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# RELATIONSHIP BETWEEN BASIC PHYSIOCHEMICAL PROPERTIES OF SEAWATER AND MAGNITUDE OF UNDERWATER ELECTRIC FIELD

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## ABSTRACT

Passive defense systems which minimize chance of vessel detection have to be utilized due to application of naval mines. Passive defense and signature minimization can be regarded as not only magnitude reduction but also as its shaping. Electric field magnitude at a given depth is a function of an electric field source but also it depends on physicochemical properties of seawater — temperature and salinity. In this paper results of underwater electric field simulations are presented. Cases of various depths, temperatures and salinities are shown. Computational results are compared to underwater electric field measurements performed with portable sensor.

Key words:
underwater electric field, minimization, vessel signature.

**Research article**

## INTRODUCTION

Naval mines are already over hundred years old. This weapon is developed due to shift of military activity towards coastal waters and due to its low price of purchase and production. Mines are considered to be one of the main threats to naval vessels and sea trade [2, 5]. During Russian-Japan war 37% of all loses occurred due to mine explosions, 38% during First World War and 20% during Second World War [2]. Importance of naval mines is recognized by actions of Polish Navy. Construction of Mine Hunter prototype — 'Kormoran II' was therefore commissioned. In 2017 two more vessels were ordered. On the other hand Armament Inspectorate of Poland initiated technical dialogue regarding commissioning naval mine fuzes for large (OD) and medium (OS) naval mines (OS, fig. 1) — naval mine fuze: for OD and OS under the codename ELEKTRON.

Fig. 1. Medium sized naval mines (OS), ORP 'Lublin' [photo M. Purman]

Furthermore, Polish Navy is armed with bottom mines MMD-2 produced by OBR CTM S.A. MMD-2 is an influence mine which fuze is triggered by physical field sensors (fig. 2). The fuze of the MMD-2 mine incorporates passive acoustic sensor (duty channel), pressure displacement and magnetic channels (tactical channels). The mine can be deployed by surface ships and is designed to combat both surface and underwater vessels [9]. Currently an additional underwater electrical potential (UEP) channel is under development.


Fig. 2. Bottom naval mine MMD-2 produced by OBR CTM S.A.

Among commercially available fuzes and complete mines there are ones which incorporate UEP sensors. Usually they consist of one to three axis sensors capable of Underwater Electric Potential and Extra Low Frequency Electric field (ELFE) detection. Such mines are offered for instance by RWM Italia and SAES. Due to the specific construction of UEP sensor and application of non-conductive materials the UEP channel is one of the latest developments in naval mine constructions. Algorithms governing mine actions can interpret data regarding UEP magnitude, its shape and spectrum. It makes assessment of the UEP source dimensions possible. An intelligent influence mine compares measured data with its database and depending upon the comparison result it eithers returns to sleep mode or triggers the mine.

In Polish National Defense Standards acceptable magnitudes of electric field parameters are given for a specific measurement depth. These parameters are: gradient of constant underwater electric field and shaft originating alternating underwater electric field, expressed in [μV/m]. The Polish National Defense Standards also require specification environmental or measurement parameters. However, it is not specified what parameters exactly have to be given, sensor depth, speed of the vessel and water salinity are mentioned as examples [8].

Magnitude of underwater electric field not only depends on source but also on physicochemical properties of the environment the measurement takes place in. In RIMPASSE trial program the formula (1) to convert signatures between different measurement depths and water conductivities was proposed [10].

$$|E|_x \sim |E|_{ref} * \frac{\sigma_{w,ref}}{\sigma_{w,x}} * \frac{(r_x)^3}{(r_{ref})^3} \tag{1}$$

where:

$\sigma$ — reference water conductivity;

$r$ — sensor depth;

$E$ — underwater electric field;

$x$ — subscript marks the data of sea area the data is recalculated for;
*ref* — subscript marks the water are the measurements were taken at.

According to formula (1) the electric field magnitude of a set source will scale reverse proportionally to conductivity of environment — electrolyte. Conductivity of the electrolyte mainly depends on the ionic species which are dissolved in water and its temperature (2).

$$\frac{\sigma}{c} \sim B^{-\frac{1}{T}} \tag{2}$$

where:
$B$ — a constant;
$C$ — concentration of ionic species;
$T$ — temperature.

In fig. 3 conductivity to water temperature relationship for several examples of water Practical Salinity Unit values (PSU) are presented. The proportionality coefficient of water conductivity to temperature varies between approximately 3.3% to 3.6% for the listed water salinities [3].

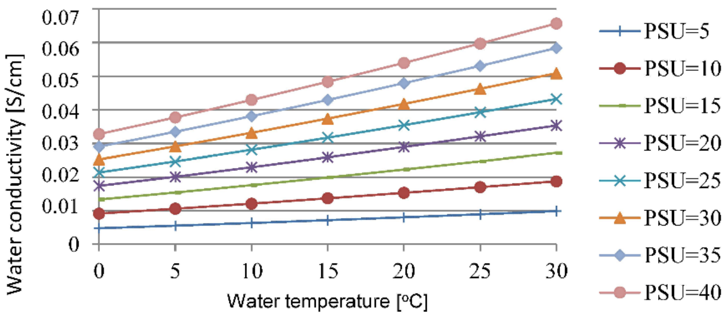


Fig. 3. Conductivity to water temperature relationship for several examples of water salinities (PSU) [3]

From naval mine's standpoint an underwater electric signature of the same object measured in two different seasons can vary from a dozen to several dozen percent. Water temperature can also be influenced by other phenomena such as upwelling. Furthermore an electric signature of the same object will vary at a given depth but in water areas which conductivity differs. When a fuze is programmed such environmental properties have to be considered. An example of extremely environmentally diverse area is the Baltic Sea.

Similarly physiochemical properties of water have great influence from management of vessel's signature standpoint. Estimated detection range of a vessel at a given depth is reversely proportional to water conductivity. The better the electrical conductor water is the lower the detection range of a vessel is. In Baltic Sea in a range of 350 NM water conductivity can easily change up to 4, 5 times.

Yet another consequence of these phenomena is difficulty in comparison of results between different measuring facilities. Non uniform sensor depth is another obstruction in proper data interpretation. Lack of coherence between several signatures measured during RIMPASSE trial struck objections [1].

## SALINITY AND CONDUCTIVITY OF WATER IN THE BALTIC SEA

In literature, seawater salinity data are far more common than conductivity. In PSS 78 scale salinity is calculated based on water conductivity with temperature correction measurement. There are several salinity scales and units: PSU/PSS (Practical Salinity Unit/Scale — PSS 78 scale, dimensionless), ppt (parts per trillion) and g/kg and their presence is explained by different measurement procedures. Salinity can be calculated from conductivity measurement, determination of mass of dissolved salts or $Cl^-$ ions titration. For many purposes those units can be considered equal. However the PSS 78 scale is referenced to conductivity of 32.4356 g/kg KCL dissolved in 15 °C water. Water salinity in oceans and most of the seas varies from approximately 33‰ to 37‰ (fig. 4).

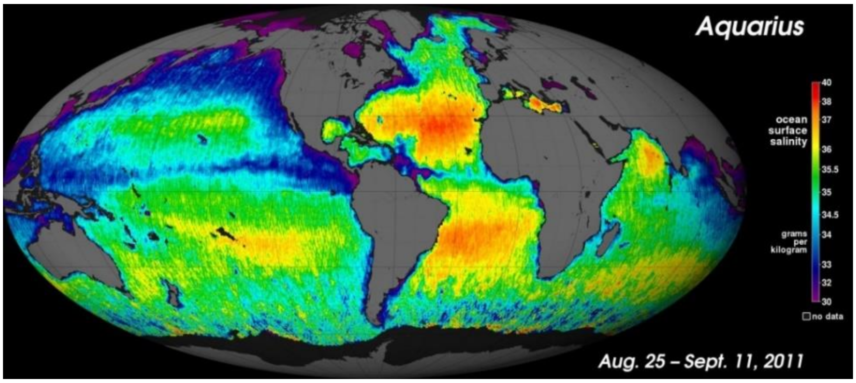


Fig. 4. Salinity map of water [g/kg] from Aquarius sensor mounted on SAC-D satellite [7]

Baltic Sea is a very specific body of water where salinity varies significantly dependent on regions considered. For instance, salinity in proximity of Skagen is only slightly lower than the salinity of ocean water reaching almost 32 PSU (fig. 5). Salinity of water in Danish straits varies from a dozen to two dozen PSU. While salinity of Proper Baltic equals approximately 7–8 PSU and 3–4 PSU in Bothnian Bay. A lower salinity is to be expected near major river mouths, such as Vistula River in Poland. Salinity in the area of operations of Polish Navy may thus vary even a dozen times — by an order of magnitude.

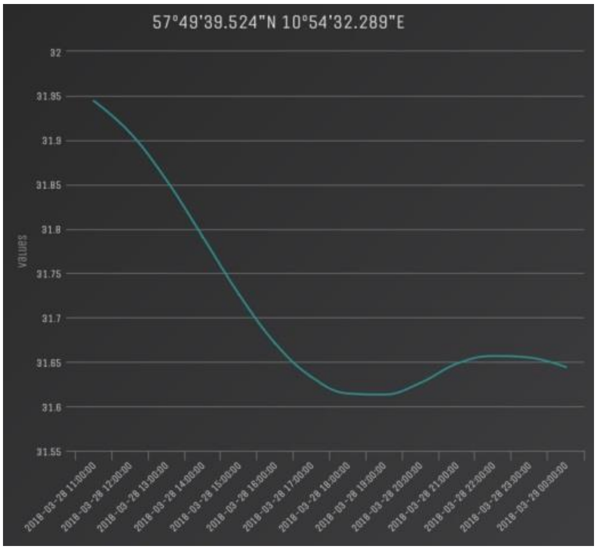


Fig. 5. Water salinity in proximity of Skagen (57°49'39.524"N 10°54'32.289"E) on 28.03.2018; data from eBaltic-Grid model [6]

Monthly average temperature of seawater in Baltic at Polish Coast is presented in fig. 6. Difference between monthly average temperature of the coldest and the warmest month equals 15.87 °C. This corresponds to a conductivity change of approximately 50% [6].

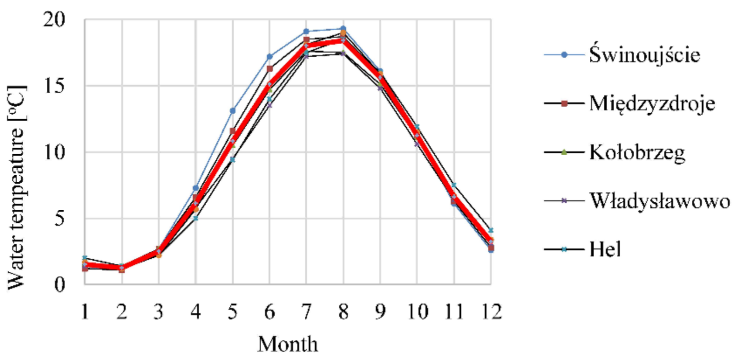


Fig. 6. Monthly average temperatures of water at several sites located along Polish Coast and mean monthly average temperature [4]

## EXPERIMENTAL RESULTS

Measurements of underwater electric field were performed. The sensor was placed 9 m under sea surface, 0.5 m above the seabed. Depth was measured with sonar. The source of electric field was a dipole which poles were 7.5 m apart. Current intensity between the poles equaled either 0.5 A or 2 A. Conductivity of the seawater was measured and equaled 0.9 S/m. Dipole velocity equaled approximately 2.5 m/s. The trials were conducted in April.

Results of underwater electric field measurements were compared to results of computer simulations. Three layer analytical model employing method of images was developed. Model includes seawater and seabed salinities and allows calculation of underwater electric potential as well as electric field intensity from combination of point like sources at chosen measurement locations (e.g. on a plane, line etc.). Model accurately estimates influence of seabed-sensor distance on electric field and was verified with Finite Element (FE) simulations in Ansys Maxwell.

Seabed conductivity of 0.03 S/m was assumed, while distance between seabed and sensor was set to 0.5 m, 1.0 m or 2.0 m for simulations presented in the article. A simplified scheme of a dipole, sea surface, seabed, sensor and coordinate system setup used for purpose of computer simulation is presented in fig. 7.

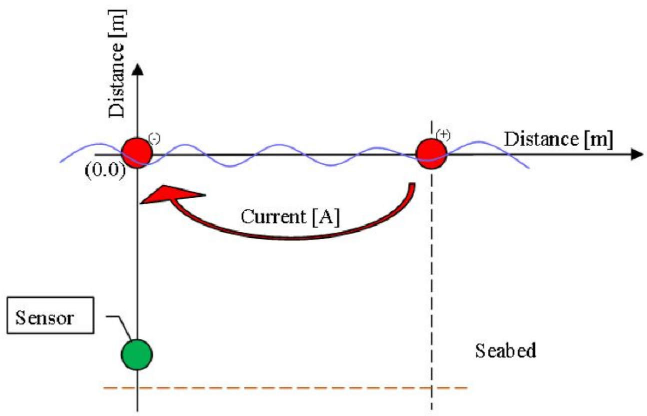


Fig. 7. A simplified scheme of a dipole, sea surface, seabed, sensor and coordinate system setup used for purpose of computer simulations

Ag|AgCl sensor was mounted on a rack made of polypropylene with extra weight added to obtain negative buoyancy. No metal parts were used in rack construction. Spacing between six Ag|AgCl|3% NaCl|Seawater electrodes equaled 1 m. Voltage measurements were performed with a 16 bit Analog-Digital Converter, sampling frequency equaled 5 kHz. Data was transferred to the PC over local network. Recorded data which is presented in this paper was bandpass filtered which bandwidth ranged from 0.01 Hz to 5 Hz.

Results of underwater electric field measurements confronted with results of computer simulations are presented in fig. 8 and 9 for 0.5 A and 2 A currents respectively.

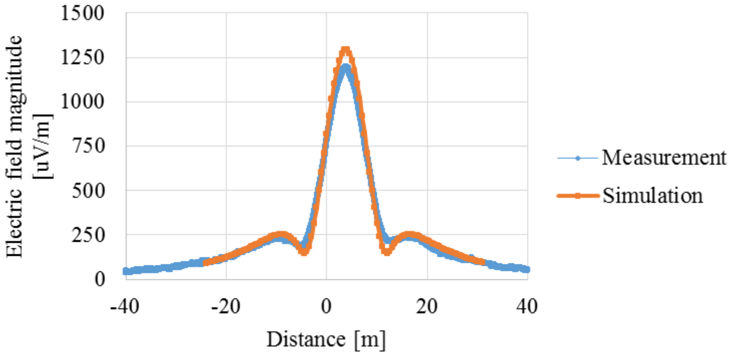


Fig. 8. Results of underwater electric field measurements confronted with results of computer simulations, current intensity 0.5 A, seawater conductivity 0.9 S/m

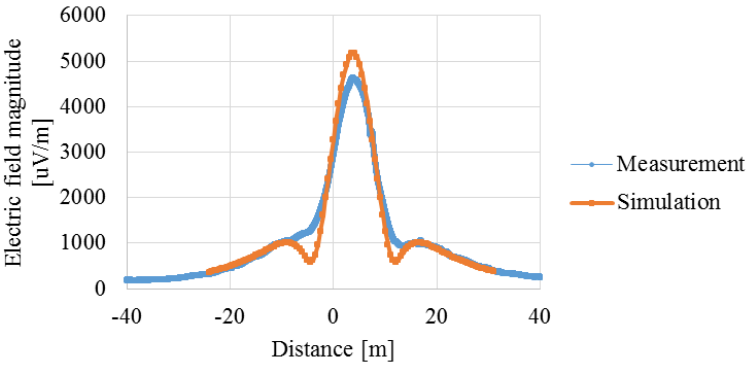


Fig. 9. Results of underwater electric field measurements confronted with results of computer simulations, current intensity 2 A, seawater conductivity 0.9 S/m

Relative error between the maximal magnitude of measured and simulated underwater electric field equaled 7.5% and 10.5% for dipole current densities of 0.5 A and 2 A respectively. The error values are influenced by uncertainty of sensor to dipole location. Sensor was marked by a buoy.

Underwater electric field originating from 0.5 A and 2 A current densities dipoles was simulated. Pole spacing equaled 7.5 m. Results are presented for a measurement depth of 9 m, 0.5 m above seabed. For purpose of simulations water conductivity was set to 3.4 S/m and 0.35 S/m and seabed conductivity to 0.03 S/m. Results are presented in fig. 10 and 11 for 0.5 A current and fig. 12 and 13 for 2 A. Conductivities of seawater correspond to Skagen area (seawater temperature of approximately 7 °C) and Bothnian Bay in April (seawater temperature of approximately 0.5 °C).

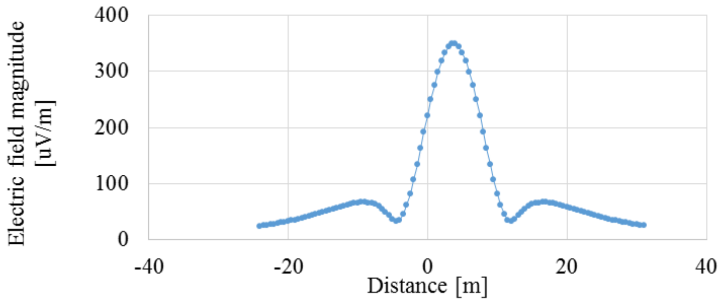


Fig. 10. Underwater electric field originating from 7.5 m, 0.5 A dipole, water conductivity of 3.4 S/m

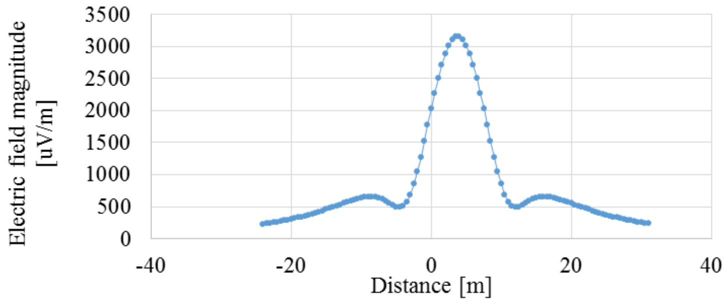


Fig. 11. Underwater electric field originating from 7.5 m, 0.5 A dipole, water conductivity of 0.35 S/m

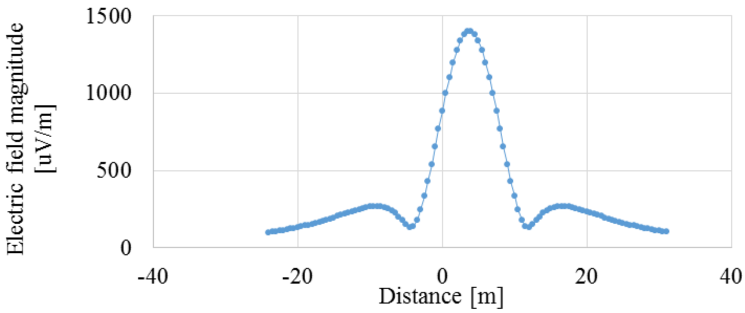


Fig. 12. Underwater electric field originating from 7.5 m, 2 A dipole, water conductivity of 3.4 S/m

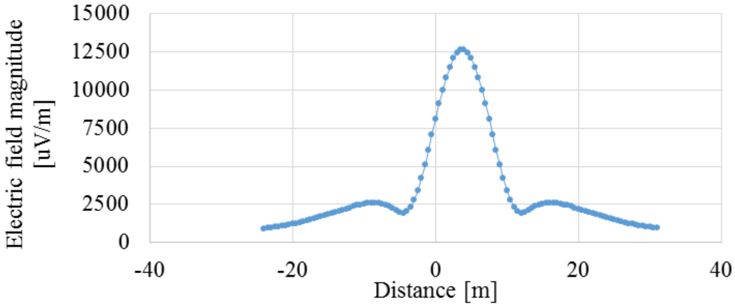


Fig. 13. Underwater electric field originating from 7.5 m, 2 A dipole, water conductivity of 0.35 S/m

A list of maximal values of underwater electric field obtained from computer simulations are presented in tab. 1.

Tab. 1. A list of maximal values of underwater electric field obtained from computer simulations

| Water conductivity/dipole current | 0.5 A | 2 A |
|---|---|---|
| 3.4 S/m | 350 μV/m | 1400 μV/m |
| 0.9 S/m | 1290 μV/m | 5161 μV/m |
| 0.35 S/m | 3156 μV/m | 12626 μV/m |

An influence of seabed to sensor distance on maximal values of simulated underwater electric field is presented in tab. 2. Notes that the sensor to sea surface is constant and equals 9 m and seabed conductivity set to 0.03 S/m.

Tab. 2. An influence of seabed to sensor distance on maximal values of simulated underwater electric field for 0.9 S/m water conductivity

| Distance between sensor and seabed | 0.5 m | 1 m | 2 m |
|---|---|---|---|
| maximal values of underwater electric field 0.5 A dipole | 1290 μV/m | 1167 μV/m | 1009 μV/m |
| maximal values of underwater electric field 2 A dipole | 5161 μV/m | 4670 μV/m | 4038 μV/m |

Alteration of maximal values of underwater electric field intensity is caused by low conductivity of seabed. Current flowing from one pole the other, just like in a current divider, chooses the least impedance path. Thus most of the electric current flows above seabed, which has low electric conductivity and as a result electric field intensity along the horizontal axis increases. Along the horizontal axis (parallel to the seabed) electric field intensity is increased with decreasing seabed to sensor distance. This phenomenon is presented in fig. 14.

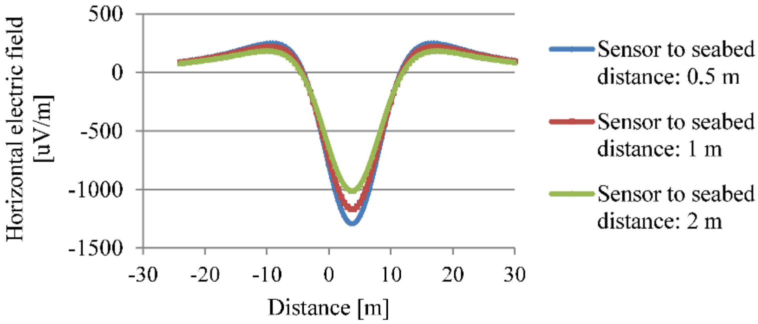


Fig. 14. Magnitudes of horizontal underwater electric field intensity for 0.5 m, 1 m and 2 m sensor to seabed distances; sensor to water surface is constant and equals 9 m; computer simulation results for 0.5 A, 7.5 m spaced dipole; water conductivity of 0.9 S/m

On the contrary — along the vertical axis (vertical to the seabed plane) electric field intensity decreases with decreasing seabed to sensor distance. This phenomenon is presented in fig. 15. Those two effects do not cancel out. Thus there is a distinctive rise in maximal values of underwater electric field, as presented in tab. 2.

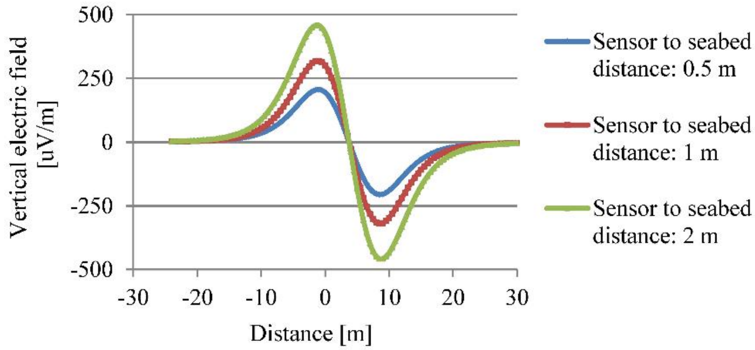


Fig. 15. Magnitudes of vertical underwater electric field intensity for 0.5 m, 1 m and 2 m sensor to seabed distances; sensor to water surface is constant and equals 9 m; computer simulation results for 0.5 A, 7.5 m spaced dipole; water conductivity of 0.9 S/m

Maximal values of underwater electric field are reversely proportional to conductivity of seawater and proportional to current intensity flowing between poles of a dipole. Maximal values measured/simulated are also influenced by the distance between sensor and seabed or universally said — between seabed and sea surface.

Usually a seabed to sensor distance is less important for moored mines. However influence of a seabed on electric field has to be considered if bottom mines are to be used. Bottom mines are harder to detect, less suspect to sweeping and are capable of carrying a greater amount of explosives than moored mines. Furthermore most of the bottom mines are influence mines and are triggered by vessel sensing devices. Average depth of a Baltic Sea is approximately 52.5 m making it a perfect area for bottom mine utilization.

## CONCLUSIONS

Absolute value of underwater electric field of an object is not complete information. The value used without context — properties of a medium: seawater where measurement took place should not be utilized. In order to correctly interpret data — for instance maximal underwater electric field values, the data should be referenced to a specific nominative which is water conductivity, depth of a sensor and seabed to sensor depth. Depending on environmental conditions maximal magnitude of simulated electric field can vary even several times for the same dipole.

Such an approach is crucial if estimation of a safe operation range is to be correctly performed in a sea area which physiochemical properties differ greatly from the area where measurement facility is located. Similarly all of the mentioned variables should be considered if a naval mine's fuze is to be programmed.

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# WPŁYW PODSTAWOWYCH PARAMETRÓW FIZYKOCHEMICZNYCH WODY NA NATĘŻENIE POLA ELEKTRYCZNEGO W WODZIE MORSKIEJ

## STRESZCZENIE


Zagrożenia wynikające ze stosowania min morskich wymuszają użycie na okrętach systemów minimalizujących prawdopodobieństwo ich wykrycia — obronę bierną. Minimalizacja pól fizycznych oznacza zmniejszenie maksymalnego natężenia pola oraz jego kształtowanie. Natężenie pola elektrycznego na zadanej głębokości pomiarowej jest zależne nie tylko od parametrów źródła, ale również od właściwości fizykochemicznych wody — jej temperatury oraz zasolenia. W artykule przedstawiono wyniki symulacji komputerowych natężenia pola elektrycznego na różnych głębokościach i w kilku wybranych środowiskach charakteryzujących się różnymi wartościami temperatury oraz zasolenia. Wyniki symulacji zestawiono z wartościami natężenia pola elektrycznego zmierzonego przez przenośny układ pomiarowy.



Słowa kluczowe:
pole elektryczne, minimalizacja, sygnatura okrętu.

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