

The author's method "The diagnostics of the degree of ship's crew readiness to the risk of danger" is used to determine the degree of risk readiness of a crew member on board a ship. The conclusion relating to the influence of the ship's crew member's predisposition to risks on the occurrence of an undesirable event was made on the base of the results of the diagnostics. The reliability of the method is determined using the Poisson distribution.

The maritime industry specialists work in accordance with the Maritime Labor Convention (MLC, 2006), that clearly defines the work operation norms on board a ship. The International Convention for the Safety of Life at Sea (SOLAS 74) is applied in case of undesirable event occurrence.

The documentary base, which regulates the work and behavior of each member of the ship's crew in any situation, and requires its strict observance, affects the probability of the desired event and allows to create a psychological portrait of maritime industry specialist. Based on obtained results, the author of the article has proposed a model of the behavior of a member of the ship's crew prone to or not prone to risk.

Key words: *human factor, human element, danger, undesirable event, risk, prone to risk.*

УДК 692.122.22

doi.org/10.33298/2226-8553.2023.2.38.06

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CONCEPTS OF THE DEVELOPMENT OF A CIVIL NETWORK SYSTEM OF UNDERWATER TRAFFIC CONTROL

The article examines the development of underwater space in the interests of maritime freight transport as such, which increases the carrying capacity of existing sea transport routes, increases energy efficiency and reduces the risks of freight transport, provided there is no negative impact on the movement of the vehicle by wind, surface waves and drift currents. It is proposed to create an extensive system of cargo transportation in the underwater space as an alternative to conventional shipping. The best underwater data exchange in terms of speed and volume of transmitted information is provided by laser methods. In second place is radio communication in the microwave range and in third place is the hydroacoustic communication channel. Thus, underwater data transmission based on lasers and radio waves is effective for data transmission only in conditions where the underwater transport vessel moves in the near-surface layer of the ocean. In the future, hybrid data exchange systems will be created under water, based on the physical principles of data transmission by radio, laser, hydroacoustic communication. Hybrid communication systems based on hydroacoustics and radar are not excluded.

Keywords: *Underwater space, underwater vehicles, hydroacoustic, navigation, cargo transportation.*

Introduction

The doctrine of transportation by sea transport is to reduce the cost price. Conceptually, the specified doctrine is ensured by savings on the construction and engineering maintenance of highways and railways. Sea routes do not exclude land area from use. An additional resource of sea transport is the ability to transport cargoes that are extremely large in volume and weight. The advantage of sea transport is the absence of settlements along the shipping routes, which allows for the safe

transportation of explosive, chemically aggressive and radioactive cargoes for the population. The use of the transport resource of the sea underwater space logically fits into the concept of the implementation of the world maritime transport doctrine. Movement under water does not depend on weather conditions, therefore it is safer and has less energy consumption.

The creation of an extensive network of cargo transportation in the underwater space, as an alternative to conventional shipping, will first of all be implemented by ensuring traffic in certain directions, that is, along underwater shipping lanes. In the open ocean, that is, at depths of more than 200 meters, traffic can be additionally organized along appropriate corridors, that is, in different directions in a certain range of depths. Thus, the analogue of the 3D cargo transportation system in the underwater space is the aircraft transport system.

Presentation of the main material. Unlike cargo transportation by land, rivers and air, where there are practically no conflicts, sea surface and underwater transportation routes conflict for space in shallow water areas. In deep-water areas, there is enough space for movement on water and under water, but the noise of ships on the surface of the ocean has a negative effect on the hydroacoustic field of the ocean. Broadband noise from shipping is an obstacle for underwater hydroacoustic information systems. Under water, noise negatively affects data exchange, traffic control, positioning, automatic identification of vessels, and the operation of SOFAR-type "Sound Fixing and Ranging" systems [1]. Broadband shipping noises have the maximum impact on the future prospects of introducing non-linear frequency modulation communication into information hydroacoustics, which prevents the negative impact of multipath sound propagation. [2].

Unlike conventional shipping, the sufficient efficiency of traffic control in the underwater space is due to the still unsolved tasks of providing reliable communication, precessional positioning, identification of submarines, warning of navigational obstacles. It should be noted that traffic management of the future system of underwater transport corridors will be created taking into account the modern experience of developed maritime countries. First of all, this is the experience of building the information layer of the network-centric system of underwater warfare (underwater positioning and underwater communication) and the sensor layer (illumination of the underwater situation, recognition of underwater targets). The implementation of the mentioned military experience into the civilian system will not be burdened by the specific problems of covert and anonymous use of underwater positioning and communication, may not meet the requirements of invulnerability to means of destruction, may not have a system of recognition of "home-foreign". The engines of underwater vehicles should not be silent, the hydrodynamics of the hull should not provide extremely high speed, and their hull should not be designed for diving to a depth of 6000 m.

Due to this, the cost of civilian underwater vehicles will be many times lower compared to submarines. It should be noted that the civil system of ensuring the control of the movement of underwater vehicles, unlike the military system, can use a wider range of physical principles of work, methods and means. It is mistakenly believed that in the conditions of the impossibility of radar and video surveillance in underwater space, the problem of navigational safety of ships is very acute. The large number of submarine collisions with each other should not be alarming, because the reason for these incidents is the noiselessness of their movement. Preventing the collision of underwater vehicles is solved very simply and effectively by installing on them hydroacoustic beacons in the sound range of 1-20 kHz with a range of up to 10-15 km. In addition, the installation of an acoustic beacon with an individual acoustic signature on each vehicle will ensure the operation of the underwater AIS segment.

The means of identification of underwater moving objects are considered by the authors of the work, which describes the tactical and technical characteristics of an AIS-type system that can simultaneously track several underwater objects with the necessary spatial and temporal resolution, demonstrating a realistic trajectory of movement [3]. The acoustic tracking system, designed for long-term tracking, thanks to the solar panel and is based on the principle of trilateration. The algorithm of the difference in the arrival time of the acoustic signal is used to determine the 2D/3D location of the moving object (three receivers provide 2D positioning, and four - 3D positioning). It should be noted that the creation of an extensive system of cargo transportation in the underwater space, in terms of

traffic control, requires the development and implementation of the so-called information and sensor layers - permanent network infrastructure - along shipping routes. This is due to the fact that the existing systems of radio communication and satellite geodesy do not work in the underwater space, or have significant limitations. An analogue of the civilian system that will need to be created is a military network-centric navigation and communication system (Fig. 1), which was put into service in the US Navy in 2005 [4].

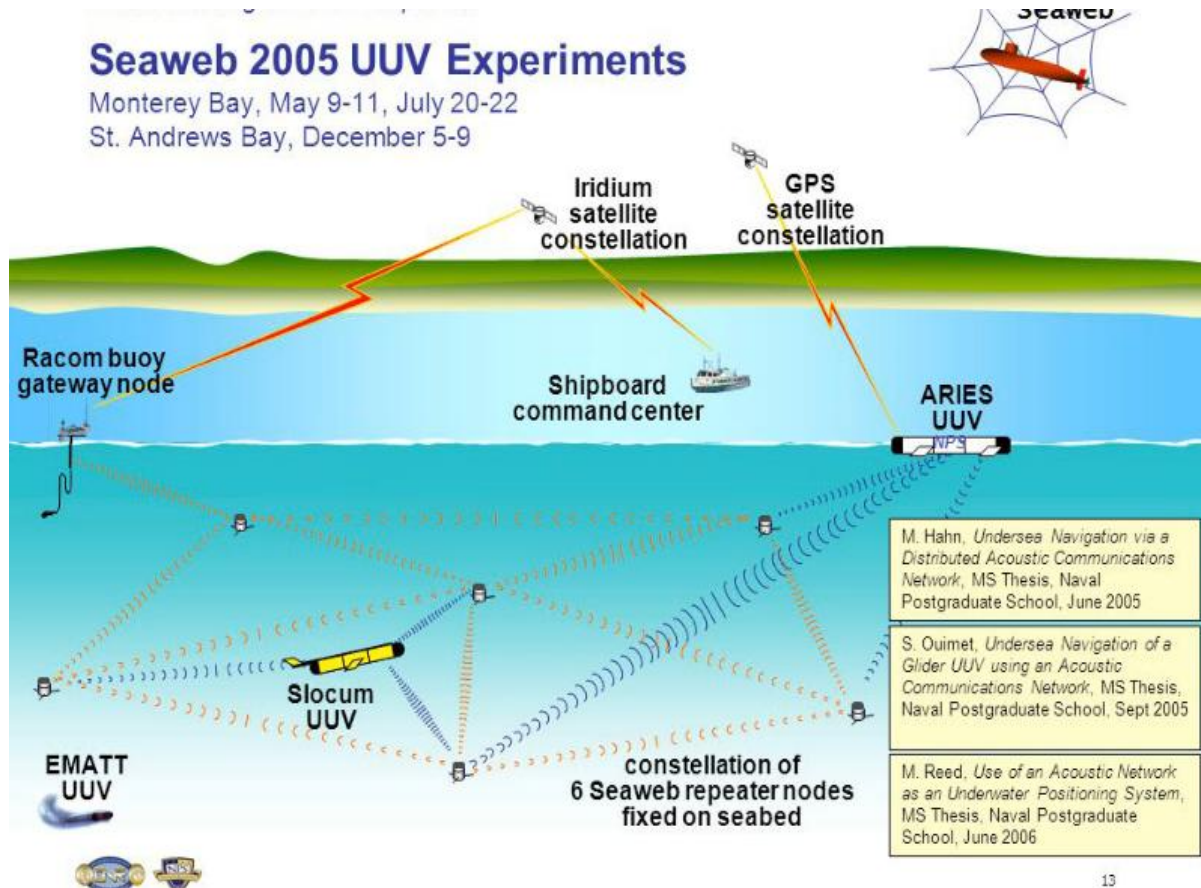


Figure 1: Scheme of bottom infrastructure of underwater positioning

Control of movement in the underwater space is connected with informational and sensory provision of situational awareness of the artificial intelligence of an autonomous unmanned underwater vehicle: own current coordinates; the coordinates of surrounding vessels, which are a navigational hazard and are determined based on the data of the vehicle's own active hydroacoustic system; communication, to transmit commands and exchange data between the underwater vehicle and the shore traffic control center. The coastal center for controlling the movement of ships in the underwater space needs to be provided with data on: current coordinates of the submarine according to AIS data; the current technical condition of the vessel and its navigation equipment. Providing underwater communication and positioning is solved by several methods. In underwater space, hydroacoustics dominates, because the range of propagation of radio and optical electromagnetic waves is limited to the first tens of meters. The minimum range of hydroacoustic communication is 1-2 km, and in deep-sea areas, if there is a hydroacoustic waveguide, it exceeds 100 km [5].

In hydroacoustics, data exchange is carried out only in the sound and infrasound frequency ranges, because ultrasound propagates anisotropically and over a distance of no more than 1 km. In hydroacoustics, data exchange has significant limitations on the speed of communication and volumes of transmitted information, which is associated with many external influences. An internal negative impact is the speed of sound propagation, which is hundreds of thousands of times smaller than the

speed of electromagnetic waves. The modern technical level of the speed of hydroacoustic communication and the volumes of transmitted information are sufficient for the successful control of the movement of underwater vehicles, that is, for the exchange of navigational information and the transmission of commands.

Theoretically, calculating the arrival time of the signal from the source to the receiver is extremely difficult. This is due to the fact that the trajectories of acoustic rays are strongly transformed on the complex topography of the bottom and that the sound wave, moving from one horizon to another, changes the speed of movement in accordance with the VSSD. Errors in distance measurement by acoustic methods should not be considered significant, depending on the paths along which the acoustic signal propagates and on changes in the speed of sound along these paths. The maximum error can be up to $3\pm 0.3\%$.

Negative external influences include the refraction of acoustic waves (curvilinear propagation of acoustic rays in water). The main negative effect of refraction on the positioning and communication of hydroacoustic data under water is multiradiation, an underestimated range, bearing error, and the presence of acoustic shadow zones. [6].

Due to acoustic shadow zones, signal transmission may not occur between the transmitter and receiver installed at a certain distance and at a certain depth, which disrupts communication and underwater positioning. We will immediately say that the specified problem is solved both mathematically and technically. Technically, this problem is solved by using a vertical antenna array instead of one acoustic receiver on the seabed. The characteristics of the vertical antenna array are known. For data exchange at a frequency of 10 kHz, the distance between the hydrophones should be 1.5 m, which corresponds to 10λ (where λ is the length of the acoustic wave) based on the frequency of 10 kHz [5].

The mathematical solution consists in calculating the spatial position of the acoustic shadow zones, ranging and bearing errors. The calculation algorithm is known. In the work [7] sonograms from sound sources placed in the conditions of the real relief of the seabed are given. It is shown that circles of an acoustic shadow with radii of approximately 7 and 15 km are created around the source of the acoustic signal (Fig. 2).

The spatial position of the acoustic shadow zones depends exclusively on the features of the vertical distribution of sound speed in water. The vertical distribution of sound speed is determined by measurements, but it is very difficult to do technically. Another solution is the use of the acoustic tomography method. Our department conducts research in this direction. The latest article published in the direction of acoustic tomography has a title «Acoustic tomography algorithm for determining the spatial isotropicity of the hydroacoustic field» DOI:10.20998/2413-4295.2022.03.07.

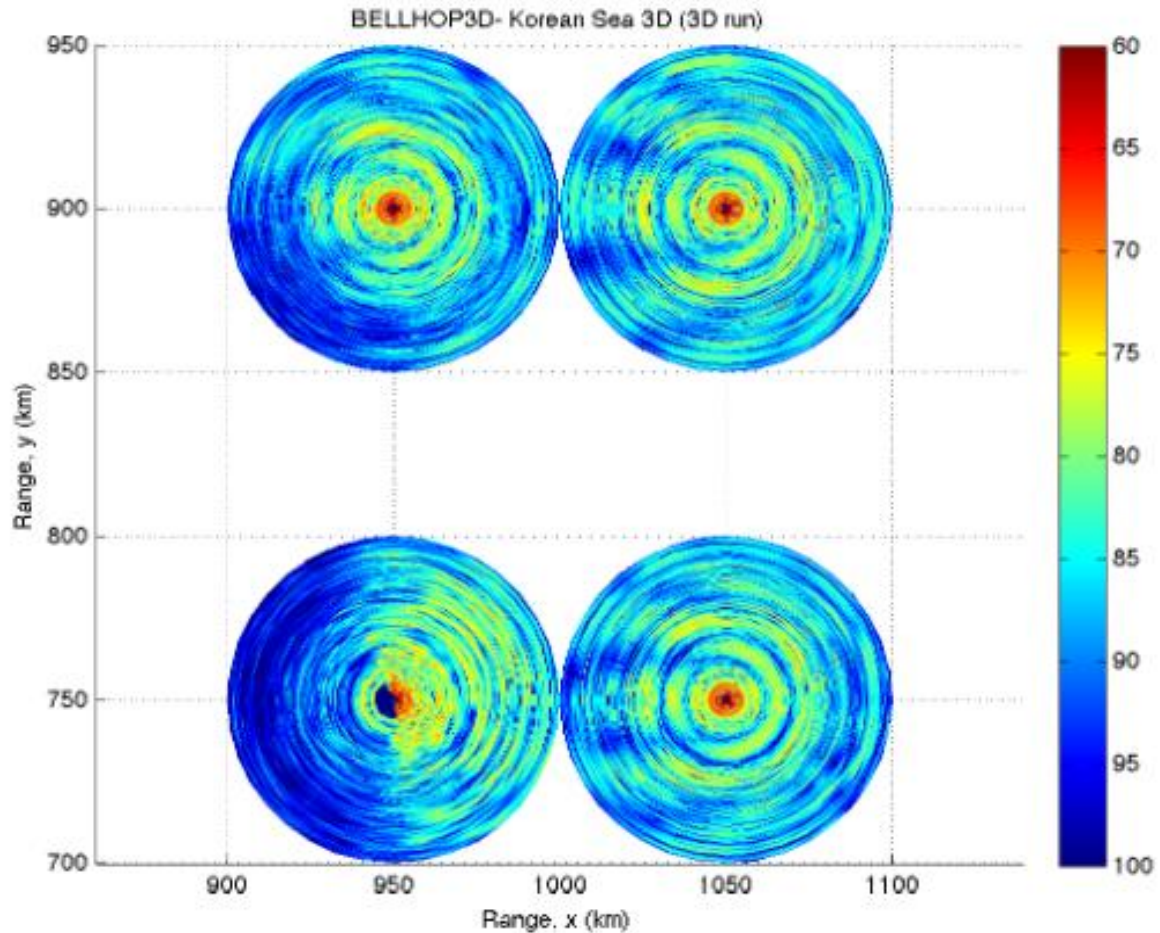


Figure 2: Scheme for calculating spatial losses of an acoustic signal

One of the primary characteristics of the marine environment is the speed of sound, which very sensitively reflects its smallest changes. Moreover, this characteristic is integral, integral. It inseparably characterizes the state of the system, which is formed by a whole complex of influences and reactions to them. By separating the effects and reactions on the so-called temperature, salinity, pressure, known to us at this stage of the development of the physics, we supposedly simplify the system and its understanding, but in fact we get confused, giving one of the factors very great or very little importance (the possibilities of influence on system). Acoustic tomography is based, among other things, on the sound irradiation of the marine environment and the analysis of the received signal for the purpose of evaluating changes in its characteristics after passing through the water space. Changes in the characteristics of the acoustic signal can occur for annual reasons, one of which is spatial changes in the vertical distribution of sound speed. As a result of theoretical research in the direction of passive acoustic tomography, using the methods of modeling the refraction of acoustic waves, a new type of quantitative characteristics of the acoustic field was determined for the first time. The principle of determining the appropriate reference characteristic of the acoustic field is proposed, on the basis of which the basis for creating algorithms for restoring the vertical distribution of sound speed is developed. The algorithm for determining the reference characteristic, including, includes the calculation of acoustic energy losses, which is translated into the frequency domain to determine the positive extremum of the amplitude spectrum and the calculation of the reference characteristic of the regional acoustic field in the time domain. One of a number of algorithms for determining the spatial isotropy of the vertical sound speed distribution has been adapted. The implementation of the specified

algorithm of passive acoustic tomography will provide ship sonar with input data for depth determination, which will increase the safety of navigation.

In this way, the technologies for determining the spatial characteristics of the sound speed distribution have been developed and are continuously being improved. Analysis of volume refraction calculations allows to determine periodic manifestations of acoustic shadow zones. Circles with good (red color) and bad (blue color) transmission of the acoustic signal are formed by the isotropic sound speed field. blue «spots» – zones of poor acoustic signal transmission are formed by the isotropic component of the sound velocity field. Sectors of no acoustic signal transmission are formed by the interaction of the acoustic field and the topography of the seabed. In Fig. 3 shows the scheme for calculating the trajectory of acoustic rays propagating in the direction of the continental slope [7]. The given calculation scheme explains why in Fig. 2, zones of sector-type acoustic shadow appear around the emitter of the acoustic signal.

That is, the coordinates of the zones of the acoustic shadow can be determined by calculations. Under the conditions of refraction of acoustic rays in the horizontal plane, bearing determination errors occur. It also happens in areas with significant slopes of the seabed. [7, 8].

3D acoustic fields are calculated as a function of bathymetry and vertical distribution of sound speed to choose the optimal arrangement scheme for underwater communication and underwater positioning. The mathematical apparatus and software have already been developed [9, 10].

The effectiveness of the deployment of the data exchange system is evaluated in terms of reliability and the area covered by the network of stations [11].

In the article [5] gives an example of the deployment of an underwater hydroacoustic data exchange network with an area of approximately 500 km² (Fig. 4). The diagram shows the acoustic relay network of underwater communication, consisting of 100 stations.

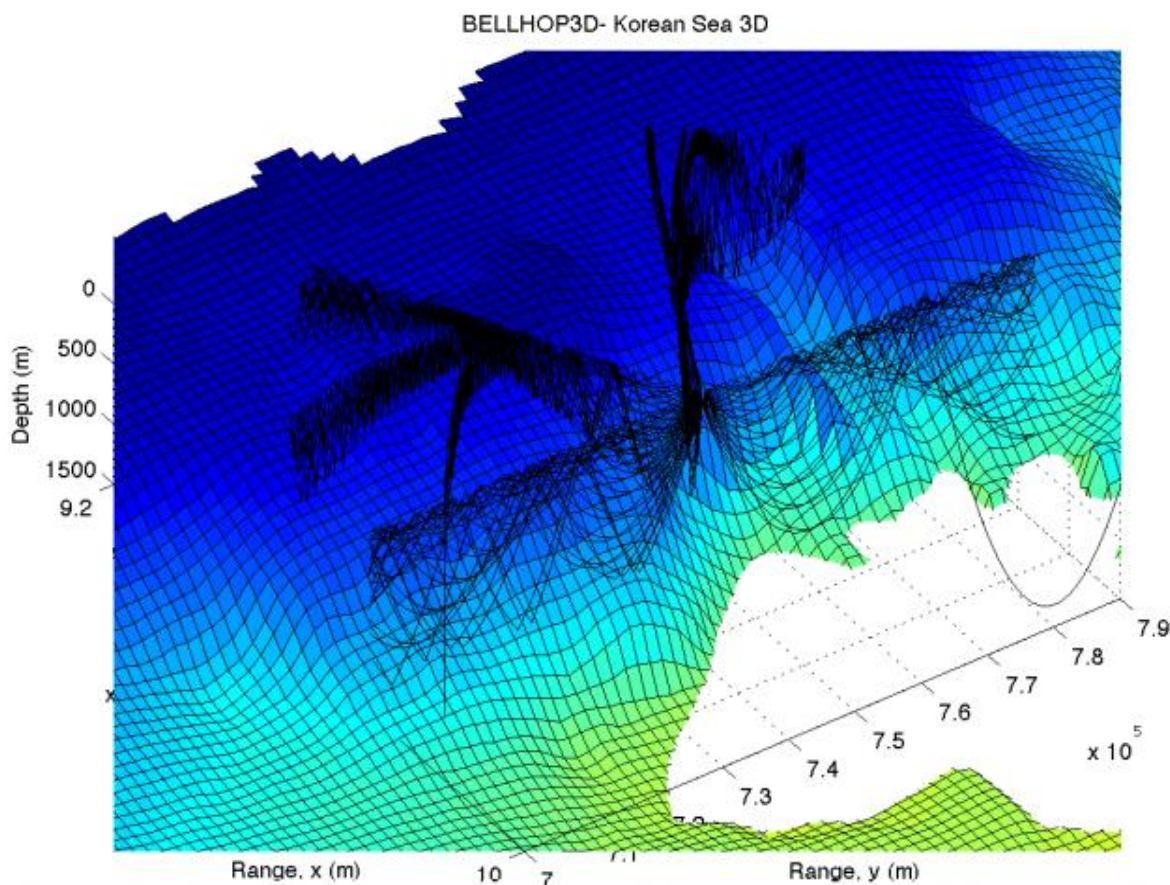


Figure 3: Scheme for calculating the trajectory of acoustic rays propagating in the direction of the continental slope

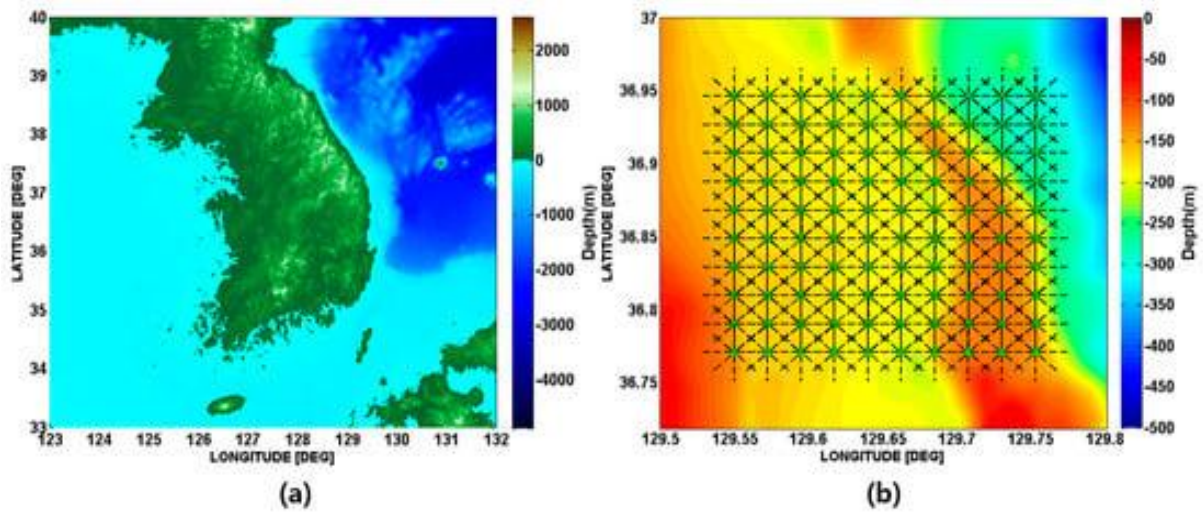


Figure 4: The map and scheme of the acoustic relay network of underwater communication, as the basis of mathematical modeling

Acoustic rays are distributed between stations in accordance with the calculation scheme shown in Fig. 5.

Fig. 5 shows the results of calculations of acoustic ray trajectories.

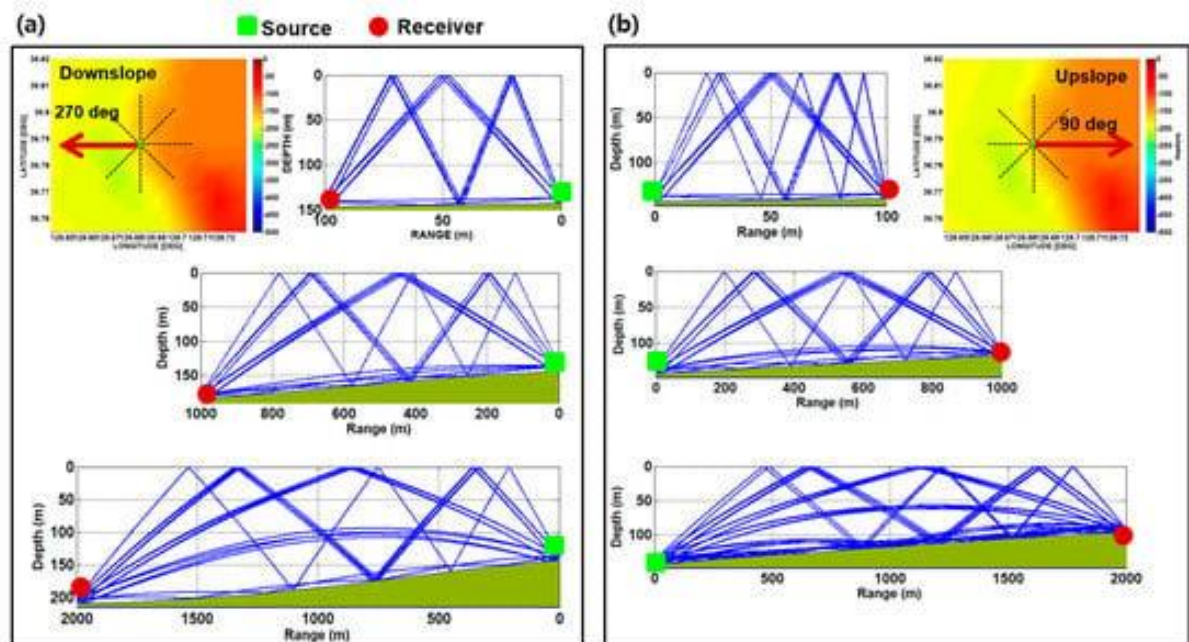


Figure 5: Results of calculations of acoustic ray trajectories for azimuthal angles (a) 90° and (b) 270°

In Fig. 5 shows that the underwater acoustic communication channel is time-varying. In addition to the distortion of acoustic signal beams due to refraction, multibeam is generated by the formation of numerous interactions of sound with the surface and seabed. This is especially evident in shallow water. Multipath slows communication by creating a delay in sound propagation. In addition, an acoustic signal whose characteristics change along the propagation path leads to the Doppler effect, which is associated with an increase in the dispersion of changes in the frequency of the acoustic signal. Due to sound reflection from the bottom and surface, the distance measured by acoustic methods is always greater than the actual distance. This effect should not be overestimated. Theoretically, it is very difficult to calculate the arrival time of the signal from the source to the receiver. This is due to the fact that the trajectories of acoustic rays are strongly transformed on the complex relief of the bottom and that the sound wave, moving along the trajectory of its own movement, changes the speed of movement. The measured distance errors by acoustic methods, depending on the trajectories along which the acoustic signal propagates, and on changes in the speed of sound along the specified trajectories, can be up to $3\pm 0.3\%$.

Thus, it can be stated that some problems of underwater communication are solved by technical means, some are taken into account by mathematical modeling. Some problems have not been solved and there are limitations in the propagation of an acoustic signal under water. Such limitations are determined by determining the bit error rate (BER). In Fig. 6 shows an example of BER changes as a function of range. A BER exceeding 2% is used as a criterion for the maximum permissible communication error.

The Figure 6 shows that the determination of the range of the communication relay station is calculated by determining the intersection of the actual constant BER value with a threshold value of BER of 2%.

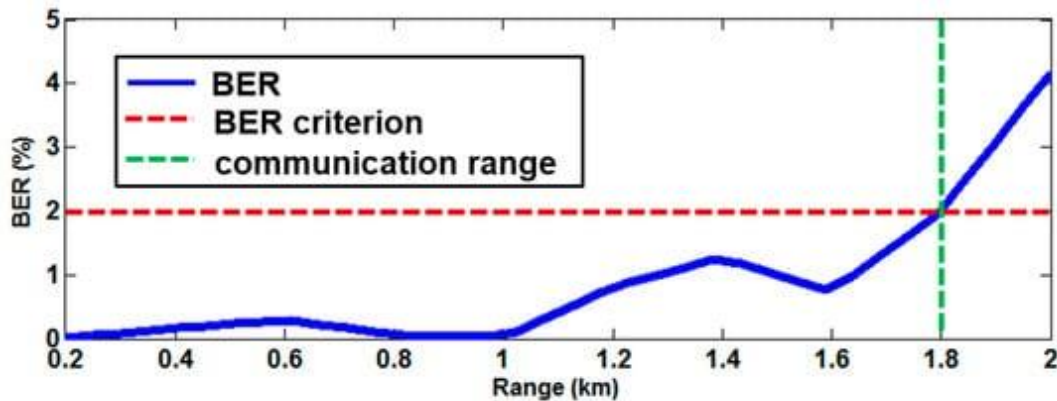


Figure 6: Example of BER variation as a function of range

A reliable data exchange system requires real-time communication with high data rates and low error rates. In Fig. 7 shows the simulation results of the optimal deployment of the underwater data exchange network for two different seasons. Certain quantitative characteristics are defined. The distance between each sensor node and its neighboring sensor nodes corresponds to the minimum communication threshold. The level of communication coverage for February was estimated at 85.2%, which is higher than in August (estimated at 80.6%).

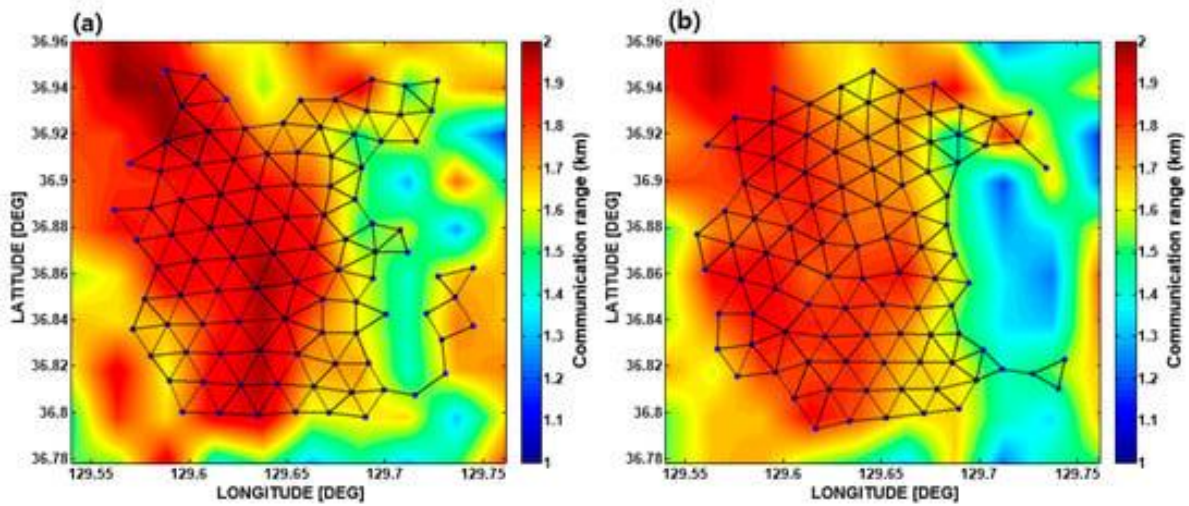


Figure 7: Simulation results of the optimal deployment of an underwater data exchange network using 100 sensor nodes

In the future, hybrid data exchange systems will be created under water, based on the physical principles of data transmission by radio, laser, hydroacoustic communication. Hybrid communication systems based on hydroacoustics and radar are not excluded. Prospects for the creation of hybrid acoustic and electromagnetic systems are considered in the work [12]. In principle, data exchange in the interests of ship control and positioning can be carried out by acoustic (mechanical) waves in the sound frequency range, lasers (coherent electromagnetic waves) in the optical wavelength range of 400–600 nm, and radio waves at frequencies of 30–300 MHz. The results of the comparison of the specified underwater communication technologies are given in the Table 1.

Table 1

The results of the comparison of the specified underwater communication technologies

Parameter	Acoustic	RF	Optical
Attenuation	Distance and frequency dependent (0.1–4 dB/km)	Frequency and conductivity dependent (3.5–5 dB/m)	0.39 dB/m (ocean) 11 dB/m (turbid)
Speed	1500 ms ⁻¹	2.3 × 10 ⁸ ms ⁻¹	2.3 × 10 ⁸ ms ⁻¹
Data Rate	kbps	Mbps	Gbps
Latency	High	Moderate	Low
Distance	more than 100 km	<10 m	10–150 m (500 m potential)
Bandwidth	1kHz–100 kHz	MHz	150 MHz
Frequency	10–15 kHz	30–300 MHz	5 × 10 ¹⁴ Hz
Power	10 W	mW–W	mW–W

The best underwater data exchange in terms of speed and volume of transmitted information is provided by laser methods. In second place is radio communication in the microwave range and in third place is the hydroacoustic communication channel. Thus, underwater data transmission based on lasers and radio waves is effective for data transmission only in conditions where the underwater transport vessel moves in the near-surface layer of the ocean. The advantage of data transmission in the radio range is that, unlike laser and acoustic methods, radio waves propagate freely through the interface between the ocean and the atmosphere [13].

As an example of the prospect of combining military and civilian technologies, we can cite a possible prospective hybrid of military communication systems "Tactical Underwater Network Architecture" [14], and civil underwater acoustic communication systems [15] and systems of hydroacoustic automatic identification of the movement of underwater targets [3].

The first system, which is an alternative to unreliable hydroacoustic underwater communication, involves the installation of autonomous surface buoys with radio receivers and radio transmitters (surface buoys under water connected by a fiber optic cable) solves the problem of reliable data transmission (traffic control). The second system provides for the installation of sonar devices on surface buoys, which provides protection of the surface system from saboteurs to the underwater vehicle and simplified underwater positioning. The third system involves retrofitting surface buoys with an acoustic vertical antenna array to provide additional underwater hydroacoustic communication of an underwater vehicle with surface radio communication buoys. The fourth system involves the additional use of an antenna array as a noise deflector. the noise direction finder is used as an element of underwater AIS to passively track the trajectory of an underwater vehicle equipped with a hydroacoustic emitter with an individual acoustic signature.

Conclusions. According to the concept of the US Navy codenamed HYDRA (HYDRA– A DARPA-led initiative that calls for a distributed undersea network of unmanned payloads and platforms “trucked in” and deployed from large UUVs.), all problems of logistics in underwater space are already assigned to large unmanned underwater LDUUV apatite [16].

This gives reason to believe that sea transportation of cargo under water will become a reality in the near future. An underwater transport fleet will be built just as quickly. Unlike conventional ships, which are difficult to design, designing a fleet of unmanned underwater vehicles will not take much time, because simplified technologies for the construction of military submarines and LDUUVs will be involved. The tasks of underwater navigation and hydrographic support for cargo transportation, tasks of traffic management, communication, and positioning require a quick solution. Problems related to the safety of navigation in the underwater space need to be solved. The solution to this problem lies in the construction of a system of observation and rescue under water. Certainly the underwater segment of the AIS must be developed and built very quickly. It should be noted that the interdisciplinary State program for the creation of a marine underwater lighting system has been approved and has been operating in Ukraine for several years. The experience of creating bottom network bottom positioning and communication systems based on the hydroacoustic principle of action should be applied in combination with systems operating on other physical principles. Microwave radio communication directly between an underwater vehicle in an underwater position and satellite means of communication certainly has prospects. There are prospects for laser communication, which is unsurpassed in the speed and volume of information transmission and the real time scale.

The most important thing is international cooperation for the purpose of development and adoption of legal and legal documents in the field of maritime freight transportation in underwater space.

REFERENCES

1. Navy Supplement to the DOD Dictionary of Military and Associated Terms (PDF). Department Of The Navy. June 2012. Archived (PDF) from the original on April 15, 2021.

2. Jeongha A, Hyungin Ra, Changhyun Youn, Kiman Kim, Experimental Results of Underwater Acoustic Communication with Nonlinear Frequency Modulation Waveform, *Sensors* 2021, 21(21), 7194; <https://doi.org/10.3390/s21217194>.
3. François-Marie Manicacci, Johann Mourier Chabi Babatounde, Jessica Garcia, Mickaël Broutta, Jean-Sébastien Gualtieri, Antoine Aiello. A Wireless Autonomous Real-Time Underwater Acoustic Positioning System, *Sensors* 2022, 22(21), 8208; <https://doi.org/10.3390/s22218208>, <https://www.mdpi.com/1424-8220/22/21/8208>.
4. M. Reed, Use of an Acoustic Network as an Underwater Positioning System, MS Thesis, Naval Postgraduate School, June 2006.
5. Sunhyo Kim and Jee Woong Choi, Optimal Deployment of Sensor Nodes Based on Performance Surface of Underwater Acoustic Communication, *Sensors* 2017, 17(10), 2389; <https://doi.org/10.3390/s17102389> *<https://www.mdpi.com/1424-8220/17/10/2389>.
6. <https://www.iacm.forth.gr/component/quix/92-groups-wave-propagation>.
7. Michael B. Porter BELLHOP3D User Heat, Light, and Sound Research Guide July 25, 2016 <https://usermanual.wiki/Document/Bellhop3D20User20Guide202016725.915656596.pdf>.
8. Комиссарова Н. Н. Горизонтальная рефракция лучей в прибрежной зоне при разных профилях скорости звука, *Акустический журнал*, 1998, том 44, № 6, с. 801–807 http://www.akzh.ru/pdf/1998_6_801-807.pdf.
9. Akyildiz, I.F.; Pompili, D.; Melodia, T. Underwater acoustic sensor networks: Research challenges. *Ad Hoc Netw.* 2005, 3, 257–279.
10. Garcia-Pineda, M.; Sendra, S.; Atenas, M.; Lloret, J. Underwater wireless ad-hoc networks: A survey. In *Mobile Ad Hoc Networks: Current Status and Future Trends*; CRC Press: Boca Raton, FL, USA, 2011; pp. 379–411.
11. Senel, F.; Akkaya, K.; Yilmaz, T. Autonomous deployment of sensors for maximized coverage and guaranteed connectivity in underwater acoustic sensor networks. In *Proceedings of the 38th IEEE Conference on Local Computer Networks (LCN)*, Sydney, Australia, 21–24 October 2013; pp. 211–218.
12. Y. Li, S. Wang, C. Jin, Y. Zhang, T. Jiang, *IEEE Commun. Surv. Tutor.*, 2019, 21, 2466–2487, doi: 10.1109/COMST.2019.2897610
13. <https://scitechdaily.com/mit-media-lab-researchers-develop-wireless-underwater-to-air-communications>.
14. <https://nplus1.ru/news/2017/01/12/tuna-DARPAtv/YouTube>.
15. Mohammad Furqan Ali, Dush Nalin K Jayakody, Yury Chursin, Sonkin Dmitry Recent Advances and Future Directions on Underwater Wireless Communications August 2019 Archives of Computational Methods in Engineering 26(100):1-34 DOI: 10.1007/s11831-019-09354-8 https://www.researchgate.net/publication/335562546_Recent_Advances_and_Future_Directions_on_Underwater_Wireless_Communications.
16. David R. Strachan, Seabed Warfare Week, Center for International Maritime Security MARCH 13, 2018, <https://cimsec.org/forwardfrom-the-seabed>.