Comprehensive Analysis of Underwater Acoustic Propagation in Shallow and Deep Water

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Abstract. At the cutting edge of technical development, underwater acoustic communication presents an exciting and demanding area for both engineers and researchers. The sound speed in underwater majorly affects the signal propagation among the nodes and leads to high transmission losses. In addition, the variations of temperature, salinity, and depth are not symmetric in shallow and deep-water scenarios. Therefore, it is essential to conduct a comprehensive analysis and gain a thorough understanding of the acoustic velocity profile in the underwater environment to effectively deploy a network tailored for a specific application. The analysis and evaluation of the differences in the sound speed profile at various factors in both water scenarios is the main goal of this work. Furthermore, rather than using distance and frequency to estimate the transmission losses, alternative sound speeds have been used for both water scenarios. The simulation findings show that overall transmission losses are affected by variations in sound speed, and that these losses decrease by 17.6% when sound speed increases from 1530 to 1620 m/s. In shallow water the transmission losses are reduced by 3.89% when the acoustic velocity increased from 1450 to 1530m/s. whereas, in deep water the reduction in transmission losses obtained is 0.34% when the acoustic velocity is increased from 1470 to 1620 m/s.

Keywords: Underwater Acoustics · Sound Speed · Signa Propagation · Transmission Loss · Temperature · Salinity · Shallow Water · Deep Water

1 Introduction

The exploration and understanding of underwater acoustic propagation play a pivotal role in various scientific, industrial, and defense applications. As the global focus intensifies on harnessing the potential of the oceans for economic and environmental purposes,

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the need for a comprehensive analysis of underwater acoustic phenomena becomes increasingly paramount [1]. This study aims to delve into the intricate details of acoustic signal propagation in both water environments, unraveling the complexities that influence the behavior of sound waves beneath the ocean surface. The underwater realm poses unique challenges to acoustic communication and sensing, as the medium through which sound travels significantly differs from air [2, 3]. Shallow water, with its variable seabed topography, presents a dynamic and complex environment where acoustic signals can undergo refraction, reflection, and absorption [4]. Deep-water scenarios, on the other hand, introduce additional factors such as temperature gradients, pressure variations, and the presence of deep-sea currents, further influencing the propagation characteristics of acoustic waves.

These uncertainties of acoustic propagation in shallow and deep water need to analyze in order to deploy a specific network for specific application [5]. In addition, the propagation and transmission losses associated with these uncertainties in sound speed has to be evaluated in shallow and deep-water settings [6]. Hence, in this work an analysis has been conducted for comprehensive understanding of sound speed profile over different temperature, salinity and depth conditions at considered water settings.

2 Literature Review

Numerous authors have examined fluctuations in sound velocity profiles beneath the surface and suggested methods for effectively implementing acoustic sensor networks in submerged settings. A thorough numerical method called the spectral element method has been used in [7] to simulate the propagation of sound across complex acoustic velocity profiles. In [8], an accurate algorithm for estimating the effective sound velocity in deep-sea channels has been proposed. In the context of long-term soundscape monitoring, the authors of [9] have provided a brief summary of the acoustic measurements. The authors of [10] have presented a succinct synopsis of the acoustic measurements.

The study in [11], explores the capability of a parabolic equation (PE) model to simulate sound propagation in the highly complex shallow water environment. The research in [12], introduced an algorithm designed to compute the sound velocity profile of ocean water. The authors of [13], have investigated the foundation for comprehending the intricacies of the underwater realm. The study in [14], demonstrates the fluctuations in sound speed within a shallow sea environment through a modeled acoustic channel. In [15], the authors have constructed a model for an acoustic channel, examining variations in sound speed in deep water. The study in [16], introduced an acoustic channel model to analyze variations in sound speed and transmission losses. In the deep-water settings, the channel features have been studied in [17]. The authors of [18], has presented a comparisons of channel features. Based on surface reflection, the channel has been modalized in [19].

3 Methodology

3.1 Sound Speed

In underwater, sound speed [20] is a function of depth (z), salinity (S), and temperature (T), and it is described as (1).

$$c(T, S, z) = a_1 + a_2T + a_3T^2 + a_4T^3 + a_5(S - 35) + a_6z + a_7z^2 + a_8T(S - 35)a_9Tz^3 \tag{1}$$

3.2 Acoustic Propagation Loss

The path loss resulting from underwater acoustic transmission is represented by (2) and (3), respectively [21–23].

$$L_{CS} = 10 \times \log(R_t) \tag{2}$$

$$L_{SS} = 20 \times \log(R_t) \tag{3}$$

3.3 Absorption Loss

The information conveyed from the source to the destination is absorbed by the chemical particles that are present in the underwater environment. Underwater absorption is a function of frequency [24], and (4) is used to illustrate the loss resulting from this and the absorption coefficient is expressed using (5).

$$L_{ab} = (\alpha \times R_t) \times 10^{-3} \tag{4}$$

$$\alpha = \frac{A_1P_1f_1f^2}{f^2 + f_1^2} + \frac{A_2P_2f_2f^2}{f^2 + f_2^2} + A_3P_3f^2 \tag{5}$$

3.4 Transmission Loss in Shallow Water

Shallow water introduces complexities due to interactions with the seafloor and the water column, leading to phenomena such as bottom reflection, refraction, and scattering [24]. These interactions contribute to the attenuation of sound waves, resulting in transmission losses which are represented using (6).

$$TL_{Shallow} = L_{CS} + L_{ab} \tag{6}$$

3.5 Transmission Loss in Deep Water

Unlike shallow water acoustics, deep water environments are characterized by significant depth, where the sound waves encounter fewer complexities in terms of interactions with the seafloor [25]. The transmission losses due to attenuation of sound speed in deep water is modeled using (7).

$$TL_{Deep} = L_{SS} + L_{ab} \tag{7}$$

4 Execution Limits

A complete list of all the simulation's parameters and their respective ranges is included in Table 1.

Table 1. Execution Parameters.

Parameter	Range
Depth $_{shallow}$	0–100 m
Depth $_{deep}$	100–7000 m
T	30 to 4 ^{0}C
S	30 to 35 ppt
pH	7.8
R_t	10–100 m
Frequency	0.1–100 kHz

5 Execution Outcomes

The variation of sound speed with respect to temperature at different shallow water has been evaluated. Figure 1 makes it abundantly evident that sound speed increases after reaching a temperature of 18 ^{0}C, after which it drops linearly with depth.

Figure 2 shows the assessed variation of sound speed with regard to salinity at various shallow water depths and makes evident, sound speed rises linearly with salinity and depth.

The variation of sound speed with respect to temperature at different deep-water depths has been evaluated and is depicted in Fig. 3. it is clearly observed from Fig. 3, the sound speed decreases linearly with temperature and increases linearly with depth.

The node transmission range (R_t) and operation frequency have a direct proportional effect on the transmission losses. However, transmission losses were also caused by differences in sound speed. When the sound speed increases from 1450 to 1530 m/s in shallow water, the transmission losses decrease by 3.89% (see Fig. 4). An increase in sound speed from 1470 to 1620 m/s results in a 0.34% reduction in transmission losses in deep water (see Fig. 5).

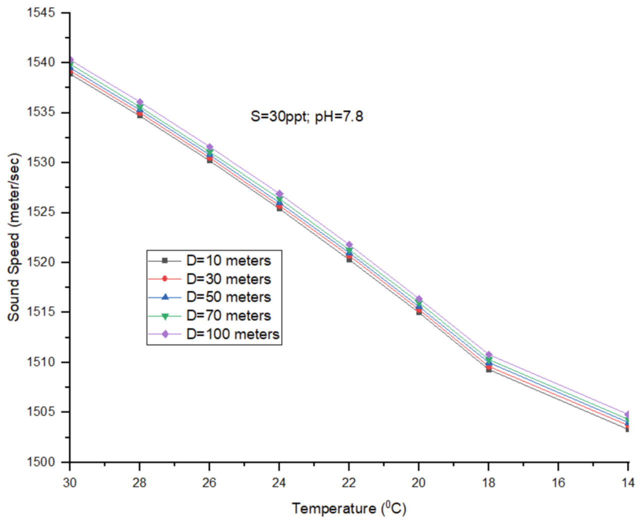

Fig. 1. Shallow water sound speed analysis with respect to temperature.

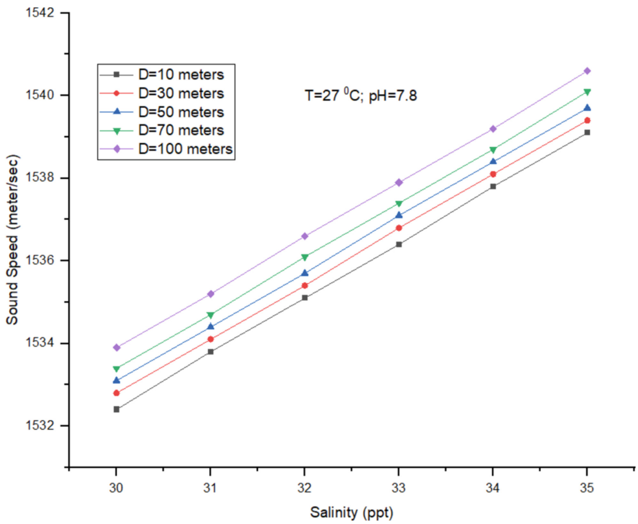

Fig. 2. Shallow water sound speed analysis with respect to salinity.

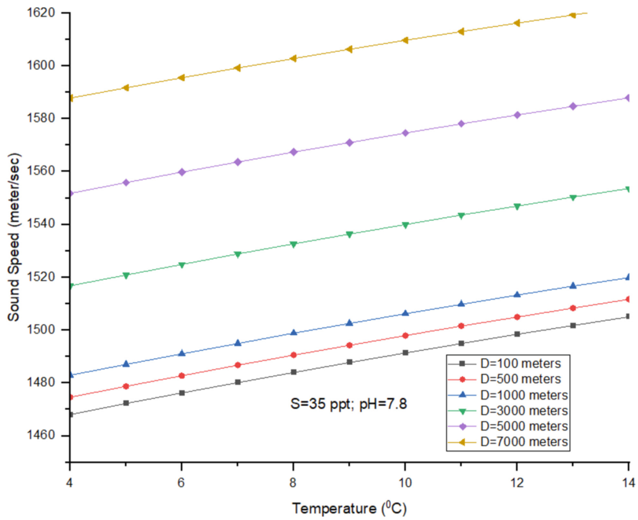

Fig. 3. Deep water sound speed analysis with respect to temperature.

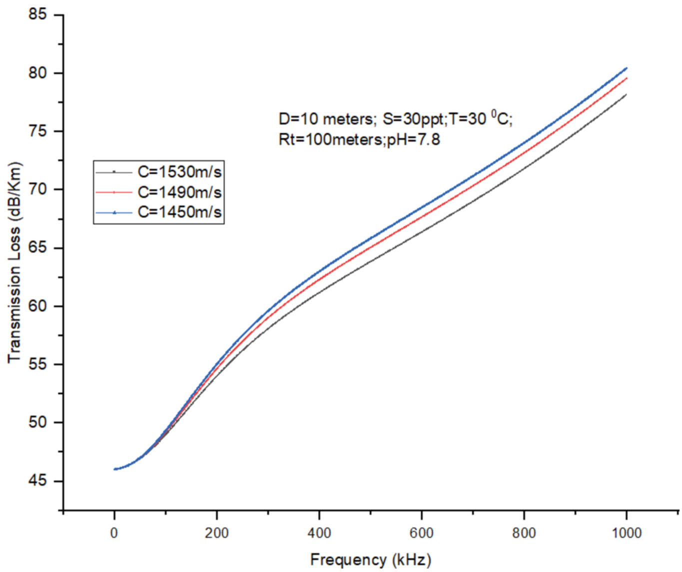

Fig. 4. Transmission losses in shallow water with different sound speeds.

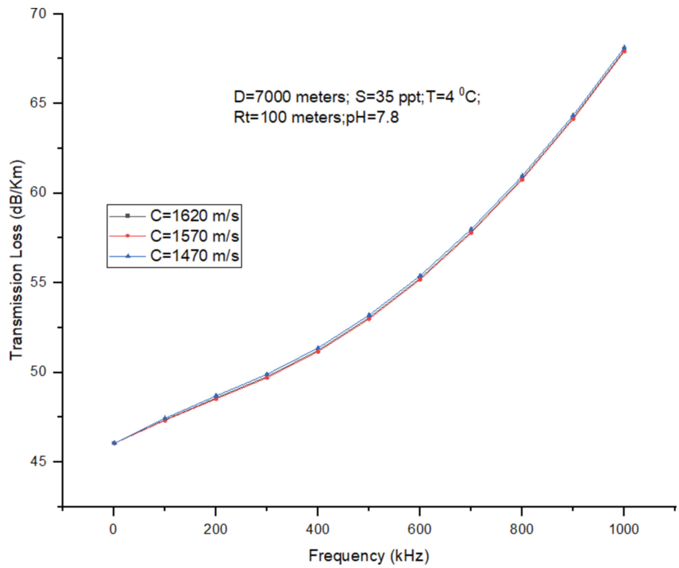

Fig. 5. Transmission losses in deep water with different sound speeds.

6 Conclusion

In assumed water settings, this study focuses on evaluating and analysing variations in sound speed profiles under varied temperature, salinity, and depth circumstances. Furthermore, the study includes assessing transmission losses in shallow and deep water by varying the speed of sound instead of changing the distance or frequency. As the sound speed increases from 1530 to 1620 m/s, the simulation results show that fluctuations in sound speed have a considerable impact on overall transmission losses, with a reduction of 17.6%. In particular, when sound speed increases from 1450 to 1530 m/s in shallow water, transmission losses drop by 3.89%, and when sound speed increases from 1470 to 1620 m/s in deep water, transmission losses reduce by 0.34%.

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