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SOUND PROPAGATION IN WATER — OVERVIEW OF RELEVANCE FOR THE SEARCH FOR SUBMARINES

ABSTRACT
Sound propagation in water is an important factor affecting submarine search operations in dive position. Knowing the distribution of sound propagation in seawater is essential for both submarines and surface ships in anti-submarine warfare (ASW) operations. The article is a review and presents examples of sound wave propagation emitted from surface and submarine ships during sea search operations. The aim of the article is to illustrate the propagation of sound waves in sea water depending on the location of the source of sound emitted by surface ships or submarines. Of course, the presented examples are general in nature, typical for ideal images of sound propagation and do not take into account their variability that occurs in real situations.

KEYWORDS: sound propagation in sea water, refraction of sound waves, underwater sound channel

1. INTRODUCTION

The characteristics of the sound propagation in sea water is a feature of significant importance for navies. The sund propagation in water in the conditions of navies is associated with ASW, which is an activity related with the use of surface warships, aircraft, submarines (Figure 1), or other platforms – nowadays and in nearest future unmanned autonomous vehicles (UAVs), to find, track, deter, damage, and/or destroy other submarines. The sound propagation in the area of operation it is important for both submarines and surface ships.

Figure 1. The Polish KILO class submarine ORP *Orzeł*
(Source: Photo — C. Dyrcz)

Sound propagation in water is a function of its velocity. And velocity is a function of water density and compressibility. As such, sound velocity is dependent upon temperature, salinity, and pressure and is normally derived expressing these three variables. The speed of sound in water changes by 3–5 metres per second per °C, by approximately 1.3 metres per second per PSU (Practical Salinity Unit) salinity change, and by about 1.7 metres per second per 100 m change in depth (compression). The speed of sound in seawater increases with increasing pressure, temperature, and salinity (and vice versa) [1].

Sample curves of temperature, salinity and density compared with depth are shown in Figure 2.

$$\frac{\sin\varphi}{\sin\psi} = \frac{c_1}{c_2} \tag{1}$$

where:
φ – an angle of incidence,
ψ – an angle of refraction,
c_1 and c_2 – speed of sound waves propagation in adjacent layers of water with different values of temperature, salinity, and pressure [4].

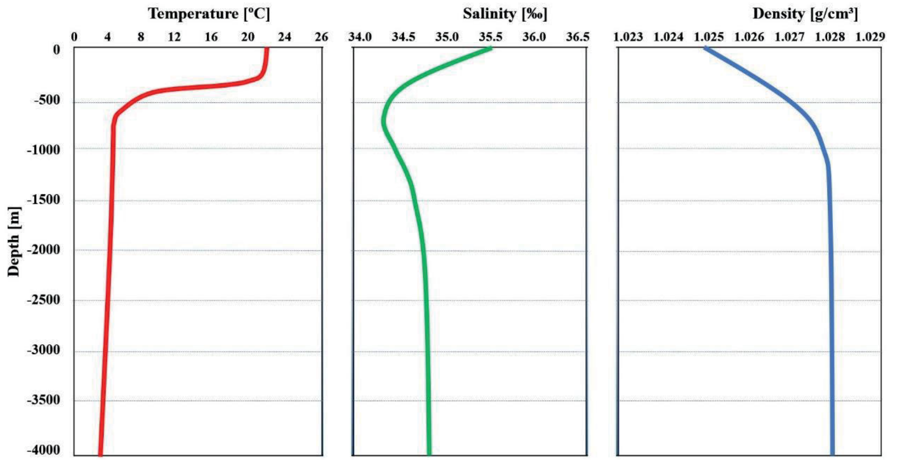

Figure 2. Sample curves of temperature (red), salinity (green) and density (purple) with depth

It follows from equation (1) that if the sound velocity in the second layer is lower than in the first, the ray direction will decrease and the sound ray will deflect towards the seabed. On the other hand, if the speed of sound in the second layer is greater than in the first, the direction of the ray will increase and the ray of sound will deviate away from the seabed. Depending on the speed of sound in the water, the direction of the sound ray propagating in the individual layers of water changes as it moves from layer to layer. In hydroacoustic, this phenomenon is called refraction of sound waves. The dependence of refraction on the speed of sound in water is shown in Figure 3.

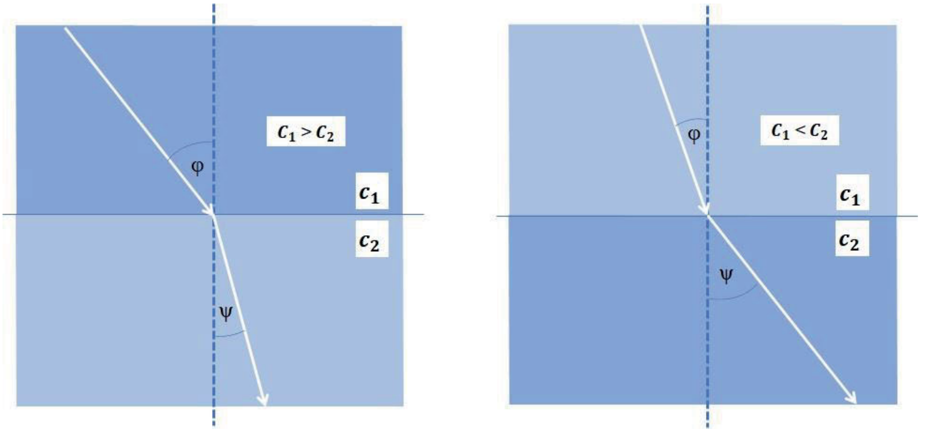

Figure 3. Refraction of sound waves in layers of water [4]

In shallow waters, the nature of refraction depends mainly on the temperature distribution, and in some cases also on salinity. In deep water, regardless of temperature and salinity distributions, hydrostatic pressure has a large influence on the nature of refraction. An example of the sound speed distribution made in shallow water (Baltic Sea) in the summer on July 22, 2022 is shown in Figure 4.

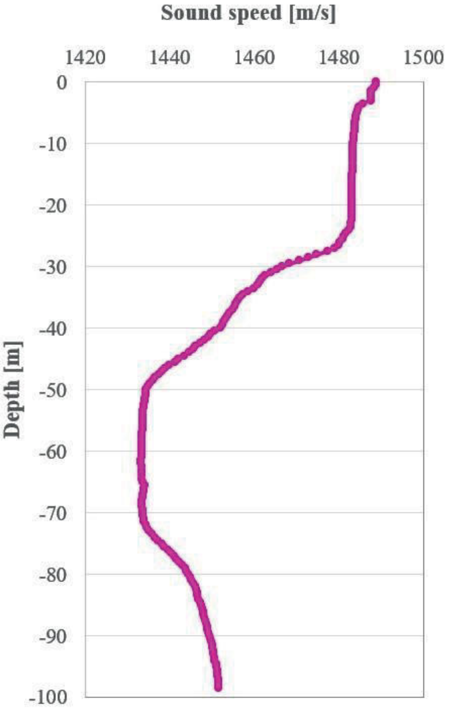

Figure 4. An example of the sound speed distribution made in shallow water (Baltic Sea) on July 22, 2022

Typical deep-sea sound profiles (Atlantic Ocean) are illustrated in Figure 5.

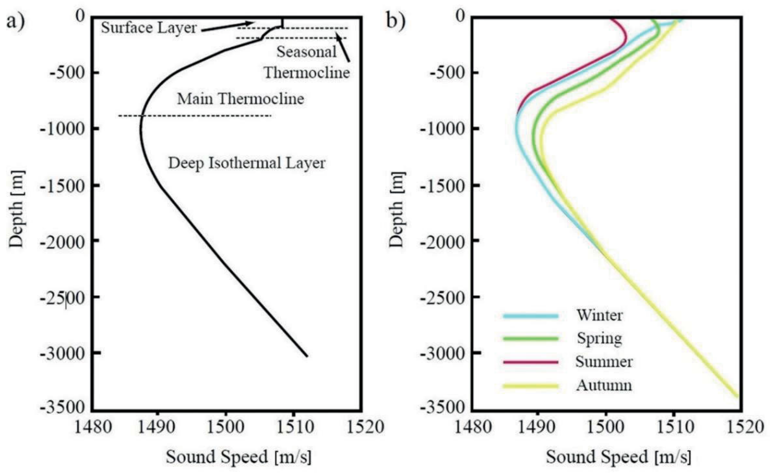

Figure 5. Typical deep-sea sound speed profiles. (a) Profile showing layer structure of the sound speed in the water due to temperature variations (b) Average sound speed profiles in different seasons in an area halfway between Newfoundland and Great Britain [5]

2. THE TYPE OF SOUND PROPAGATION IN SEA WATER AND ITS IMPORTANCE FOR SUBMARINES

Depending on the hydrological conditions, the following types of sound propagation in water occur:

- Linear propagation,
- Negative refraction,
- Positive refraction,
- Underwater Sound Channel (USC).

In the article, the figures below present the ideal distributions of sound propagation in water, which is a simplification used to clearly illustrate the individual types of propagation. In real conditions, the variation in the speed of sound in water is significant [2, 3].

Linear propagation – is a characteristic phenomenon for shallow water areas, especially in the autumn and winter season. As a result of the mixing process, the temperature of the water in the layer equalizes from the surface to the bottom. Such conditions may also arise in summer with an intensive mixing process during storms. During these hydrological conditions, when the speed of sound is constant, the phenomenon of refraction does not occur, and the sound rays propagate linearly. Linear propagation of sound from the position of the submarine and the surface ship is illustrated in the Figures 6 and 7 below. These are good detection conditions in both cases. However, it does happen in shallow waters.

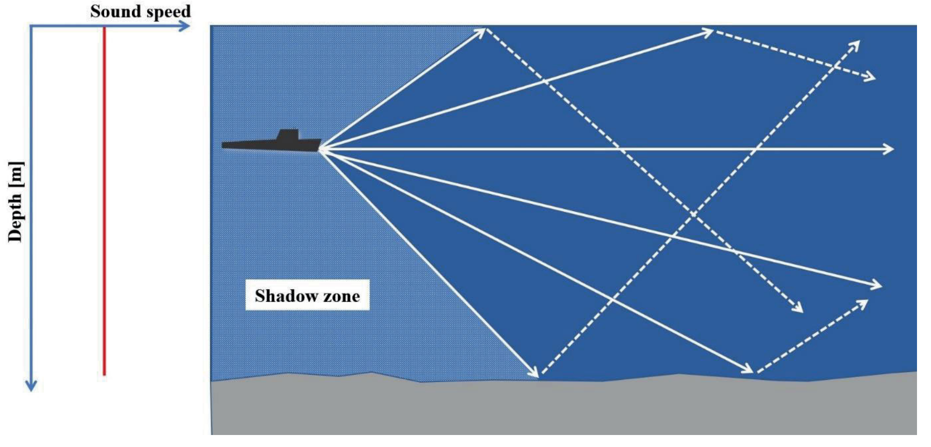

Figure 6. Linear propagation of sound waves from a submarine [3]

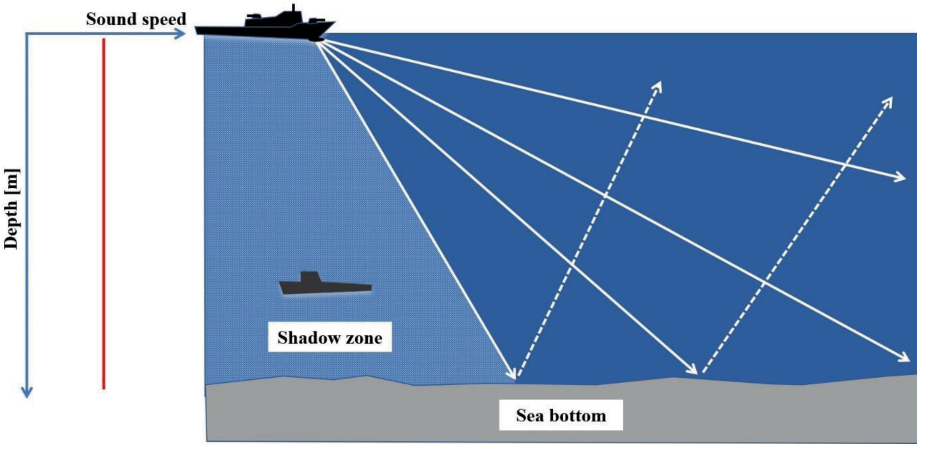

Figure 7. Linear propagation of sound waves from a surface ship [3]

Positive refraction – it is characteristic for deep-water areas, where surface waters cool down during autumn and winter and the influence of hydrostatic pressure on the speed of sound is large. The speed of the sound increases with the depth. Sound waves coming from the sound source deflect towards the surface of the sea, are then reflected and then return through the water depth to the surface. With this refraction, there are favorable conditions for the propagation of sound in the water. Positive refraction is beneficial for conducting ASW operations. The phenomenon of damping and absorbing sound energy by water is the result of shortening the sound range. The positive refraction of sound waves in the water from the position of the submarine and the surface of the sea is illustrated in Figures 8 and 9 below.

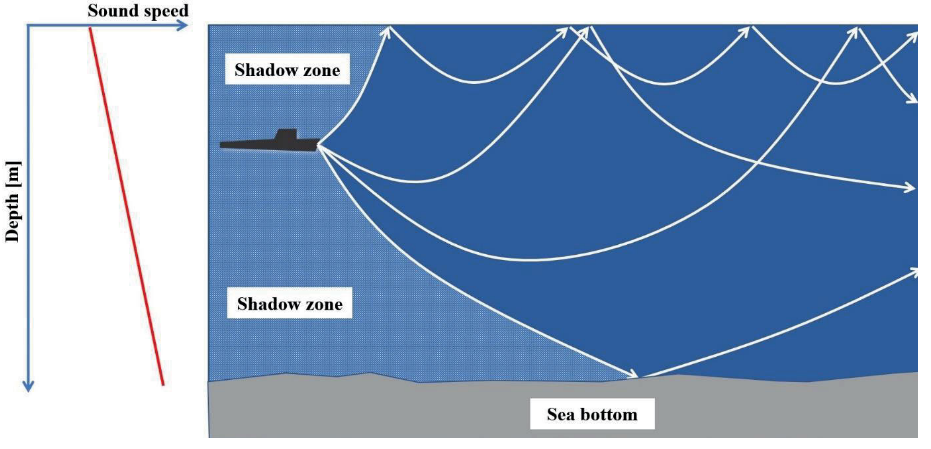

Figure 8. Positive refraction of sound waves from a submarine [3]

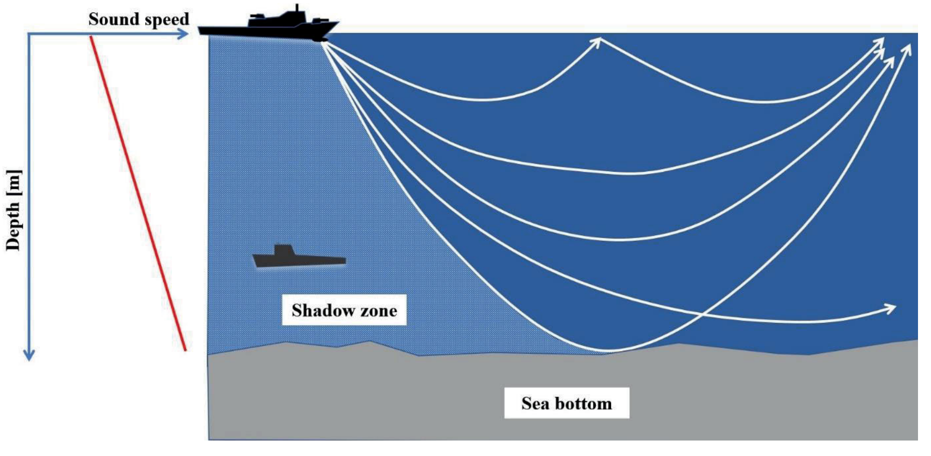

Figure 9. Positive refraction of sound waves from a surface ship [3]

Negative refraction – occurs when a decrease in the speed of sound in the water causes the sound rays to deflect towards the seabed (towards lower velocity values). It occurs in shallow waters during spring and summer, when the surface layer of water is strongly heated and the speed of sound reaches the highest value on the surface, and the depth dimension decreases. Sound rays come out of the sound source, deflect towards the seafloor, reflect off it and deflect again. In the case of negative refraction, the range of sound in water is the smallest and there are shadow zones that cannot be reached by sound rays. Negative refraction is an unfavourable phenomenon in ASW. The negative refraction of sound waves in the water from the position of the submarine and the surface of the sea is illustrated in Figures 10 and 11 below.

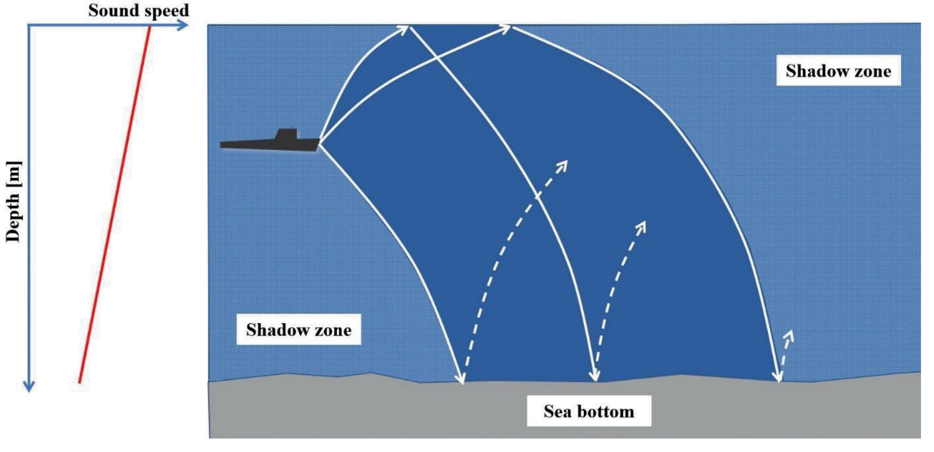

Figure 10. Negative refraction of sound waves from a submarine [3]

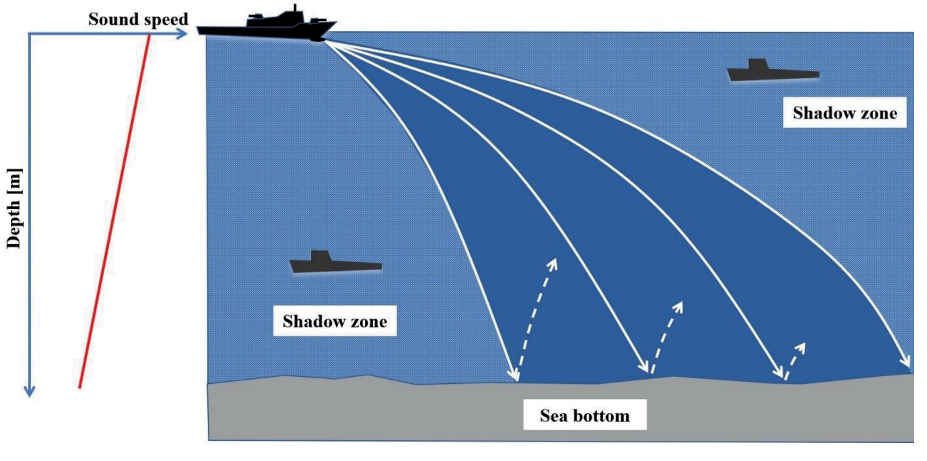

Figure 11. Negative refraction of sound waves from a surface ship [3]

Underwater Sound Channel (USC) – occurs in conditions where in the upper layer of sea water the sound velocity distribution is determined by negative refraction, and in the lower layer – by positive refraction. A characteristic feature of the underwater sound channel is the existence of a layer at a certain depth with a minimum value of the speed of sound. This layer is called the axis of the underwater sound channel. Due to changes in the refractive nature, sound rays experience multiple full internal reflection on both sides of the channel axis. If the sound source is placed close to the channel axis, the hearing range is extremely large. The range of sound in the underwater sound channel areas is up to several thousand nautical miles. Underwater sound channel from the position of the submarine and the surface of the sea is illustrated in Figures 12 and 13 below.

An underwater sound channel is formed in the oceans and open sea areas, when there is a constant or seasonal warm water layer, the speed of sound slows down and then increases. Underwater sound channels exist at depths of up to several hundred meters, however, subsurface sound channels are observed at depths of 10 to 60 m. This is the case, for example, in the Baltic Sea.

The phenomenon of super-long ranges related to the propagation of sound in the underwater sound channel was used to build a distance determination system based on measuring the differ-

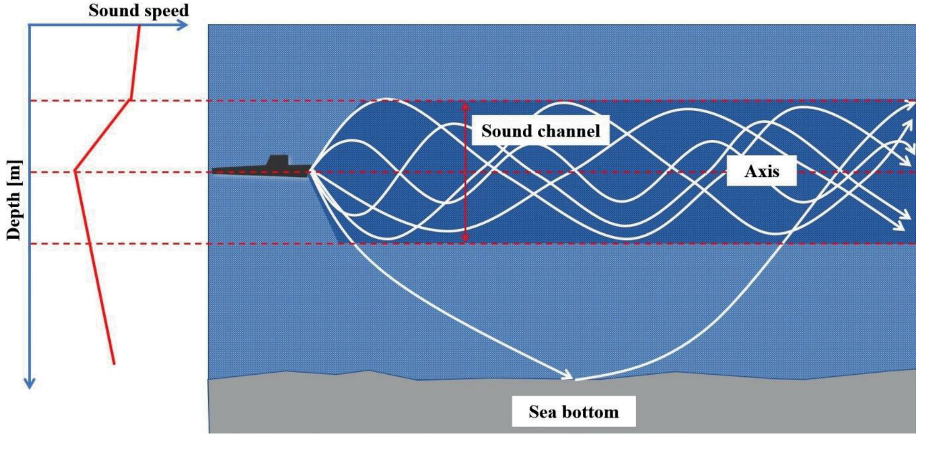

Figure 12. Underwater sound channel from a submarine [3]

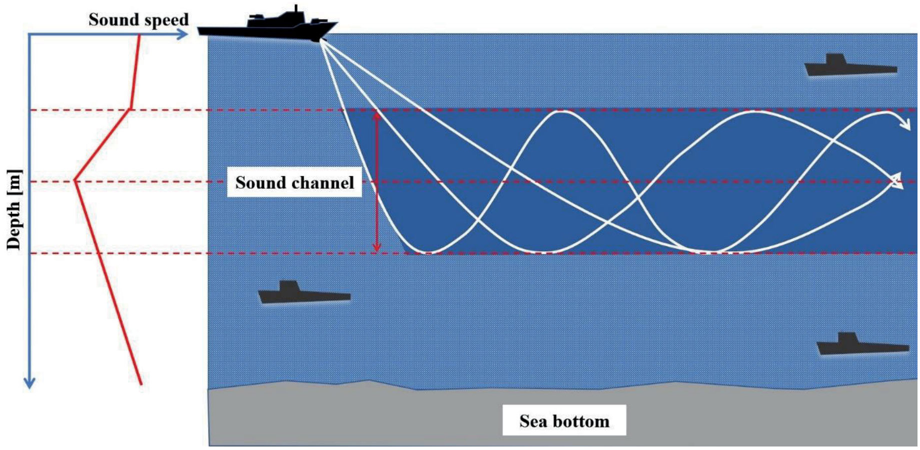

Figure 13. Underwater sound channel from a surface ship [3]

ences in the arrival time of a sound pulse called the Sound Fixing and Ranging (SOFAR). The system was developed during World War II and was used by the US Navy. Currently, the system is being developed not only in military applications, mainly for ASW, but also for the identification of earthquakes and other events.

Positive refraction in the upper layer and negative in the lower layer – this is the opposite of the underwater sound channel formation conditions and at a certain depth there is a maximum value of the speed of sound. Above we have positive refraction and below negative refraction. In the layer with positive refraction, there are conditions for distant sound propagation. This situation is referred to as the **near-surface sound channel**. Positive refraction in the upper layer and negative in the lower layer from the position of the submarine and the surface of the sea is illustrated in Figures 14 and 15 below.

The examples of refraction presented above have been simplified, because in fact, due to the complicated shapes of the sound velocity profiles, the images of sound rays are more complicated. The energy of sound waves propagating in the sea water environment is weakened by the process of absorbing and dispersing sound in the water [3].

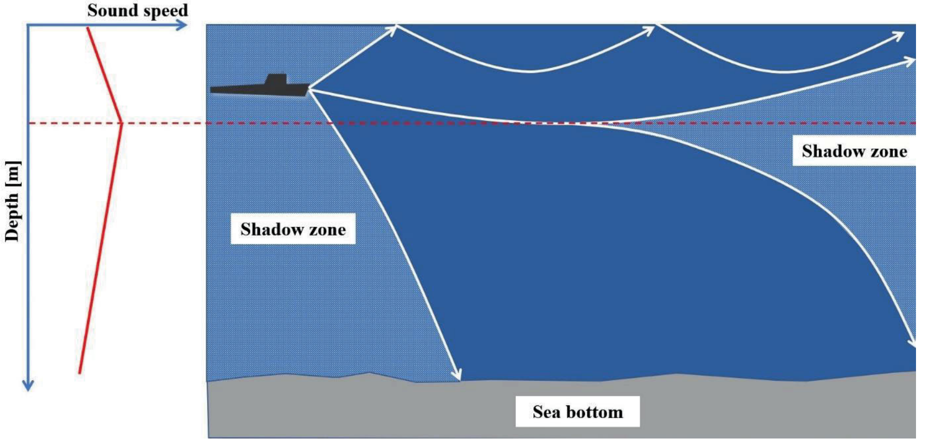

Figure 14. Positive refraction in the upper layer and negative in the lower layer from a submarine [3]

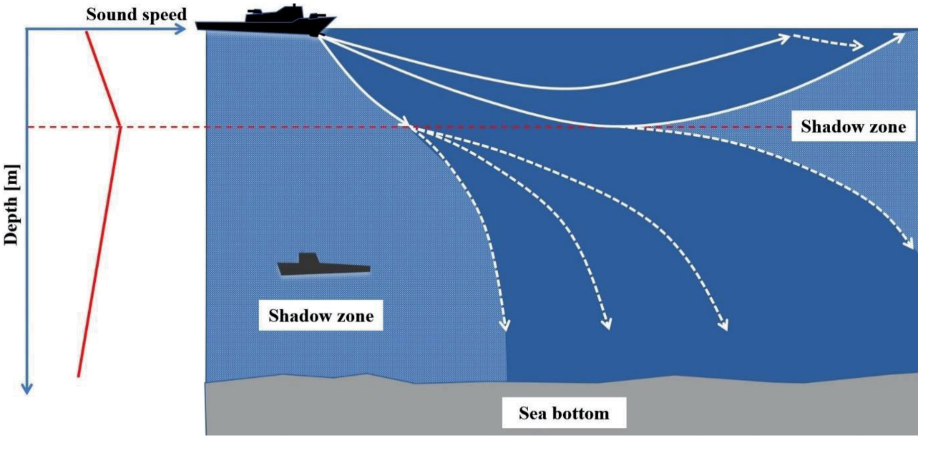

Figure 15. Positive refraction in the upper layer and negative in the lower layer from a surface ship [3]

3. CONCLUSION

Knowing the speed of sound in seawater at a particular location is essential for naval search for submarines. The above-presented examples of refraction dependent on the sound velocity distribution include the idea of tactical use of this phenomenon in the conducted operations. It emphasizes the importance of this phenomenon for both surface forces and submarines. The considered phenomenon is necessarily taken into account during hydrographic works. When performing hydrographic measurements with the use of sonars, the sound speed distributions should be measured each time before and after the measurements, because refraction, especially at a large penetration angle, can cause large errors in determining the position of objects. For the above-described operations, the measurement of sound speed before commencement of operations is of particular importance.

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