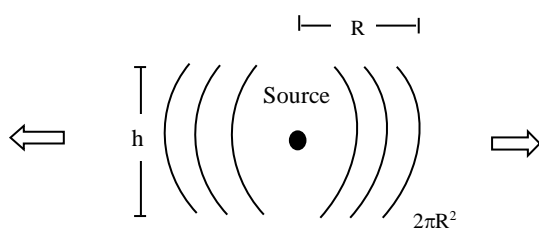


Fig 3:Cylindrical Spread.

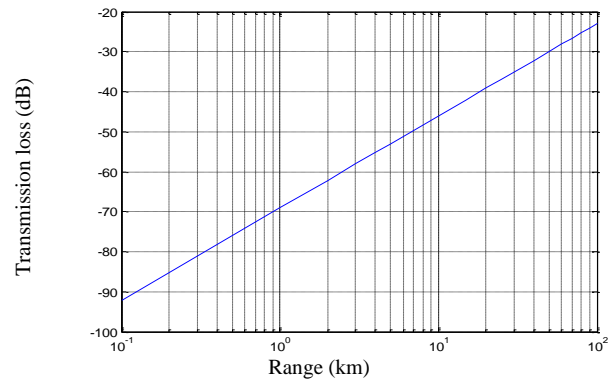


Fig. 4:Typical Transmission Loss Curve of Band Limited Signal.

Table 2:Range Prediction by Calculation of Transmission Loss for Cylindrical Spread

Range(m)	Transmission loss(dB)
1	-69.0
5	-52.9
10	-46.0
20	-39.1
50	-29.9
70	-26.5
100	-23.0

$$TL(R) = 10 \log R$$

The only limitation of this equation is that it does not take into account the spreading of the wave spherically until it reaches the “transition range” where the wave starts to spread cylindrically.

2.4. Sound absorption in underwater

Sound absorption in sea water is one of the important characteristics of an acoustic channel. This is because, as the information carrier, in the propagation of a sound wave, energy dissipation is the main characteristic of a channel. Sea water is not an ideal medium for sound transmission. The absorption of sound in seawater forms part of the total transmission loss of sound from a source to a receiver [9]. It depends on the seawater properties, such as temperature, salinity and acidity as well as the frequency of the sound. Absorption is the conversion of acoustic energy to heat in the fluid. There are three main causes of absorption losses:

- i) Viscosity
- ii) Change in molecular structure
- iii) Heat conduction

Attenuation losses in sea water occur from both sound absorption losses and scattering losses. This attenuation causes a decrease in the amplitude of the wave and an exponential decrease in the acoustics pressure resulting in more spreading loss. To account for attenuation in the transmission loss equation, a new term, α must be defined, the attenuation coefficient. Using this new term, the transmission loss can be calculated using the equation:

$$TL_{attenuation} = \alpha(r - (1yd)) \times 10^{-3} dB$$

Where r is in yards. Generally, since the range, r , is usually much greater than 1 yard, we can ignore the -1yard term in the equation. Thus the transmission loss can be expressed as:

$$TL_{attenuation} = \alpha(r \times 10^{-3}) dB$$

The most difficult problem in the transmission loss is to determine a correct value for α , i.e., the attenuation coefficient and the various factors that affect the attenuation coefficient are given below.

- i) Viscosity

The viscosity losses are due to two distinct effects. Each of these effects is dependent on not only how the molecules act together in the medium as defined by the coefficients of both shear and volume viscosity but also the frequency of the sound waves [10].

When both terms are combined and nominal values used for the density, speed of sound and the coefficients, the value for the attenuation coefficient becomes

$$\alpha = 2.75 \times 10^{-4} f^2$$

Where f is the sound wave frequency in kHz.

ii) Ionic Relaxation

The below equation describes how Ionic Relaxation affects the attenuation coefficient is

$$\alpha_{MgSO4} = \frac{40f}{4100 + f^2}$$

Where frequency, f , is in kHz.

Though many factors affect this complex process, simply suffice it to say that an equation for this process' affect on α would be

$$\alpha_{boron-borate} = \frac{0.1f^2}{1 + f^2}$$

iii) A non-absorption factor, scattering

The last factor that contributes to losses is the scattering of sound energy due to in homogeneities in seawater. This factor can be approximate as a constant, not dependant on frequency and would only be a dominant factor below 100 Hz or so. This can be expressed as

$$\alpha_{scattering} = 0.003dB / kyd$$

When all these factors are combined, the equation for transmission loss then becomes:

$$TL = \alpha(r \times 10^{-3})dB$$

Where

$$\alpha = \left(0.003 + \frac{0.1f^2}{1 + f^2} + \frac{40f^2}{4100 + f^2} + 2.75 \times 10^{-4} f^2 \right) \text{dB/kyd}$$

The unit dB / ky can be converted to dB / km by multiplying with a factor of 1.094 then absorption coefficient can be written as

$$\alpha = 1.094 \times \alpha_0 \text{ (dB / km)}$$

The characteristics of absorption of sound in water is shown in Fig. 5 and corresponding values are given in Table 3

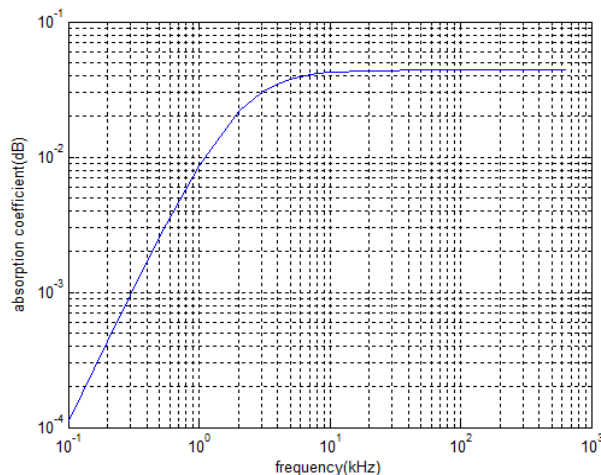


Fig. 5: Absorption of Sound in Sea Water.

Table 3: Variation of Absorption Coefficient with Frequency

Frequency (kHz)	Absorption coefficient (dB)
0.1	1.1114e-004
0.5	0.0025
1.0	0.0086
2.0	0.0217
3.0	0.0302
4.0	0.0349

3. Conclusion

In this paper sound wave propagation in underwater medium is analyzed which will help in developing the channel model in underwater. Cylindrical spreading presents underwater only when the sea surface and the sea floor are flat. The transmission loss increases linearly in both spherical and cylindrical spreading and the transmission loss due to spherical spreading is twice the transmission loss due to cylindrical spreading. For example the transmission loss due to spherical spreading and cylindrical spreading at 100 m range are -46.0 dB and -23.0 dB respectively.

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