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Sea bottom influence on sound propagation for underwater equipment detection

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Abstract. The protection of maritime communication routes, ships and coastal installations involves the use of hydroacoustic equipment (sonars) to detect underwater equipment (means) that may operate in the aquatic environment. This paper examines the influence of seafloor topography and structure on sound propagation and sonar detection probability.

1. Factors influencing sound propagation in the aquatic environment

The research activities carried out in the aquatic environment by different forces with different means involve taking measures for the protection of maritime communication routes, physical infrastructure, various areas of interest against these means as well as against sea mines. Thus, it is increasingly important that in parallel with the development of new methods and means of detection / discovery, in order to achieve a continuous presence in time and space, to analyze the variation of the factors that determine the propagation of sound in the areas of interest considering the METOC (meteorological and oceanographic) conditions, in order to determine the propagation conditions, the acoustic channel, allowing the detection / discovery of targets with a high probability. Knowing the sound speed profile (SSP) in the areas of interest allows determining the mode of action in these areas - using a towed sonar, a variable depth sonar (VDS) which allows avoiding shadow areas, a sonar installed on the ship's hull, in order to carry out research in the respective areas.

Knowing the structure and shape of the sea bottom is important from the point of view of [1, 2]:

- of ship navigation (for example, establishing the anchorage, assessing the safety of the anchorage depending on the type of sea bottom in the anchorage, installing navigation buoys, etc.);
- commercial/environmental (installation of marine drilling platforms, protective seawalls, beacon buoys for environmental monitoring, etc.);
- military (military operations - landing, mine warfare, installation of hydroacoustic buoys, anti-submarine warfare, etc.).

For example, environmental parameters that influence sea mine detection and countermeasures are: bathymetry, sound propagation, sea bottom type and composition, density of non-mine-like bottom objects (debris and small bottom features influence mine densities perceived by various active sonar), tides and currents, sea state, water clarity [3].

The analysis of sea bottom characteristics must contain information on the nature and texture of the sea bottom, contacts (wrecks, sandbars, seamounts, etc.), depth contours, etc., as these elements influence sound propagation in the aquatic environment.

The ray of the hydroacoustic wave, passing through layers of water with different temperature and salinity, does not propagate linearly but curves, always leaning in the part with the lower sound speed. When the temperature gradient in the layer is negative (negative refraction), the water temperature decreases with depth, the propagation speed decreases, and the sound rays are deflected towards the bottom of the sea regardless of their initial direction. Also, water salinity influences compressibility, sound speed, refractive index, thermal expansion, freezing point, and maximum density temperature [4].

2. Characteristics of the sea bottom

The sea bottom is characterized by a variable composition and a layered structure. This structure consists of rocks of different types over which unconsolidated sediments from two main sources are superimposed in most places:

- material brought by the adjacent land waters or from the erosion of the sea bottom itself;
- sediments of biological origin, resulting from the decomposition of plants and animals in ocean basins.

Sediment composition and roughness can vary over relatively short distances. Due to these characteristics at the level of the sea bottom, reflection, reverberation, dispersion, sound interference and sound attenuation occur inside the sediment layers (figure 1), Table 1.

Table 1. Sound attenuation in the sea bottom (1-100kHz) [5].

Sediment	Sound speed ratio c_s / c_w		Desity ratio ρ_s / ρ_w		Attenuation coefficient $\beta(dB/\lambda)$	
	z = 0	z = h	z = 0	z = h	z = 0	z = h
Fine sand	1.1073	1.1534	1.451	1.945	0.85	0.89
Medium silt	0.9885	1.049	1.149	1.601	0.36	0.38
Coarse clay	0.9812	0.9911	1.145	1.378	0.08	0.08

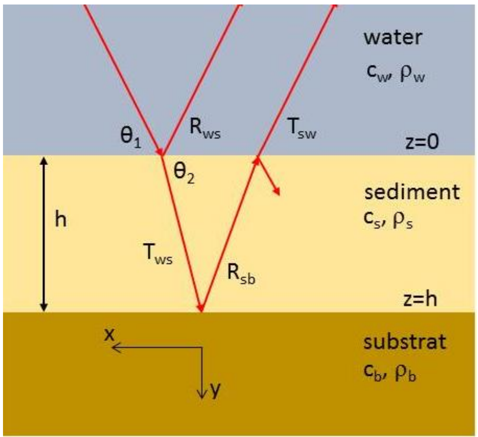

Figure 1. The structure of the sea bottom [5, 6].

In the analysis of the influence of the sea bottom on the reflection of the hydroacoustic wave / sound, the frequency of the sound, the angle of incidence and the nature of the sea bottom must be taken into account (mud – clay, silt; sand – very fine sand, medium sand, coarse sand, very course sand; gravel – granules, pebbles, cobbles; rock – boulders, rock) [6].

In the case of propagation in shallow waters, at vertical incidence, the losses are generally high and their value depends on the relationship between the impedances of the sediment and those of the water (mud has a lower reflection coefficient than sand or rock). A ratio $c_s/c_w>1$ (sediments with low porosity - for example, hard sands), where c_s is the speed of sound in the upper sediment and c_w is the speed of sound at the base of the water column, determines a critical angle [$\theta = \cos^{-1}(c_s/c_w)$] below which most of the incident energy is reflected (bottom loss is almost zero). In the case of a ratio $c_s/c_w<1$ (sediments with high porosity - for example, silts), the wave is refracted in the sediments resulting in higher losses at low angles [6, 7].

In the situation of propagation in deep waters, the hydroacoustic waves are reflected several times at the boundaries, and the waves that reach the bottom with a sufficiently large angle of incidence are reflected.

Regarding the variation of wave attenuation by the sea bottom with respect to frequency, the US Navy adopted three different models [9].

- LFBL (Low-Frequency Bottom Loss), f < 1kHz,;
- HFBL (High-Frequency Bottom Loss), f = 1,5 - 4 kHz;
- HFEVA (High-Frequency Environment Acoustic), f > 10 kHz.

3. Sea bottom influence on sound propagation and sonar detection probability

Carrying out activities related to mapping the sea bottom and determining its structure from a civil point of view, as well as carrying out certain military operations, require the use of sonars and taking measures so that the influence of the composition of the sea bottom is as small as possible. From a military point of view, it is desired to detect targets with a volumetric size of 0.5m on the continental shelf at depths of up to 200m [1].

Considering the Neyman-Pearson criterion in order to maximize the probability of detection for a certain probability of false alarm (established in advance) in the sense of making the decision of the existence of the useful signal in the absence of it at the input of the receiver (there is only noise).

The sea bottom, depending on its structure and topography, can cause absorption (attenuation) or reflection of the sonar signal resulting in a decrease or increase in the signal at the receiving point. For example, rock causes the reflection of sound instead, soft sediments or sand absorb the sound, reducing the strength of the received signal and reducing the probability of detection.

Noises that influence the useful signal at the receiving point are background noise, reverberation, biological substances or non-threatening platforms [8, 10].

Considering a signal with constant level (s) and a noise (n) with Gaussian distribution the false alarm probability is [9]:

$$P_{fa} = \frac{1}{\sqrt{2\pi}} \int_r^{\infty} e^{-\frac{y^2}{2}} dy \tag{1}$$

r representing the detection threshold.

The probability of detection depending on the detection threshold level is [9]:

$$P_D = \frac{1}{\sqrt{2\pi}} \int_r^{\infty} e^{-\frac{(y-s)^2}{2}} dy \tag{2}$$

Variation of detection probability as a function of false alarm probability and detection threshold is shown in figure 2.

In the analysis of the influence of the sea bottom on sound propagation, a sound speed profile corresponding to the month of July for the Black Sea was considered [11, 12, 13], figures 2-4 and the following main operational characteristics of the sonar: operating frequency 20-30 kHz, pulse bandwidth 3kHz, pulse type CW, pulse length 1-80ms, source level 200dB, beamwidth 30°, transducer depth 6m, tilt angle (-2°).

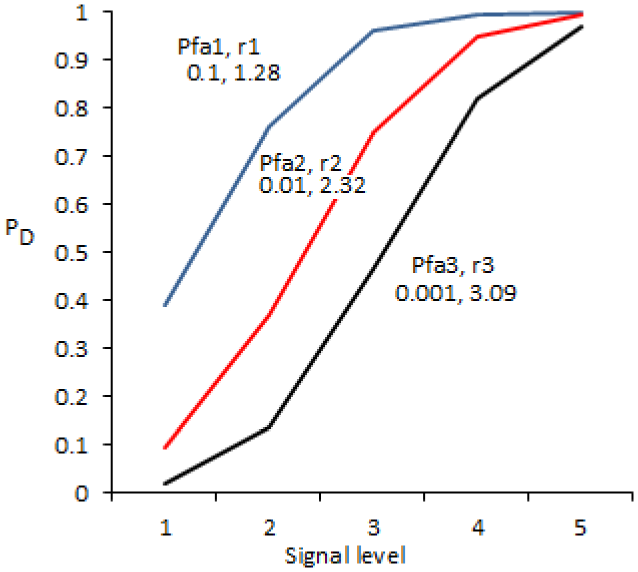

Figure 2. Variation of detection probability as a function of false alarm probability and detection threshold.

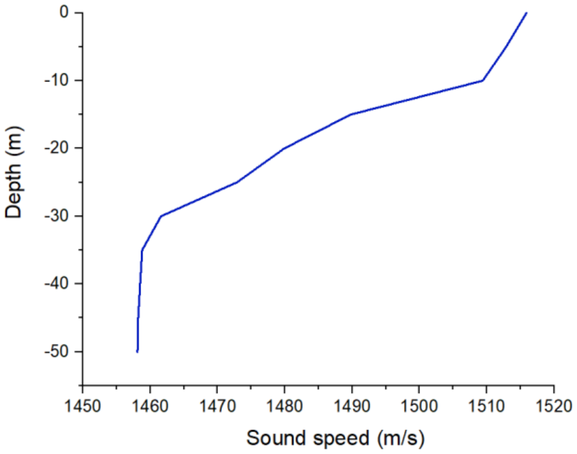

Figure 2. Sound speed profile.

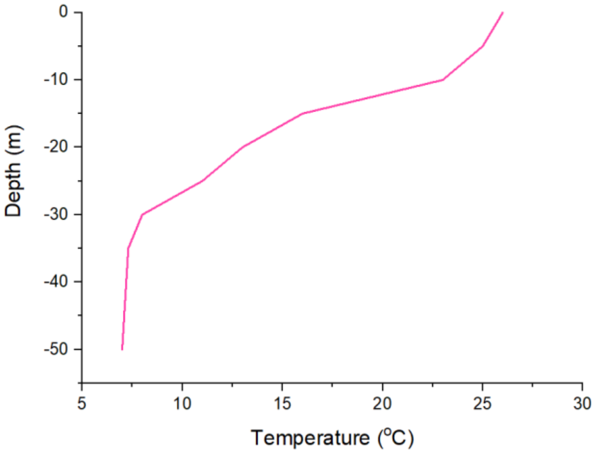

Figure 3. Vertical temperature distribution.

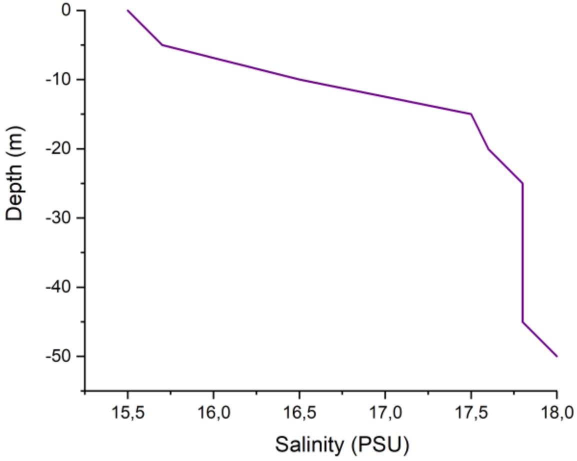

Figure 4. Vertical salinity distribution.

For the simulation, the LYBIN program was used, which allows the analysis of the influence for different types of sea bottom marked from 1 to 9, where 1 represents a hard rock type bottom with low reflection losses on the bottom and 9 represents a soft bottom with a high loss of reflection. The results are shown in the figures 5-7.

It is noted that the detection probability of about 98-90% is obtained at a distance of about 2.8-3 km from the ship for type 1, 1-1.3 km for type 5 and 0.5-0.6 km for type 9, which represents a considerable reduction in the detection distance with a high probability.

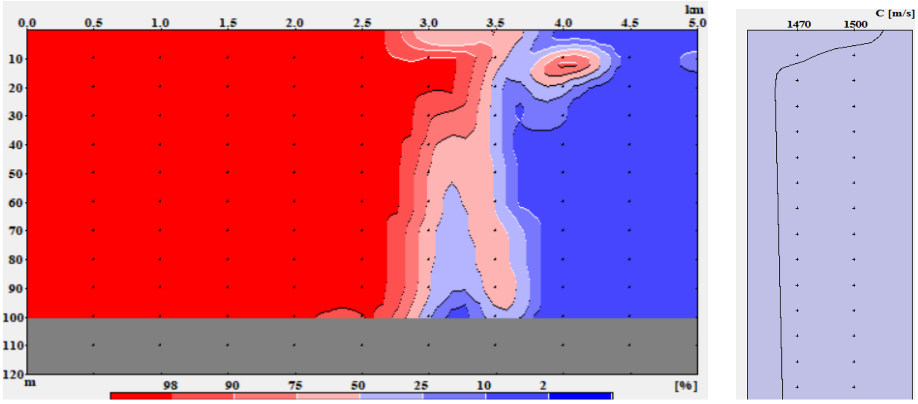

Figure 5. Probability of detection for bottom type 1.

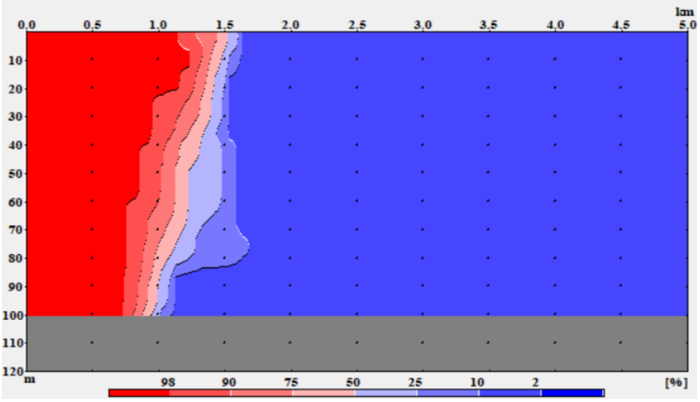

Figure 6. Probability of detection for bottom type 5.

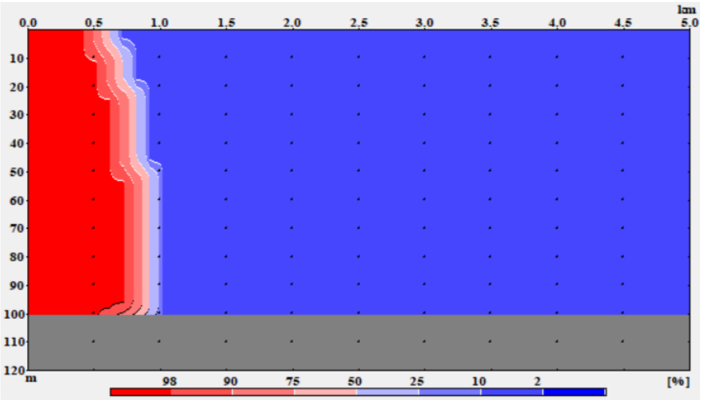

Figure 7. Probability of detection for bottom type 9.

Outside the continental shelf (figures 8, 10, 11), a probability of discovery of 98-90% is obtained at a distance of 3-3.2 km for type 1 and 1-1.3 km for type 5 (depth over 150m). In the case of type 2, the high-probability discovery distance is greatly reduced for depths below 150m, which is approximately 0.5-0.7 km. This observation also holds for type 9.

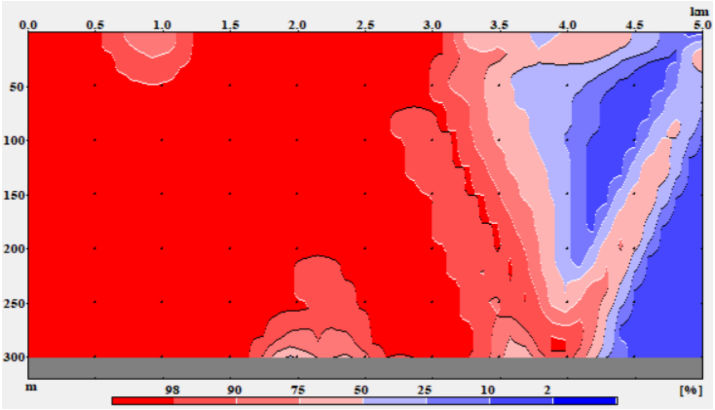

Figure 8. Probability of detection for bottom type 1.

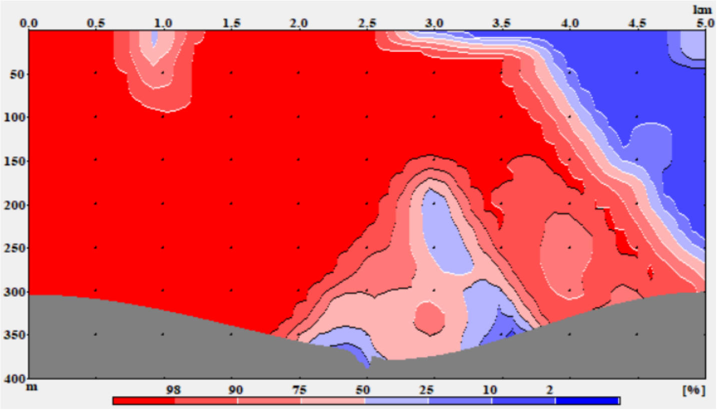

Figure 9. Probability of detection for bottom type 1 (modified topography).

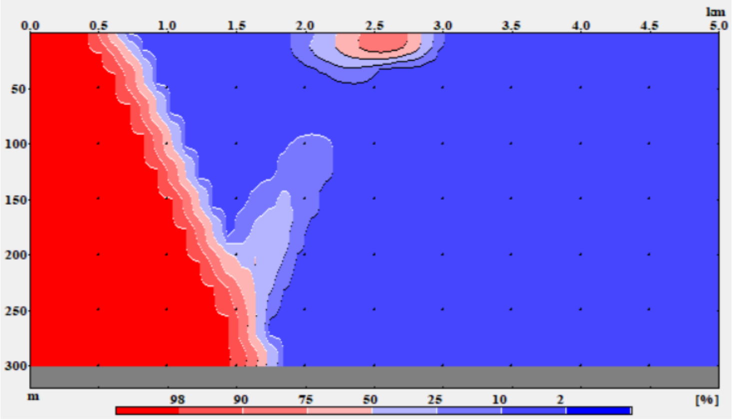

Figure 10. Probability of detection for bottom type 5.

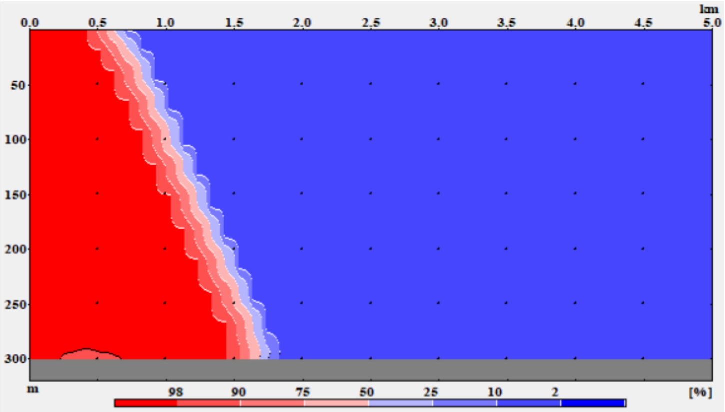

Figure 11. Probability of detection for bottom type 9.

In figure 9, compared to figure 8, there is a reduction in the probability of discovery in the area with greater depth and also an increase in the probability of discovery in the slope area, which demonstrates that the shape of the sea bottom (its topography) influences the ability to detection of targets by a sonar.

4. Conclusions

Knowing the sound speed profile (SSP) in the areas of interest allows measures to be taken in order to discover underwater means that may constitute a danger to maritime communication routes, critical coastal infrastructure etc.

The sea bottom having a variable composition and layered structure causes the absorption (attenuation) or reflection of the sonar signal resulting in a decrease or increase of the signal at the reception point, thus influencing the probability of detection.

From the simulations, a considerable reduction of the discovery distance is observed with a high probability, in the situation where the sea bottom represents a soft bottom (eg sand) compared to a hard rock type bottom.

Also, the shape of the sea bottom causes a change in sound propagation resulting in shadow areas with a very low probability of discovery.

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