A passive sonar based underwater acoustic channel model for improved search and rescue operations in deep sea

Afsar Ali Mohamed Abbas[1], Kaja Mohideen Sultan Mohideen[1], Vedachalam Narayanaswamy[2]
[1]Department of Electronics and Communication Engineering, B.S. Abdur Rahman Crescent Institute of Science and Technology, Chennai, India
[2]Deep Sea Technology, National Institute of Ocean Technology, Chennai, India

Article Info

Article history:

Received Apr 19, 2024
Revised Aug 1, 2024
Accepted Aug 6, 2024

Keywords:

Deep sea direct and multipath propagation
Passive sonar
Search and rescue
Signal-to-noise-ratio
Underwater acoustic channel model

ABSTRACT

Active and passive sonar are the two types of empirical underwater acoustic channel models (UWACMs). Passive sonar UWACMs have applications in military, ocean exploration, and search and rescue (SAR) activities. However, high transmission loss (TL), multipath propagation, and ambient noise pose significant challenges to signal-to-noise ratio (SNR) and communication effectiveness. To address these challenges, this paper develops a UWACM based on the passive sonar equation method to determine SNR in deep-sea environments, specifically for SAR operations. Determining SNR involves characterizing signal propagation in terms of TL. Existing models lack analysis of TL and SNR for various deep-sea multipath propagation scenarios relevant to SAR applications. Therefore, this paper analyses TL and SNR for both direct and various multipath propagation modes, including surface reflection (SR), surface duct (SD), bottom bounce (BB), convergence zone (CZ), deep sound channel (DSC), and reliable acoustic paths (RAPs) in the deep sea. This work aims to quantify the detection capabilities of underwater location beacons (ULBs) under various deep-sea scenarios and configurations. By analyzing ULB signal propagation characteristics, this research seeks to address key challenges related to ULB performance and ultimately improve SAR operations. The results of the proposed model significantly correlate with existing literature, confirming its accuracy.

Corresponding Author:

Kaja Mohideen Sultan Mohideen
Department of Electronics and Communication Engineering, B.S. Abdur Rahman Crescent Institute of Science and Technology
Chennai, Tamil Nadu, India
Email: kajamohideen@crescent.education

1. INTRODUCTION

Underwater acoustic communication (UAC) finds applications in various fields such as maritime navigation, offshore oil and gas exploration, environmental monitoring, underwater robotics, and military and search and rescue (SAR) operations [1]–[11]. Reliable underwater communication is critical for effective SAR operations in the vast and challenging environment of the deep sea. However, high transmission loss (TL), multipath propagation, and ambient noise significantly hinder signal quality and communication effectiveness in UAC for SAR applications [12]–[16]. Deep-sea SAR missions for downed aircraft are critical but face significant challenges. Despite the crucial role of underwater beacons, vast distances and limited battery life hinder their detection. Understanding TL, which weakens the signal over distance, and SNR, which determines how well the beacon's message stands out from background noise, is critical for developing effective deep-sea rescue strategies. In complex deep-sea environments, current underwater acoustic channel models (UWACMs) struggle to predict signal behavior. Variations in sound speed due to temperature, salinity, and pressure, coupled with scattering from the rough seabed, complicate the modelling process. Multipath propagation, where signals travel via multiple paths, can further disrupt the signal. Additionally, various noise sources, such as animals, human activity, and natural phenomena, add complexity. High signal attenuation, limited bandwidth, and slow sound speed further restrict communication range and introduce delays. These challenges necessitate advanced techniques for accurate UWACM development, ultimately improving deep-sea SAR success rates [17]–[24].

The existing channel models address these challenges in modeling underwater acoustic channels in a variety of ways. Onasami *et al.* [25] explore reservoir computing as a machine learning (ML) technique for UWACM, potentially achieving better performance than traditional methods. In [26], deep neural networks (DNN) and long short-term memory (LSTM) networks are utilized in UWACM to enhance performance. However, a notable challenge in applying machine learning and deep learning techniques to underwater acoustic communications is the risk of outdated channel state information due to significant propagation delays and dynamic underwater environments. To simulate realistic underwater acoustic channels, researchers often rely on specialized beam-tracing software such as BELLHOP [27]. Researchers have proposed mathematical models to address inaccuracies in sound velocity estimation. These models provide a conversion framework between atmospheric pressure and depth, aiding in sound speed determination. Advanced modeling techniques like mode theory, parabolic equations, and finite element methods are also employed to simulate the propagation of sound underwater, incorporating factors such as range dependence and the influence of surface and bottom conditions [28]. These methods help to better understand the underwater acoustic channel and design effective underwater communication systems for SAR operations. Despite the application of these models as UWACM, a universal UWACM that caters to all applications and diverse ocean environments remains undefined. However, one of the existing UWACM for SAR operation model [24] primarily addresses direct path propagation, leaving a gap in understanding the impacts of various multipaths in deep-ocean environments. Thus, for SAR missions in the deep sea, there is a need for a more accurate and less complex UWACM. Hence, to optimize search efforts, this research focuses on developing a model to accurately determine both TL and SNR for direct and various multipaths of deep-sea, ultimately improving the success rate of rescue missions.

This research work's primary contributions are:

- Initially, the model gets various environmental parameters like channel depth, transmitter and receiver distance, temperature, salinity, pH, and operating frequency as inputs to calculate the absorption coefficient.
- Then, for various ranges, the proposed model calculates TL for direct path propagation.
- Next, the model calculates the TL for various multipath propagation modes in the deep sea, such as SR, SD, BB, CZ, DSC, and RAP.
- This model uses a passive sonar equation to provide a more accurate picture of underwater beacon signal behavior in the deep sea by determining SNR for both direct and various multipaths. For SNR determination, the source level (SL), noise level (NL), and directivity index (DI) values can be considered from the existing literature, whereas the proposed model focuses primarily on TL and SNR calculation.
- This paper compares the results with existing models to ensure accuracy. This is critical for optimizing SAR strategies, thereby enhancing the success rate of deep-sea rescue missions.

The rest of the paper is structured as follows: section 2 presents the proposed UWACM system for deep-sea SAR operations. Section 3 discusses the results of SNR for direct and various multipaths in the deep sea. Section 4 concludes the primary outcomes and provides the scope for future work.

2. PROPOSED PASSIVE UWACM FOR DEEP SEA SAR OPERATION

Figure 1 presents an overview of UWACM for detecting underwater locator acoustic beacons using passive sonar equations. The determination of SNR is critical in detecting acoustic beacons from underwater location beacons (ULBs) in complex ocean environments. The multipath propagation and ambient noise affect the estimation of SNR as shown in Figure 1. Accurate SNR estimation is essential to ensure the effectiveness of the detection process in various ocean conditions.

Figure 2 provides the flow diagram for the proposed UWACM for SAR operation, using a passive sonar equation to determine the SNR of both direct and various multipaths in the deep sea. This research concentrates on the deep-sea environment for SAR operations. As a result, this paper proposes a UWACM for direct and various multipaths in the deep sea based on a passive sonar equation. The model leverages a passive sonar equation to estimate the SNR [29].

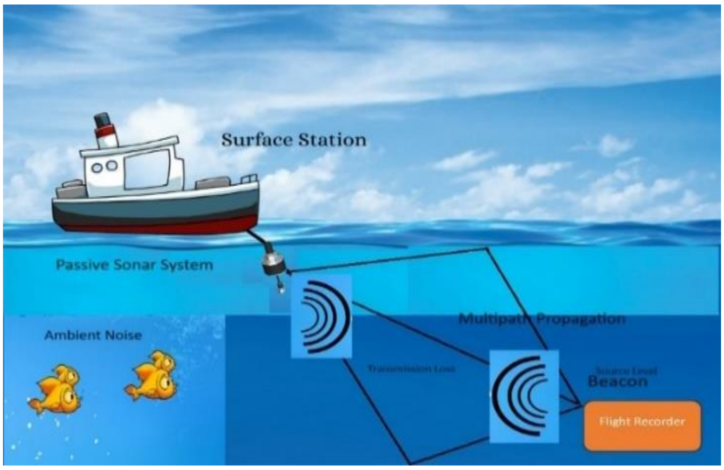

Figure 1. Proposed UWACM for SAR operation in deep sea

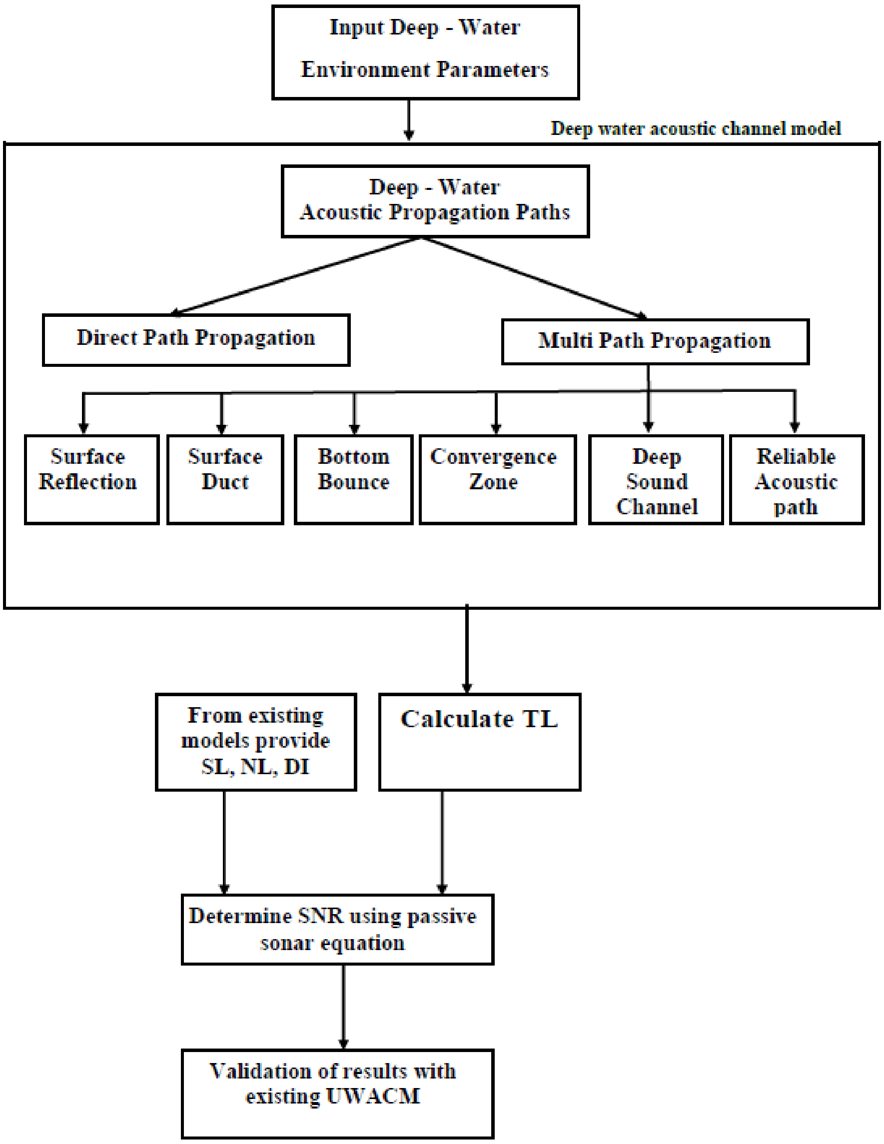

Figure 2. Work flow diagram for the proposed UWACM

Equation (1) depicts this relationship

$$SNR = S_{ULB} - TL - N_{amb} + DI \tag{1}$$

where $S_{ULB}(dB\ re\ 1\ \mu Pa\ @\ 1\ m)$ denotes the source level, indicating the sound power emitted by the ULB. TL (dB) signifies the transmission loss, quantifying the weakening of the ULB signal as it travels through the water. $N_{amb}(dB\ re\ 1\ \mu Pa)$ denotes the ambient noise level, reflecting the background noise present in the underwater environment. DI (dB) represents the directivity index of the ULB and receiver system, accounting for the focusing or spreading of the acoustic signal. This research priorities determining TL and SNR for both direct and various multipath propagation scenarios in the deep sea. Table 1 provides specific reference values that were adopted based on research [24] for the determination of TL and SNR in this research.

Table 1. Reference values for S_{ULB}, N_{amb}, DI and operating frequency

Parameter	Reference Values
S_{ULB}	160.5 dB re 1 μPa @ 1 m
N_{amb}	61 dB re 1 μPa
DI	0 dB
Operating frequency of ULB	37.5 kHz

2.1. Determination of transmission loss

In the deep-sea environment, the determination of transmission loss (TL) plays a vital role in the calculation of SNR. High TL restricts the maximum distance that enables reliable communication. TL weakens the signal, while background noise remains relatively constant. This reduces the SNR, making it harder to demodulate the transmitted information. Thus, TL determination using the channel model helps to ensure reliable communication.

In the deep sea, TL is primarily responsible for absorption and spreading losses. The spherical expansion of the acoustic wave as it travels away from the transmitter causes spreading loss in the deep sea. However, absorption loss plays a more critical role, converting sound intensity into heat energy. This loss occurs in both direct and multipath propagation paths. Equation (2) gives the absorption coefficient considered in this paper as [30],

$$\alpha = 0.106\frac{f_1 f^2}{f_1^2+f^2}e^{\frac{(pH-8)}{0.56}} + 0.52\left(1+\frac{T}{43}\right)\frac{S}{35}\frac{f_2 f^2}{f_2^2+f^2}e^{\frac{-z}{6}} + 4.9 * 10^{-4} f^2 e^{-\left(T/_{27}+z/_{17}\right)} \tag{2}$$

where

$$f_1 = 0.78(S/35)^{\frac{1}{2}}e^{T/_{26}} \tag{3}$$

and

$$f_2 = 42e^{T/_{17}} \tag{4}$$

This equation is valid for

$$-6 < T < 35^0C\ (S = 35ppt, pH = 8, z = 0$$
$$7.7 < pH < 8.3\ (T = 10^0C, S = 35ppt, z = 0$$
$$5 < S < 50ppt\ (T = 10^0C, pH = 8, z = 0$$
$$0 < z < 7km\ (T = 10^0C, S = 35\ ppt, pH = 8$$

The first, second, and third terms in (2) represent the attenuation resulting from boric acid relaxation, magnesium sulphate relaxation, and viscous and compressive losses in pure water. The equation uses the variables T (°C), which is the water temperature, S (ppt), which is the salinity of the water, z (m), which is the depth of the underwater channel, and f (kHz), which is the operating frequency of the ULB.

Given the complex and time-varying nature of the ocean, temperature, salinity, and pH values differ significantly across various regions. Therefore, this research focuses on analyzing the deep Indian Ocean with specific parameters [31] given in Table 2. This research calculates the absorption coefficient as 6.57 dB/km for deep-sea analysis at a depth of z=3,000 meters by substituting these values into (2). In this research, both direct and various multipaths of deep water use this absorption coefficient value. In the following analysis, α and r denote the absorption coefficient in dB/km and the transmission range in meters, respectively.

Table 2. Simulation parameters for deep-water TL calculation

Parameters	Values
Temperature (T)	2 °C
Salinity (S)	34 ppt
pH	8

2.1.1. TL for direct path propagation in deep water

In UAC, the direct path refers to the straight-line trajectory through which sound waves travel from the source to the receiver. Despite appearing to be the most efficient path, TL still occurs along the direct path as a result of spreading loss. In deep water, spherical spreading and absorption provide the TL for direct path propagation [32] as (5).

$$TL = 20\log_{10} r + \alpha\, r\, X\, 10^{-3} \quad (5)$$

The direct path represents the ideal scenario with minimal reflections and interactions with the environment. When the TL on the direct path is compared with the overall received signal strength, the additional losses due to multipath propagation and other factors can be estimated.

2.1.2. TL for multipath propagation in deep water

Real-time TL predictions, based on factors like depth and water conditions, aid in dynamic decision-making during SAR operations. This enables SAR teams to prioritize search areas so that they focus search efforts on areas with lower predicted TL, where the chances of detecting survivors are higher. While existing channel models involve more complex algorithms to determine TL, this model simplifies this process by using mathematical equations to calculate the TL of various multipaths in the deep sea. The multipaths in deep water are due to SR, SD, BB, CZ, DSC, and RAP. Implementing the TL expressions in these propagation paths allows us to design the TL model for deep water. The following analysis demonstrates the TL determination for these various multipath propagation paths in a deep-water environment. Knowing the SNR for these various multipath propagation paths could improve the SAR application's performance.

a. Surface reflection (SR)

The SR is used to refer to the bouncing back of sound from the surface of the ocean. The term Rayleigh parameter R provides the ocean surface acoustic roughness as [32].

$$R = kH\sin\theta \quad (6)$$

In (6), H indicates the crest-to-trough rms wave height, the acoustic wavenumber is $k = 2\pi/\lambda$ and θ is the grazing angle. The total TL for this propagation is given by (7).

$$TL = 20logr + \alpha r * 10^{-3} + TL_{dwsr} \quad (7)$$

where TL_{dwsr} is the deep-water surface reflection transmission loss. It is given by (8):

$$TL_{dwsr} = 10log\left[\frac{1+(f+f_1)^2}{1+(f+f_2)^2}\right] - \left(1 + \frac{(90-w)}{60}\right)\left(\frac{\theta}{30}\right)^2 \quad (8)$$

where $f_1 = \sqrt{10}f_2$ and $f_2 = 378w^{-2}$ in which w is the wind speed in knots, and θ is the horizontal angle of incidence in degrees. For this analysis to find TL, wind speed w =10 knots, $\theta = 30°$ values are considered.

b. Surface duct (SD)

When there is a positive temperature gradient in the surface layer, acoustic waves can bend back to the surface and reflect back into the layer off the surface, resulting in surface duct. The TL model equations for surface duct are:

$$TL = 20logr + (\alpha + \alpha_L)r * 10^{-3}\ for\ r < 350H^{1/2}\ , short\ ranges \quad (9)$$

and

$$TL = 10logr_0 + 10logr + (\alpha + \alpha_L)r * 10^{-3} \; for \; r > 350H^{1/2}, long \; ranges \tag{10}$$

where $10logr_0 = 20.9 + 5logH$ in which H is the mixed-layer depth (MLD) in meters ($H = 80$ to 220 feet), and

$$\alpha_L = \frac{26.6f(1.4)^S}{[(1452+3.5T)H]^{1/2}} \tag{11}$$

In (11), S is the sea state number ($S = 2$ to 5) and T is the temperature. The TL for this scenario is obtained by substituting mixed layer depth H of 100 feet, then $H = 30.48$ m, temperature $T = 2$ °C and sea state number S = 2. By substituting these values into (11), the value of α_L is 9.3.

c. Bottom bounce (BB)

The Rayleigh formula figures out how much sound is reflected when it hits a flat surface between two fluids that have different densities ($\rho 1$ and $\rho 2$) and sound speeds ($c1$ and $c2$) at a grazing angle of θ_1. This ratio of the intensity of the reflected wave (I_r) to the intensity of the incident wave (I_i) represents this reflection loss. The TL due to deep water bottom bounce reflection loss is denoted by $TL_{dwbotref}$ and is given by (12),

$$TL_{dwbotref} = 10log\left[{}^{I_r}/_{I_i}\right] \tag{12}$$

$$TL_{dwbotref} = 10log\left(\left[\frac{msin\theta_1 - (n^2 - \cos^2\theta_1)^{1/2}}{m\sin\theta_1 + (n^2 - \cos^2\theta_1)^{1/2}}\right]^2\right) \tag{13}$$

in which $m = \frac{\rho_2}{\rho_1}$ and $n = \frac{c_1}{c_2}$. The attenuation coefficient α_S caused by sediment presence on the ocean floor can be given as (14),

$$\alpha_S = kf^n \tag{14}$$

where n is the empirical constant, and it is usually 1, f is the frequency in kHz and k depends on porosity, and its value is 0.5 over the porosity range of 35% to 60%. The term "BB" is used to refer to the sound reflection from the ocean floor. The total TL in the bottom bounce is,

$$TL_{totbb} = 20logr + \alpha r * 10^{-3} + \alpha_S r + |TL_{dwbotref}| \tag{15}$$

The values of $TL_{dwbotref}$ are 4, 16, 10, and 6 dB for sandy bottom, clayed mud, muddy very fine sand, and sand-mud-clay respectively [29]. Here, $\alpha_s = 18.75$ as obtained from (14) for n = 1, f = 37.5 kHz, and k = 0.5.

d. Convergence zone (CZ)

In the deep sea, acoustic propagation from a shallow source led to the creation of CZ, where sound rays intersect and create areas of higher intensity. The occurrence of CZ depends on the sound-velocity profile (SVP), with specific requirements such as the depth excess between the ocean bottom and the depth where the upper sound ray becomes horizontal. If the water is not deep enough, the bottom reflects sound waves, preventing convergence zones from forming. The total TL in the convergence zone is given by (16):

$$TL_{TOT\_CZ} = 20logr + \alpha r * 10^{-3} - G_{CZ} \tag{16}$$

where G_{CZ} is the CZ gain, and it is between 5 and 20 dB. This plot is obtained by substituting a convergence zone gain of 10 dB.

e. Deep sound channel (DSC)

The SVP in the deep sea, with a minimum velocity at mid-latitudes and near the surface in polar regions, creates the DSC, also known as the sound fixing and ranging (SOFAR) channel. This minimum velocity causes sound rays to be bent towards the minimum speed depth, leading to excellent sound propagation over long ranges with minimal acoustic losses from reflection and low TL, especially when the transmitter and receiver are positioned near the depth of minimum velocity. However, if the transmitter is at low depths, the DSC can include CZ and shadow zones, where some rays may be reflected at the sea surface and bottom or refracted and reflected from either of them. The TL for a DSC is given by (17):

$$TL_{DSC} = 10logr_0 + 10logr + \alpha r * 10^{-3} \tag{17}$$

where r_0 is the cylindrical to spherical spreading transition range and is defined as (18),

$$r_0 = \left(\frac{r_s}{8}\right)\left(\frac{D_s}{z_s}\right)^{1/2} \quad (18)$$

in which r_s is the skip distance, z_s is the source depth, and D_s is the axis depth. The skip distance r_s is given by (19):

$$r_s = 2(D_s + D_r)(2c_{max}/\Delta c)^{1/2} \quad (19)$$

in which $(D_s + D_r)$ is the channel vertical extent, c_{max} is the maximum channel sound speed, and Δc is the difference between c_{max} and the sound speed on the channel axis c_{min}. In this analysis, the parameters considered are f =37.5 kHz, c_{max} = 1,500 m/s, Δc = 100 m/s, D_s = 1,500 m/s and D_r = 1,500 m/s, and z = r_s = 3,000 meters.

f. Reliable acoustic path (RAP)

If the transmitter is situated in the deep sea and the receiver is positioned in a shallow area, sound propagation to moderate ranges occurs via a RAP. The RAP is trustworthy as it is unaffected by bottom reflection or near-surface effects, and the formula can approximate its *TL* is given as (20).

$$TL = 20logr + \alpha r * 10^{-3} \quad (20)$$

where r is the slant range.

3. RESULTS AND DISCUSSION

For the SAR application, TL and SNR are crucial UACM parameters to estimate. A higher SNR indicates a clearer signal and easier detection. Equation (1) determines the SNR in this proposed model. The TL vs. range analysis and SNR calculation for direct and multipath propagation of deep sea for various ranges are analyzed in sections 3.1 and 3.2.

3.1. Transmission loss vs range analysis

Figure 3 displays the plot of the transmission loss (TL) analysis for both direct and various cases of multipath propagation of deep water. Table 3 tabulates the values of TL for various ranges. In Table 3, the notations followed are: sandy bottom (SB), clayed mud (CM), muddy very fine sand (MVFS), sand mud clay (SMC).

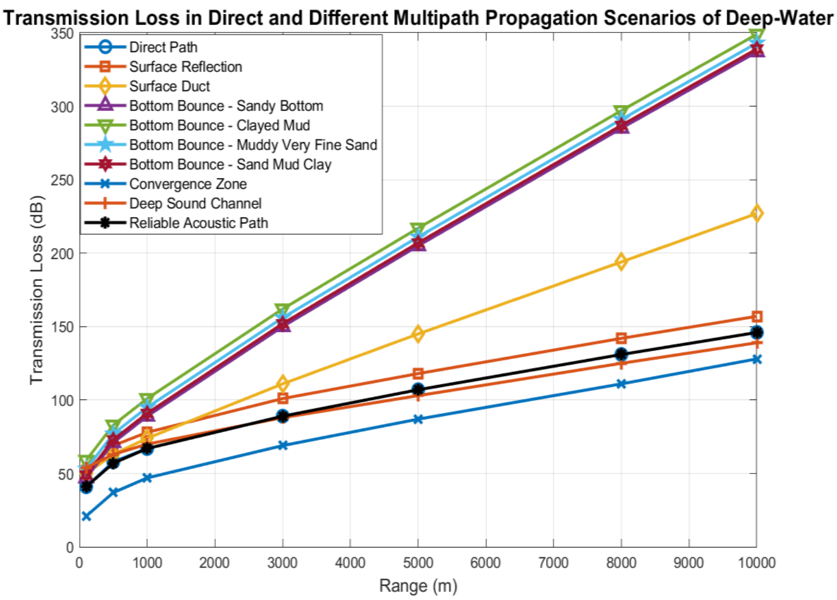

Figure 3. TL vs range in different multipath propagation scenarios of deep-water

Table 3. TL in different multipath propagation of deep-water for various ranges

Range (m)	TL for direct path (dB)	TL for multipath propagation (dB)								
		SR	SD	BB-SB	BB-CM	BB-MVFS	BB-SMC	CZ	DSC	RAP
100	41	52	50	47	59	53	49	21	54	41
500	58	69	63	71	83	77	73	37	63	57
1,000	67	78	74	89	101	95	91	47	70	67
3,000	89	101	111	150	162	156	152	69	88	89
5,000	107	118	145	205	217	211	207	87	103	107
8,000	131	142	194	285	297	291	287	111	125	131
10,000	146	157	227	337	349	343	339	128	139	146

Figure 3 shows the TL vs. range for direct and various multipaths in a deep-sea environment. The corresponding values are tabulated in Table 3 for a depth of 3,000 m and for an operating pinger frequency of 37.5 kHz. From the plot, it is observed that as the range increases, the TL increases. Though the absorption coefficient is lower in deep water when compared to shallow water, the TL is higher in deep water due to spherical spreading. The determination of TL values helps to find SNR for various UAC applications.

The TL for surface reflection multipath propagation increases as the range increases. It is based on the operating frequency, wind speed, and grazing angle. Based on the operating frequency, mixed layer depth, and temperature, surface duct TL increases as the range increases. The TL for long ranges is very high in surface duct environments. Depending on the operating frequency and bottom types, there is a considerable transmission loss variation for a bottom bounce, sandy bottom, clayed mud, muddy very fine sand, and sand-mud-clay multipath propagation of deep water. Compared with all the other cases, the bottom bounce TL is high for long ranges. Based on the operating frequency and convergence zone gain, there is an increase in TL for increased ranges for a convergence multipath propagation of deep water. Depending on the operating frequency, speed of sound, and depth of source and receiver, there is an increase in TL for increased ranges for DSC multipath propagation of deep water. The operating frequency and range between source and receiver in RAP increase TL for increased ranges.

Thus, SAR operations should prioritize paths with lower TL for communication. Adjustments to transmitter power and receiver sensitivity are essential to compensate for higher TL in certain paths, particularly for surface reflection and bottom bounce scenarios. Understanding the impact of the seafloor type and water surface conditions on TL helps in planning SAR operations more effectively, ensuring robust communication and detection strategies. Incorporating multiple propagation paths into the communication strategy ensures redundancy and flexibility, crucial for handling dynamic and challenging deep-water environments.

3.2. Signal-to-noise ratio vs range analysis

The SNR is calculated for deep-water direct and multipath propagation and is shown in Table 4. It is evaluated for a depth of 3,000 m, at an operating frequency of 37.5 kHz, SL=160.5 dB, NL=61 dB, DI=0 dB, and the calculated values of TL provided in Table 3. These parameters are critical for accurate SNR computation. The calculated SNR values provide insights into signal detectability.

Table 4. SNR calculation for direct and various multipath propagation of deep-water

Range (m)	Direct path SNR (dB)	Multipath SNR (dB)								
		SR	SD	BB-SB	BB-CM	BB-MVFS	BB-SMC	CZ	DSC	RAP
100	58.5	47.5	49.5	52.5	40.5	46.5	50.5	78.5	45.5	58.5
500	41.5	30.5	36.5	28.5	16.5	22.5	26.5	62.5	36.5	42.5
1000	32.5	21.5	25.5	10.5	-1.5	4.5	8.5	52.5	29.5	32.5
3000	10.5	-1.5	-11.5	-50.5	-62.5	-56.5	-52.5	30.5	11.5	10.5
5000	-7.5	-18.5	-45.5	-105.5	-117.5	-111.5	-107.5	12.5	-3.5	-7.5
8000	-31.5	-42.5	-94.5	-185.5	-197.5	-191.5	-187.5	-11.5	-25.5	-31.5
10,000	-46.5	-57.5	-127.5	-237.5	-249.5	-243.5	-239.5	-28.5	-39.5	-46.5

Figure 4 provides valuable insights into the SNR for both direct path and various multipath propagation scenarios in deep-water environments. As expected, due to signal attenuation over distance, the SNR decreases as the range increases. All scenarios consistently observe this trend. Different multipath scenarios exhibit distinct patterns of signal attenuation compared to the direct path. Multipaths such as SR, SD, and BB, lead to additional signal degradation, resulting in lower SNR values. Environmental factors, such as seabed composition and water depth, play an important role in shaping the propagation characteristics and signal quality. For instance, scenarios involving bottom bounce on different types of sea beds show varying degrees of signal attenuation. The convergence zone scenario demonstrates a unique behavior where the SNR initially increases with range before decreasing again. This behavior is characteristic of the convergence of acoustic rays at specific depths, leading to enhanced signal strength within the convergence zone. The deep sound channel scenario exhibits relatively stable SNR values across different ranges compared to other scenarios. This indicates the presence of a deep sound channel where acoustic signals propagate with minimal attenuation, resulting in consistent SNR values over distance.

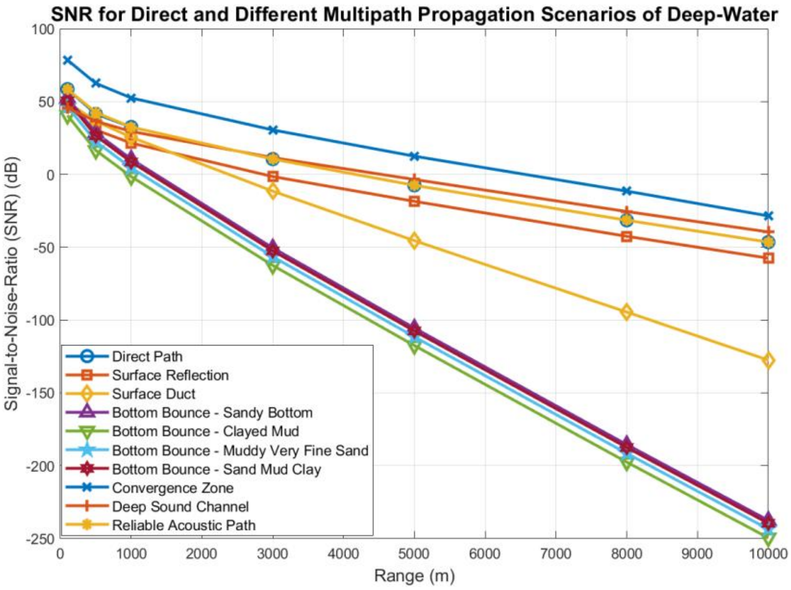

Figure 4. SNR for direct and various multipath propagation of deep-water

Figure 5 displays SNR comparison of proposed and existing [24] UWACM for direct path propagation of deep-water at a depth of 3,000 m. The proposed UWACM significantly outperforms the existing model in terms of SNR for direct path propagation at all tested ranges (100 to 10,000 meters). The proposed model consistently exhibits higher SNR values, indicating better signal transmission quality and improved noise mitigation. This enhancement is crucial for applications such as black box detection and search and rescue operations in deep sea environments.

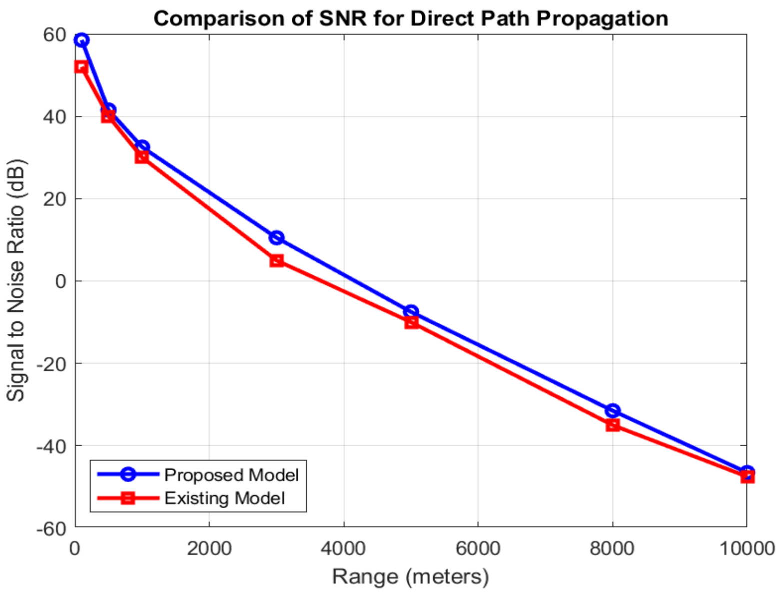

Figure 5. SNR comparison of proposed and existing UWACM for direct path propagation of deep-water

Understanding the different propagation paths helps in planning the operational range and choosing the appropriate communication systems. For instance, knowing that convergence zones and deep sound channels support longer ranges allows for strategic deployment of assets. Areas with expected low SNR (e.g., certain bottom bounce paths) can be identified as challenging for communication, prompting the need for alternative methods or more frequent relay points. Choosing the right acoustic equipment (e.g., transducers, receivers) that can optimize the SNR for specific paths will improve the efficiency and success rate of SAR operations. SAR teams can adapt their strategies based on the environmental characteristics (e.g., bottom type, presence of ducts), ensuring better preparedness and response in different deep-sea scenarios. Thus, the SNR results provide a detailed understanding of how different acoustic propagation paths perform in a deep-sea environment, directly influencing the strategies and effectiveness of search and rescue operations.

Understanding the variations in SNR under different propagation scenarios is crucial for designing robust underwater communication systems such as SAR applications. The specific environmental conditions encountered in deep-water environments should tailor strategies for mitigating multipath interference and optimizing signal transmission. Overall, the findings underscore the complexity of sound propagation in deep ocean scenarios and highlight the importance of considering multipath effects when designing and deploying underwater communication systems. These findings of the model introduced in this paper closely align with existing literature [22], [24], demonstrating a high level of consistency and validation.

4. CONCLUSION

This paper introduces an underwater acoustic channel model based on the passive sonar equation method, specifically tailored for deep-sea environments and targeted towards SAR operations. The model addresses the challenges posed by high TL, multipath propagation, and ambient noise, which significantly impact the SNR and communication effectiveness in deep-sea scenarios. By focusing on characterizing SNR through an in-depth analysis of TL for various multipath propagation modes, including SR, SD, BB, CZ, DSC, and RAP, this work fills a critical gap in existing literature by providing comprehensive insights into SNR determination relevant to SAR applications. The proposed model aims to quantify the detection capabilities of ULBs under diverse deep-sea scenarios and configurations, thus offering valuable insights for improving ULB performance and enhancing SAR operations efficiency. Through rigorous analysis and validation against existing literature, the accuracy of the proposed model is confirmed, bolstering its utility and reliability in practical applications. Overall, this research contributes significantly to the advancement of underwater acoustic channel model, particularly in the context of SAR operations in deep-sea environments. The insights gained from this research have the potential to inform the design and deployment of UAC systems and improve the effectiveness of SAR missions, ultimately contributing to enhanced safety and security in maritime environments. Future work could focus on extending the proposed model to incorporate dynamic environmental factors and real-time data assimilation for enhanced accuracy in SNR prediction.

ACKNOWLEDGMENT

The authors would like to thank the National Institute of Ocean Technology (NIOT), Chennai for providing support to perform this research work.

REFERENCES

[1] M. Stojanovic, "Underwater wireless communications: current achievements and research challenges," *IEEE Oceanic Engineering Society Newsletter*, vol. 41, no. 2, pp. 1–5, 2006.

[2] I. F. Akyildiz, D. Pompili, and T. Melodia, "Underwater acoustic sensor networks: research challenges," *Ad Hoc Networks*, vol. 3, no. 3, pp. 257–279, May 2005, doi: 10.1016/j.adhoc.2005.01.004.

[3] I. F. Akyildiz, D. Pompili, and T. Melodia, "Challenges for efficient communication in underwater acoustic sensor networks," *ACM SIGBED Review*, vol. 1, no. 2, pp. 3–8, Jul. 2004, doi: 10.1145/1121776.1121779.

[4] K. M. Awan, P. A. Shah, K. Iqbal, S. Gillani, W. Ahmad, and Y. Nam, "Underwater wireless sensor networks: a review of recent issues and challenges," *Wireless Communications and Mobile Computing*, vol. 2019, pp. 1–20, Jan. 2019, doi: 10.1155/2019/6470359.

[5] H. Esmaiel and D. Jiang, "Review article: multicarrier communication for underwater acoustic channel," *International Journal of Communications, Network and System Sciences*, vol. 06, no. 08, pp. 361–376, 2013, doi: 10.4236/ijcns.2013.68039.

[6] M. F. Ali, D. N. K. Jayakody, Y. A. Chursin, S. Affes, and S. Dmitry, "Recent advances and future directions on underwater wireless communications," *Archives of Computational Methods in Engineering*, vol. 27, no. 5, pp. 1379–1412, Nov. 2020, doi: 10.1007/s11831-019-09354-8.

[7] C. M. G. Gussen, P. S. R. Diniz, M. L. R. Campos, W. A. Martins, F. M. Costa, and J. N. Gois, "A survey of underwater wireless communication technologies," *Journal of Communication and Information Systems*, vol. 31, no. 1, pp. 242–255, 2016, doi: 10.14209/jcis.2016.22.

[8] M. Y. I. Zia, J. Poncela, and P. Otero, "State-of-the-art underwater acoustic communication modems: classifications, analyses and design challenges," *Wireless Personal Communications*, vol. 116, no. 2, pp. 1325–1360, Jan. 2021, doi: 10.1007/s11277-020-07431-x.
[9] H. Wang, S. Peng, Q. He, and X. Zeng, "Predicting underwater acoustic transmission loss in the SOFAR channel from ray trajectories via deep learning," *JASA Express Letters*, vol. 4, no. 5, May 2024, doi: 10.1121/10.0025976.
[10] Buddesab T, Thriveni J, and Venugopal K R, "Trust model genetic node recovery based on cloud theory for underwater acoustic sensor network," *International Journal of Electrical and Computer Engineering*, vol. 9, no. 5, pp. 3759–3771, Oct. 2019, doi: 10.11591/ijece.v9i5.pp3759-3771.
[11] J. Zhou, H. Jiang, P. Wu, and Q. Chen, "Study of propagation channel characteristics for underwater acoustic communication environments," *IEEE Access*, vol. 7, pp. 79438–79445, 2019, doi: 10.1109/ACCESS.2019.2921808.
[12] M. Stojanovic and J. Preisig, "Underwater acoustic communication channels: propagation models and statistical characterization," *IEEE Communications Magazine*, vol. 47, no. 1, pp. 84–89, Jan. 2009, doi: 10.1109/MCOM.2009.4752682.
[13] L. Lanbo, Z. Shengli, and C. Jun-Hong, "Prospects and problems of wireless communication for underwater sensor networks," *Wireless Communications and Mobile Computing*, vol. 8, no. 8, pp. 977–994, Oct. 2008, doi: 10.1002/wcm.654.
[14] M. Stojanovic, "On the relationship between capacity and distance in an underwater acoustic communication channel," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 11, no. 4, pp. 34–43, Oct. 2007, doi: 10.1145/1347364.1347373.
[15] J. Huang, H. Wang, C. He, Q. Zhang, and L. Jing, "Underwater acoustic communication and the general performance evaluation criteria," *Frontiers of Information Technology & Electronic Engineering*, vol. 19, no. 8, pp. 951–971, Aug. 2018, doi: 10.1631/FITEE.1700775.
[16] A. Song, M. Stojanovic, and M. Chitre, "Editorial underwater acoustic communications: Where we stand and what is next?," *IEEE Journal of Oceanic Engineering*, vol. 44, no. 1, 2019.
[17] S. Yao and Y. Liu, "A novel feature-based detector for underwater acoustic beacon signals using superimposed envelope spectrum of multi-pulses," *Journal of Marine Science and Engineering*, vol. 9, no. 12, Nov. 2021, doi: 10.3390/jmse9121337.
[18] J. Kojima, K. Nitadori, and T. Fukuchi, "A passive sonar system for searching acoustic beacons in deep sea," in *OCEANS 2007*, Sep. 2007, pp. 1–4, doi: 10.1109/OCEANS.2007.4449289.
[19] J. Luo, L. Fan, S. Wu, and X. Yan, "Research on localization algorithms based on acoustic communication for underwater sensor networks," *Sensors*, vol. 18, no. 1, Jan. 2018, doi: 10.3390/s18010067.
[20] H.-P. Tan, R. Diamant, W. K. G. Seah, and M. Waldmeyer, "A survey of techniques and challenges in underwater localization," *Ocean Engineering*, vol. 38, no. 14–15, pp. 1663–1676, Oct. 2011, doi: 10.1016/j.oceaneng.2011.07.017.
[21] B. M. Ferreira, P. A. Graça, J. C. Alves, and N. A. Cruz, "Single receiver underwater localization of an unsynchronized periodic acoustic beacon using synthetic baseline," *IEEE Journal of Oceanic Engineering*, vol. 48, no. 4, pp. 1112–1126, Oct. 2023, doi: 10.1109/JOE.2023.3275611.
[22] N. Morozs, W. Gorma, B. T. Henson, L. Shen, P. D. Mitchell, and Y. V. Zakharov, "Channel modeling for underwater acoustic network simulation," *IEEE Access*, vol. 8, pp. 136151–136175, 2020, doi: 10.1109/ACCESS.2020.3011620.
[23] T. Zhang, S. Qin, X. Wang, and J. Tang, "Deep-sea search and recovery: with and without operating an underwater vehicle," *Ocean Science Discussions*, vol. 1–16, 2018.
[24] R. Barmak, A. L. S. C. de Oliveira, P. S. Thiago, F. dos Santos, M. V. R. Lopes, and G. Cernicchiaro, "Underwater locator beacon signal propagation on tropical waters," in *2017 IEEE/OES Acoustics in Underwater Geosciences Symposium (RIO Acoustics)*, Jul. 2017, pp. 1–4, doi: 10.1109/RIOAcoustics.2017.8349738.
[25] O. Onasami, M. Feng, H. Xu, M. Haile, and L. Qian, "Underwater acoustic communication channel modeling using reservoir computing," *IEEE Access*, vol. 10, pp. 56550–56563, 2022, doi: 10.1109/ACCESS.2022.3177728.
[26] O. Onasami, D. Adesina, and L. Qian, "Underwater acoustic communication channel modeling using deep learning," in *The 15th International Conference on Underwater Networks & Systems*, Nov. 2021, pp. 1–8, doi: 10.1145/3491315.3491323.
[27] M. B. Porter, *The BELLHOP manual and user's guide: preliminary draft*. USA: Tech. Rep, 2011.
[28] L. S. Wang, K. Heaney, T. Pangerc, P. Theobald, S. P. Robinson, and M. Ainslie, *Review of underwater acoustic propagation models*. 2014.
[29] R. J. Urick, *Principles of underwater sound*. New York: McGraw-Hill, 1983.
[30] M. A. Ainslie and J. G. McColm, "A simplified formula for viscous and chemical absorption in sea water," *The Journal of the Acoustical Society of America*, vol. 103, no. 3, pp. 1671–1672, Mar. 1998, doi: 10.1121/1.421258.
[31] T. Kim, H. Obata, and T. Gamo, "Dissolved Zn and its speciation in the Northeastern Indian Ocean and the Andaman Sea," *Frontiers in Marine Science*, vol. 2, Aug. 2015, doi: 10.3389/fmars.2015.00060.
[32] M. C. Domingo, "Overview of channel models for underwater wireless communication networks," *Physical Communication*, vol. 1, no. 3, pp. 163–182, Sep. 2008, doi: 10.1016/j.phycom.2008.09.001.

BIOGRAPHIES OF AUTHORS

Afsar Ali Mohamed Abbas received the B.E. degree with distinction in electronics and communication engineering from Jaya Engineering College, University of Madras, Chennai, India, in 2000. He has received M.E. degree with distinction in applied electronics from Sathyabama Institute of Science and Technology, Chennai, India in 2006. He is currently pursuing the Ph.D. degree in the Department of Electronics and Communication Engineering with B.S. Abdur Rahman Crescent Institute of Science and Technology, Chennai, India. He has around 15 years of teaching experience in various engineering colleges and technical universities. He has published several papers in journals and conferences. His research interests include wireless communication, underwater channel model development, underwater acoustic communication and internet of things. He can be contacted at email: afsarmail123@gmail.com.

Kaja Mohideen Sultan Mohideen received his Bachelor of Engineering degree in electronics and communication engineering from Thiagarajar College of Engineering, Madurai, in the year 1988. He did his masters in M.E. applied electronics at Coimbatore Institute of Technology, Coimbatore, in the year 1991. He received his Ph.D. degree from Anna University, Chennai in 2008 for his research in the area of VLSI design. He has got more than thirty years of teaching experience and currently is the senior professor, Department of Electronics and Communication Engineering, B.S. Abdur Rahman Crescent Institute of Science and Technology, Chennai, India. His area of interest includes VLSI, microcontroller-based system designs, antenna design, digital system design and image processing. He has 40 publications in international journals and more than 30 publications in National/International conferences to his credit. He is the founding member of the Department of Electronics and Communication Engineering of Crescent Institute. The major developments and achievements of the Department of Electronics and Communication Engineering of Crescent Institute are from his initiatives. He can be contacted at email: kajamohideen@crescent.education.

Vedachalam Narayanaswamy is currently a senior scientist with NIOT, Chennai, leading the indigenous development of the deep-ocean manned and unmanned scientific submersibles under Government of India's Deep Ocean Mission program. His 26 years of experience includes industrial power, process, offshore, and subsea domains at Aditya Birla Group and GE Power Conversion and Alstom-Converteam in France. His technical exposure includes development of multi-megawatt power and control systems for deep-water enhanced hydrocarbon recovery systems of Ormen Lange subsea compression pilot with GE; Ocean renewable energy systems including ocean thermal energy conversion, wave energy systems and remotely operated vehicles with NIOT; subsea grids for tidal energy farms for Paimpol Brehat, France and industrial power generation, utilization and boiler control systems in process industries. He has about 100 publications in indexed journals, holds an international and two national patents in subsea robotics and subsea process. He is a recipient of the National Meritorious Invention Award in 2019 for the development and usage of underwater robotic vehicles. He is presently a Member of Indian Naval Research Board, Bureau of Indian Standards and was the Secretary of IEEE Ocean Engineering Society-India Chapter and Executive Member of Marine Technology Society-India Section. He can be contacted at email: veda@niot.res.in.