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Determining the Angle of Bearing on a Sound Source in Water Using Signals Spread Spectrum

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Abstract: This paper presents a method and results of simulation and laboratory studies of the use of direct spread spectrum signals in underwater navigation. The method was evaluated depending on the parameters of signal acquisition, the effect of interference and the configuration of the receiving antenna.

Keywords: underwater navigation, spread spectrum, hydroacoustics, cross correlation

1. Introduction

One of the most important elements when conducting an underwater mission is to have information about the current position of the object relative to the adopted reference system. This task is usually accomplished by conducting current navigation, the primary task of which is to determine the geographic position of the moving object. In the case of surface objects, the matter is significantly simplified due to the possibility of using satellite navigation. The situation becomes significantly more complicated in the case of conducting navigation for fully submerged objects, such as underwater vehicles or divers. The satellite signal does not propagate in the water, its disappearance occurs at a depth of up to about 0.5 m, so other solutions must be sought to determine the current position of the underwater object [1].

One possibility is to conduct inertial navigation, which involves determining the position of an object using the principles of Newtonian dynamics. The latest inertial navigation systems use MEMS (microelectromechanical system) technology and fiber optic gyroscopes. They are made in various accuracy classes, making them suitable for a range of underwater applications, including autonomous underwater vehicles (AUVs) remotely operated vehicles (ROVs) and other underwater objects used for hydrographic surveys, for example. INS navigation is often integrated with other systems like DVL (Doppler Velocity Log) and USBL (Ultra Short Baseline) to enable greater positioning accuracy over longer distances. Such solutions are discussed in a number of publications, including by Marco Morgoto et al. [2], which deals with an INS navigation system intended for AUVs, as well as in an article by Randy Hartman et al. [3] where the problems of using an INS navigation system intended for diver safety are addressed. On the other hand, the article [4] by Qingjun Zeng et al. presents a solution to a set of inertial navigation system intended for ROVs in which MEMS devices are used, including a gyroscope, accelerometer, magnetic compass and also a depth sensor and microprocessor chip. The cited publications show that the introduction of additional information acquisition elements into the INS system improves the accuracy of position determination however, the disadvantages of this type of navigation are not completely eliminated as indicated by the article published by Huiming Xing et al [5] and by Xiaoshuang Ma et al [6]. They discuss the problems of the influence of measurement noise from navigation sensors on the performance of the Kalman filtering algorithm in the INS navigation system. This interference results in a degradation of the filtering performance, and thus causes a deterioration in the accuracy of object position determination. In addition, the inaccuracy of the position determined by the INS is affected by the disadvantages of the inertial method itself, such as the decrease in the accuracy of position determination and velocity with the passage of time, regardless of whether the object is moving or not. It should also be noted that systems of this type require time-consuming initial calibration involving setting the direction and vertical of the object, and it is additionally difficult to level the inertial system on a moving object. Also, for latitudes above 75°, calibration of the system is difficult, which significantly affects the accuracy of the determined position at these latitudes. Due to the disadvantages of the INS system, attempts have been made to use hydroacoustic systems in underwater navigation [7].

Hydroacoustic positioning systems locate an object relative to a structure of base stations that must be deployed in a body of water, which is a drawback. In this system, an artificially generated sound wave is used to determine the position of an underwater object and to orient it relative to predetermined reference points or baselines. These systems [8] are used to track and navigate underwater vehicles or divers by measuring distance and bearing and then triangulating the position. These systems are generally divided into three classes [9, 1] i.e., long baseline (LBL) systems, short baseline (SBL) systems, and ultra-short baseline (USBL) or otherwise known as super-short baseline (SSBL) systems. LBL systems use a network of seafloor baseline transponders that are typi-

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cally deployed in the basin of operations and allow for very high accuracy sometimes as low as 0.01 m [10]. USBL/SSBL systems use small integrated transducer systems that are typically lowered from the hull of a surface vessel. The advantage of these systems, compared to other hydroacoustic systems, is that they do not require deployment of the transponder array on the seabed. The disadvantage, on the other hand, is that positioning accuracy and reliability are not as good as with LBL systems. To eliminate the need to build a network of transponders placed on the seabed in this system, GPS Intelligent Buoy (GIB) systems were developed in the 1990s. These systems are inverted LBL devices in which transponders are replaced by floating buoys that are independently positioned by GPS (Global Positioning System) [11]. GIB systems, unlike LBL, SBL or USBL systems, use unidirectional acoustic signals from the emitter to the buoy making them less sensitive to reflections from surfaces or walls [10]. GIB systems are used to track AUVs, torpedoes, divers and can be used to determine weapon strike coordinates, test them as well as for training purposes, and to locate searches for black boxes of crashed aircraft [11, 12]. Several trends in underwater acoustic positioning have emerged in recent years. One of them, in order to increase performance, is the introduction of composite systems such as the combination of LBL and USBL in the so-called LUSBL (long ultra short baseline) configuration [13]. These systems are widely used primarily in the offshore oil and gas sector. In 2023, a fourth class of 3D positioning of underwater objects was demonstrated for these smart devices, which do not require infrastructure support such as buoys [14]. Instead, these systems use distributed localization techniques [15], calculating the pairwise distance between a network of different devices to determine the shape of the resulting network topology.

Hydroacoustic navigation systems are characterized by high accuracy in determining the position of an underwater floating vehicle, reaching up to several centimeters regardless of the duration of the mission. However, they also have disadvantages, among others, they do not provide information on the heading angle and tilt of the vehicle, as well as radiating acoustic energy and being sensitive to external interference such as noise of technical origin of high intensity. In addition, in the case of heavily hydro-engineered or shallow bodies of water, due to numerous reflections and multipath propagation, the specified position is subject to a large error or even impossible to determine. The problem here is also the possibility of uninterrupted operation of several such devices in one body of water. Despite this, underwater navigation systems using acoustic waves are currently very popular.

Currently, new solutions for underwater navigation systems are still being sought that would eliminate the disadvantages of existing solutions. Among others, in underwater navigation systems there are attempts to use different forms of acoustic measurement signals such as a sinusoidal acoustic wave, emitted from a floating underwater object, for which the Doppler deviations of the received signals are determined and, based on them, the position of the object and its moving speed are determined, as reflected in the works [16, 17]. Also, an interesting solution has been used in Tritech's MicroNav underwater navigation system, where linearly variable frequency (Chirp type) signals are used to create the transmitted sound.

Figure 1 shows the spectrogram obtained from measurements of the operation of this system and the amplitude spectrum averaged for the duration of a pulse, where a pulse is defined as a signal generated without interruption that makes it possible to locate an object. The sequence of ascending and descending frequencies forms a peculiar code that allows identification of a single device and simultaneous operation of several devices with different codes in a single body of water.

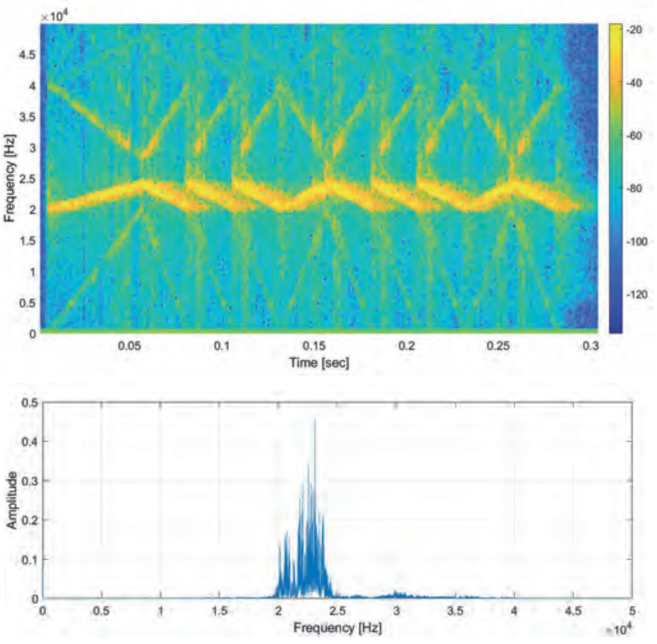

Fig. 1. Spectrogram and amplitude spectrum averaged for the duration of the signal pulse transmitted as part of Tritech's MicroNav underwater navigation system

Rys. 1 Spektrogram i widmo amplitudy uśrednione dla czasu trwania impulsu sygnału przesyłanego w ramach systemu nawigacji podwodnej MicroNav firmy Tritech

Methods are also being sought to determine the position of underwater objects by developing, for example, sequential algorithms for synchronizing time and location in an underwater acoustic channel, as presented in a paper [18]. In the proposed solution, it is assumed that the nodes are not synchronized in time, and the speed of sound in the water is unknown. For such conditions, the localization problem was formulated as a sequence of two linear estimation problems. The results presented in the paper show that the developed algorithm compensates for uncertainties in time synchronization and signal propagation speed and achieves good localization accuracy using only two anchor nodes.

It seems that some alternative to the use of chirp signals may be direct spread spectrum signals. Spectrum spreading technique involves converting a narrowband information signal into a signal with a spectrum several times wider and reducing its power below the noise level. This has several advantages, first and foremost that the methods used for spread spectrum, allow a single frequency band to be used by many users simultaneously, in addition, the signal processed in this way is immune to disturbance. This type of signal, due to its advantages, is used in underwater wireless communications providing high quality signal transmission. The most popular are two scattering methods, i.e. the FHSS (Frequency Hopping Spread Spectrum) method, i.e. spreading the spectrum with carrier frequency hopping, and DSSS (Direct Sequence Spread Spectrum), i.e. direct spreading the spectrum with a pseudo-random sequence. Communication systems using the spread spectrum technique provide the ability to handle multiple users bases of mutual interference, stealthy operation, elimination of errors due to multipath signals, and thus improve the quality of communication. It is reasonable to assume that the application of this technique in underwater navigation systems will also make it possible to accurately determine the position of floating underwater objects.

In the literature, the author has not encountered solutions based on the use of signals with direct spread spectrum in underwater navigation applications. Therefore, the purpose of the conducted research was to evaluate the possibility of using signals with direct spread spectrum in underwater navigation and, in particular, determining the angle of bearing on an artificial sound source. Accordingly, a number of simulation studies were carried out as well as under laboratory conditions selected results of which are presented in this article.

2. Method Description

The proposed method assumes that the system consists of two subsystems: sending and receiving. The system will determine the bearing angle from the receiving system to the transmission system. Therefore, on the object at which the bearing angle is to be determined, there is placed the transmitting subsystem responsible for sound generation. Such a subsystem should consist of a piezoceramic element generating an elastic wave and an electronic system responsible for forming the correct signal. The signal is formed in accordance with the diagram shown in the figure.

The carrier signal at a specific frequency is modulated by the Pseudo Random Binary Sequence PRBS using the Binary Phase Shift Keying BPSK modulation. The use of pseudo-random sequences for spreading the carrier signal, allows multiple devices to operate in the same band (the spreading sequence of each device must be different). In addition, spreading spectrum and knowing spread codes allows generating relatively low power signals, even below background noises, and the same correct reception on the user's side [19].

The receiving subsystem may be located on a sailing object, permanently attached to the hydrotechnical structure or may be lowered from the aircraft. This subsystem should consist of piezoceramic elements - hydrophones responsible for the reception of the elastic wave, the analog-to-digital converter, the signal processing block and the data visualization block. The number of hydrophones determines the possibilities of the system. To determine the bearing angle, at least three elements are required. In addition, individual piezoceramic elements, forming the receiving antenna, should be placed in relation to each other in a specific geometrical configuration. The most common is a triangular arrangement. To determine the bearing angle to the sound source, it is necessary to specify the time delays in reaching the individual receiving elements by the transmitted signal, as it was shown on Fig 3. The following notations are adopted in the figure: T – transmitter, R_1, R_2 – receiver 1 and 2, α – bearing angle, b – distance between receivers, c – sound speed in water, τ – time delay in reaching receiver 1 and 2 by transmitted signal.

Knowing the delay time τ, it is possible to determine the bearing angle according to the following formula:

$$\alpha = \arcsin\left(\frac{\tau c}{b}\right) \tag{1}$$

where: α – bearing angle, τ – time delay in reaching sound-sensitive elements by transmitted signal, c – sound speed in water, b – distance between sound-sensitive elements.

In order to determine the time delays in reaching the individual hydrophone by transmitted signal, the received signal is digitally processed according to the diagram shown in Fig. 4.

In the first phase, the cross correlation of the received signal imported to the baseband with the spread code according to which the signal was generated is determined. The obtaining results is the estimation of impulse response of the hydroacoustic

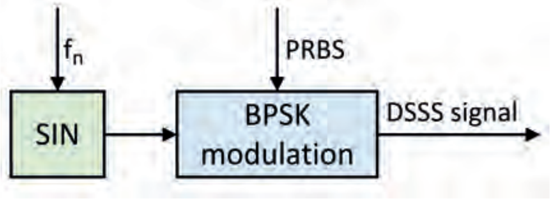

Fig. 2. Block diagram of the transmitted signal forming
Rys. 2 Schemat blokowy formowania transmitowanego sygnału

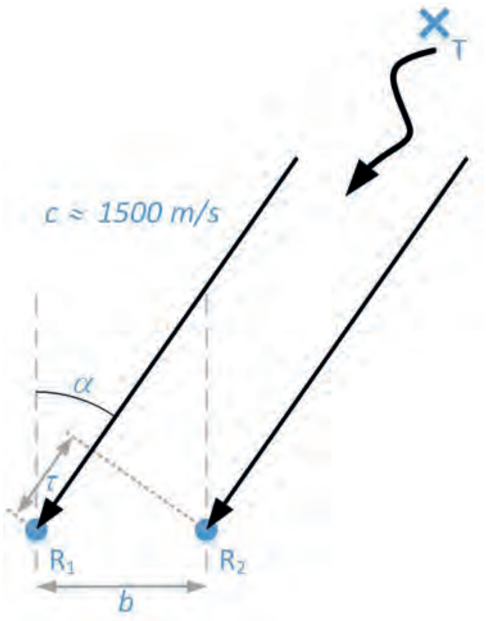

Fig. 3. Principle of bearing angle estimation
Rys. 3. Zasada szacowania kąta namiaru

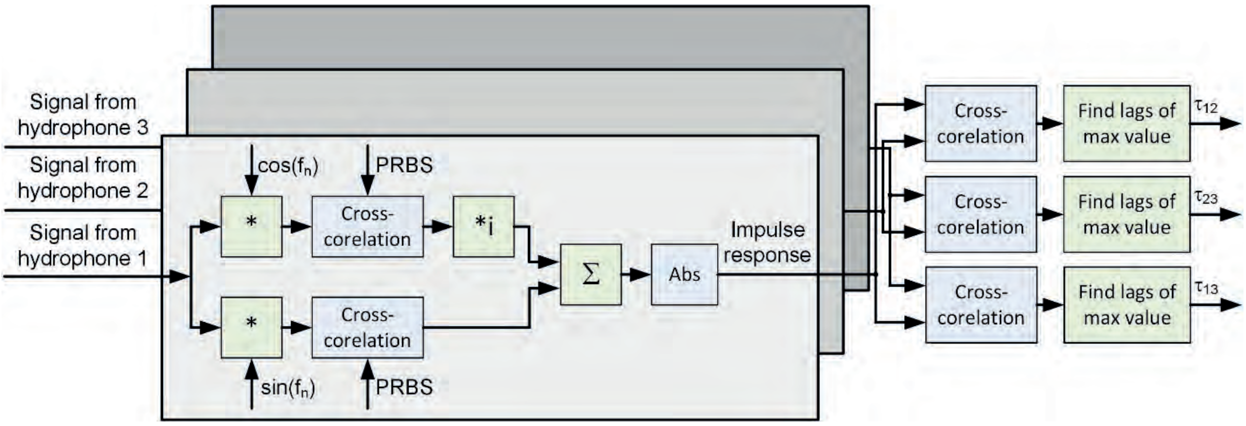

Fig. 4. Block diagram of the received signal processing
Rys. 4 Schemat blokowy przetwarzania odebranego sygnału

channel [19]. This process, for a single sensor, can be described by equations in the following way:

$$\begin{cases}\hat{x}_s(n) = x(n)\sin(2\pi f_n n)\\[2ex] \hat{x}_c(n) = x(n)\cos(2\pi f_n n)\end{cases} \qquad (2)$$

where: $x(n)$ – received signal, f_n – carrier frequency, n – discreet time, $\hat{x}_s$, $\hat{x}_c$ – the sine and cosine component of the received signal brought to the baseband, respectively.

$$\begin{cases}R_{x_s k} = \sum_{n=0}^{N-m-1} \hat{x}_s(n+m)k(n)\\[2ex] R_{x_c k} = \sum_{n=0}^{N-m-1} \hat{x}_c(n+m)k(n)\end{cases} \qquad (3)$$

where: $k(n)$ – used spread code, m – discreet time delay, $R_{x_s k}$, $R_{x_c k}$ – the result of the cross correlation of the sine and cosine components of the received signal brought to the baseband with used spreading code.

$$R_{xk} = \left|R_{x_c k} + iR_{x_s k}\right| \qquad (4)$$

where: R_{xk} – estimate of the impulse response of the hydroacoustic channel.

Using of direct spread spectrum signals, it is possible to precisely determine time when the signal reaches the receivers. This is due to the possibility of determining the propagation delay of the signal which has reached sensor by the shortest path. It can be assumed that the delay resolution is not worse than the duration of a single chip. Then, on each combination of the obtained estimations of impulse responses, a cross correlation operation is performed. On this basis, by searching for the maximum value (means the maximum similarity of the correlated signals), it is possible to determine the time delay in reaching individual hydrophones by transmitted signal. Now knowing the geometric placement of the sensors and using the Eq. (1) the bearing angle for artificial sound sources can be easily determined.

Expanding the antenna with another sound-sensitive element and placed in such a way that the antenna has a spatial arrangement (e.g. tetrahedron) it is also possible to determine the angle of elevation. By measuring bearing and elevation angles from two different positions, it is also possible to determine the distance to the object. Due to the fact that the calculation procedure is identical to the presented above, both the angle of elevation and distance to the object determination will not be considered in this article.

3. Results of Research

In order to verify the proposed solutions, a series of simulation and laboratory conditions tests were carried out. During research were used a signal with a carrier frequency of 15 kHz which was modulated with a linear binary code of 2047 bits long.

3.1. Simulation Results

Simulation tests were carried out in the MATLAB environment. For different bearing angles, based on the mutual position of the transmitter relative to the receivers, and assuming the speed of sound in water (1499 m/s), the delay time for the transmitted signal to reach each receiver was determined. During the simulation of the test, a hydrophone configuration was adopted as in Fig. 3. This arrangement is the simplest array for determining bearing angle, which can be replicated by adding hydrophones and thus increasing the accuracy of bearing angle determination. The corresponding delayed signals for each receiver were summed with white Gaussian noise at a specified Signal-to-Noise Ratio (SNR), given in dB. The signal level was calculated to determine the noise level required to achieve the specified SNR. The simulated received signals were then processed as described in Chapter 2. The studies examined the impact of signal registration parameters (sampling frequency), hydrophone distances and environmental disturbances (noise) on the accuracy of the obtained results. In the simulations, it was assumed that the distance to the object was 12 m and the bearing angle was changed in the range of ±90° with a resolution of 1°. Figure 5 presents the maximum and average values of the bearing angle determination errors depending on the sampling frequency for the hydrophone placed at distance of 0.4 m, the distance between receiving hydrophones at the sampling frequency of 1.25 MHz and Signal-to-Noise Ratio at sampling frequency of 1 MHz and

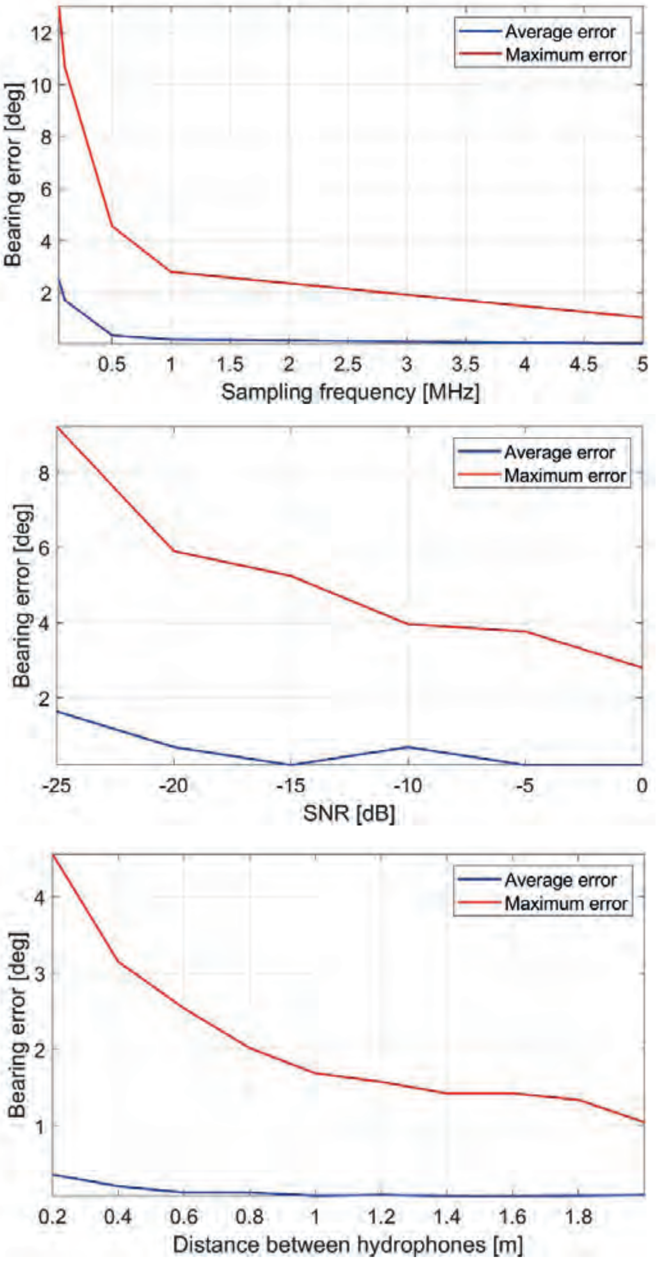

Fig. 5. Error of determining the bearing angle, depending on a) change in sampling frequency b) distance between receiving sensors, c) Signal-to-Noise Ratio

Rys. 5. Błąd określenia kąta namiaru w zależności od a) zmiany częstotliwości próbkowania, b) odległości między czujnikami odbiorczymi, c) stosunku sygnału do szumu SNR hydrophone placed at distance of 0.4 m. The obtained results indicate that the increase in the sampling frequency and the increase in the distance between the receiving sensors leads to a minimization of the error in determining the bearing angle.

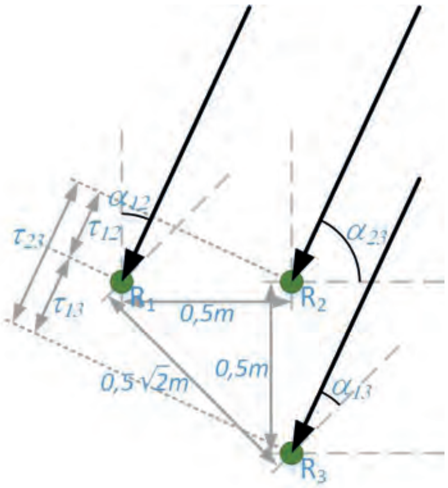

Fig. 6. Hydrophone array used in laboratory tests
Rys. 6. Układ hydrofonów wykorzystany w badaniach laboratoryjnych

As a result of the research, it was also found that the increase the noise (in the form of white Gaussian noise) measured by the Signal-to-Noise Ratio to the level of 0 dB does not cause any negative changes in the obtained results

3.2. Laboratory Condition Results

Laboratory tests were carried out at the pool of the Polish Army Divers and Scuba Training Center. The dimensions of the pool are: (length × width × depth) 16 m × 10 m × 10 m. A research station consisting of:

- Transmission path:
- Underwater loudspeaker LubellLabs LL9162T;
- Power amplifier Pevey IPA300T;
- Vector Signal Generator Rhode&Schwarz SMBV100A.
- Receiving path:
- Three hydrophones Reson TC4032;
- Analog-digital converter NI USB-6259;
- Mobile computer with NI SignalExpress software.

The underwater loudspeaker in the transmission path has been lowered to a depth of 2 m. The distance between the loudspeaker and the receiving antenna was 12 m. The hydrophones in the receiving path were installed on the frame in a configu-

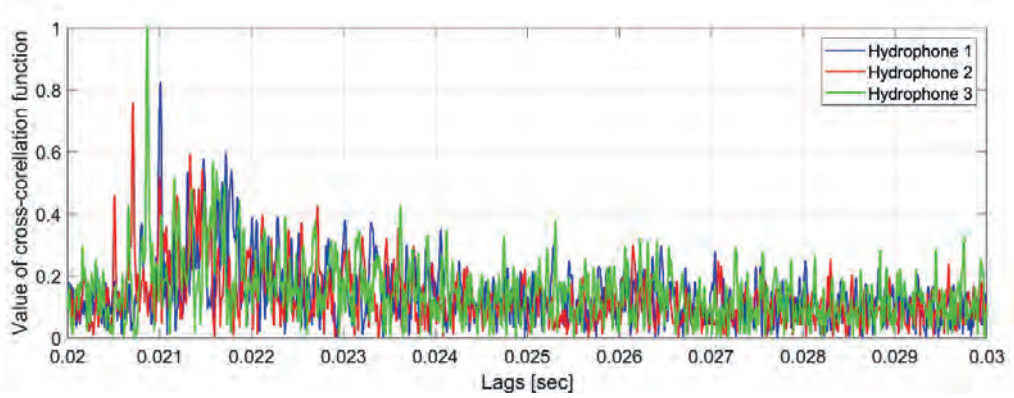

Fig. 7. The amplitude spectrum of the received signal averaged over the pulse duration
Rys. 7. Widmo amplitudowe odebranego sygnału uśrednione dla czasu trwania impulsu

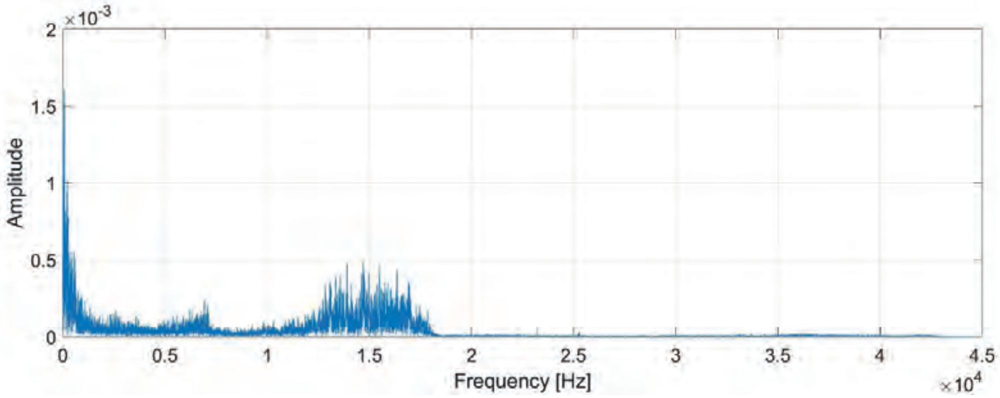

Fig. 8. Estimates of impulse responses determined for signals received from individual hydrophones for the bearing angle of –30°
Rys. 8. Estymowane odpowiedzi impulsowe dla sygnałów odbieranych z poszczególnych hydrofonów dla kąta namiaru –30°

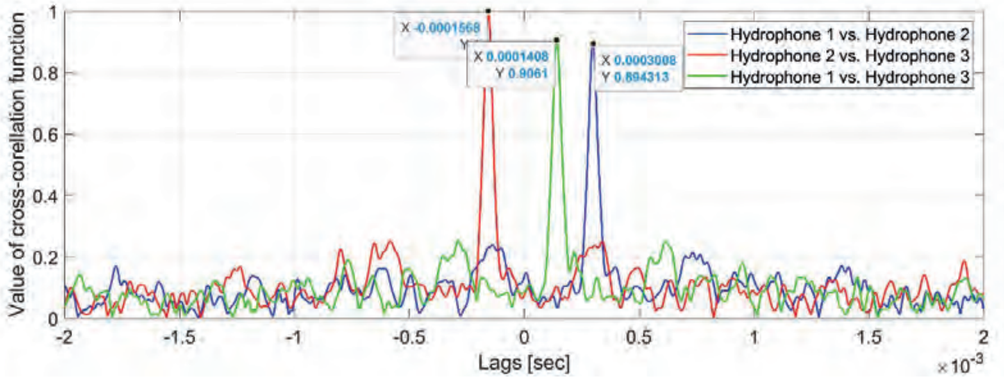

Fig. 9. The result of the cross-correlation between individual estimates of impulse responses for the bearing angle of –30°
Rys. 9. Wynik korelacji krzyżowej między poszczególnymi estymatami odpowiedzi impulsowych dla kąta namiaru –30°

ration of rectangular triangle at distances of 0.5 m from each other (Fig. 6) and lowered to a depth of 2 m. The receiving antenna was rotated relative to the underwater loudspeaker in an angle range of ±90° with a resolution of 15°. The sound speed measured with the CTD/STD probe at the depth of 2 m was 1499.70 m/s. During the tests, receiving signals were sampled with a frequency of 1 MHz. The resulting bearing angle is an average of the angles determined for three pairs of hydrophones namely: hydrophones 1 and 2, hydrophones 2 and 3 as well as hydrophones 1 and 3. It must be noted, that result obtained from pair 2 and 3 must be rotated by 90 deg (because of perpendicular location according to pair of hydrophones 1 and 2). Calculation for pair 1 and 3 must be made for distance between hydrophones equal to 0.707 what follows from Pitagoras theorem. More over obtained bearing angle for this pair must be rotated by 45 deg (difference in position in relation to pair 1 and 2). The obtained results of the bearing angle determination are shown in Table 1. The results were based to first decimal places. During the tests, filtering devices worked in the pool and generates sounds which were the source of additive disturbances. Fig. 7 shows the amplitude spectrum, averaged for the duration of the impulse (the duration of the spread code), of the recorded signals. Fig. 8 shows the estimate of impulse responses for individual hydrophones normalized to value 1 and Fig. 9 shows the result of cross correlation of individual estimates of impulse responses normalized to value 1 obtained during laboratory tests for the bearing angle of –30°.

Analyzing the results of the obtained measurements, it should be noted that there is a constant error of about 3.1° in the measurements. This is most likely due to inaccuracies in the mutual position of the receiving antenna and the sound source. However, a high accuracy of determining the bearing angle was obtained, which resulted from relatively large distances between the sensors and the high sampling frequency. The average error (after subtracting a constant error of 3.1° from absolute error) was 0.3° and standard deviation was 0.15°. The value of bearing angle determination errors and their distribution depending on the actual bearing angle are congruent with the results obtained during simulation tests.

Tab. 1. Obtained results of the bearing angle measurement in tests carried out in laboratory conditions
Tab. 1. Uzyskane wyniki pomiaru kąta namiaru w testach przeprowadzonych w warunkach laboratoryjnych

Given bearing angle [°]	Determined bearing angle [°]	Absolute error of bearing angle determination [°]
–90	–86.3	3.7
–75	–72.1	2.9
–60	–57.1	2.9
–45	–41.5	3.5
–30	–27.1	2.9
–15	–12.1	2.9
0	3.5	3.5
15	17.9	2.9
30	32.9	2.9
45	47.8	2.8
60	62.8	2.8
75	77.9	2.9
90	93.7	3.7

4. Summary

Despite the development of technology, underwater navigation is still a difficult task. The most commonly used method is based on the use of an elastic wave. However, in difficult hydrological conditions (multi-directional propagation, numerous reflections) it often does not meet the requirements for the accuracy of position determination and sometimes it is not possible to use it. Therefore, they are still sought new methods in this field. The popularization of digital technology and digital signal processing opens the way to the application of many new methods.

In the presented method, it was proposed to calculate the bearing angle by determining the time delays in reaching the transmitted signal to the individual sensors of the receiving antenna. In the conducted tests were used signals with direct spread spectrum. This technique allows to generate signals with a relatively short duration, but most importantly to detect them in spite of low power. Due to the determination of time delays based on the estimate of impulse responses of the hydroacoustic channel, a high time resolution was obtained. In addition, it allowed for independence from the unfavorable phenomenon of multi-directional propagation and the occurrence of numerous reflections. The conducted simulation tests and laboratory conditions confirmed the correctness of the adopted solutions.

In further research, solutions which allow to determine the distance to the object using properly formed transmitted signals will be sought. This should allow to increase the accuracy of determining the position of an underwater object and will facilitate precise underwater navigation.

Bibliografia

1. Christ R.D., Wernli R.L., *The ROV Manual*, Elsevier Ltd, 2007.
2. Morgado M., Batista P., Oliveira P., Silvestr C., *Position USBL/DVL Sensor-based Navigation Filter in the presence of Unknown Ocean Currents*, The 49th IEEE Conference on Decision and Control, CDC 2010, December 15–17, 2010, Atlanta, Georgia, USA, DOI: 10.1109/CDC.2010.5717740.
3. Hartman R., Hawkinson W., Sweeney K., *Tactical underwater navigation system* (*TUNS*), 2008 IEEE/ION Position, Location and Navigation Symposium, 05–08 May 2008, Monterey, CA, USA, 898–911, DOI: 10.1109/PLANS.2008.4570032.
4. Zeng Q., Zhang M., Liu H., Sui X., Liang S., Song Z, *Research of underwater navigation on a ROV with structure detection and decontamination*, The 27th Chinese Control and Decision Conference (2015 CCDC), 2015, 2585–2589, DOI: 10.1109/CCDC.2015.7162358.
5. Xing H., Liu Y., Guo S., Shi L., Hou X., Liu W., Zhao Y., *A Multi-Sensor Fusion Self-Localization System of a Miniature Underwater Robot in Structured and GPS-Denied Environments*, “IEEE Sensors Journal”, Vol. 21, No. 23, 2021, 27136–27146, DOI: 10.1109/JSEN.2021.3120663.
6. Ma X., Zhang T., Liu X., *Application of Adaptive Federated Filter Based on Innovation Covariance in Underwater Integrated Navigation System*, IEEE International Conference on Manipulation, Manufacturing and Measurement on the Nanoscale (3M-NANO), 2018, 209–213, DOI: 10.1109/3M-NANO.2018.8552184.

7. Gucma M., Montewka J., *Podstawy morskiej nawigacji inercyjnej*, Akademia Morska w Szczecinie, Szczecin 2006.
8. Milne P.H., *Underwater Acoustic Positioning System*, Gulf Publishing Company, 1983; ISBN 9780872010123.
9. Foley B.P., Mindell D.A., *Precision Survey and Archaeological Methodology in Deep Water*, "ENALIA The Journal of the Hellenic Institute of Marine Archaeology", Vol. VI, 2002, 49–56.
10. Bechaz C., Thomas H., *The Underwater use of GPS GIB Portable Tracking Systems*, https://hydro-international.com/content/article/gib-portable-tracking-systems, 2008.
11. Kayser J.R., Cardoza M.A., Wade W.F., Merts J.H., Casey D.R., *Weapon Scoring Results from a GPS Acoustic Weapons Test and Training System*, National Technical Meeting of The Institute of Navigation, San Diego, 2005, 416–430.
12. Cardoza M.A., Kayser J.R., Wade W.F., Bennett R.L., Merts J.H., Casey D.R., *Offshore Weapon Scoring Using Rapidly Deployed Realtime Acoustic Sensors* (PDF), 21st Annual National Test & Evaluation Conference. Charlotte, North Carolina, 2005.
13. Jonathan P.D., *Flexible Acoustic Positioning System Architecture*, Marine Technology Society, Dynamic Positioning Conference, 2002.
14. Chen T., Chan J., Gollakota S., *Underwater 3D positioning on smart devices*, Proceedings of the ACM SIGCOMM 2023 Conference, 33–48, DOI: 10.1145/3603269.3604851.
15. Alrajeh N.A., Bashir M., Shams B., *Localization Techniques in Wireless Sensor Networks*, "International Journal of Distributed Sensor Networks", 2022, DOI: 10.1155/2013/304628.
16. Ostrowski Z., Marszal J., Salamon R., *Underwater Navigation System Based on Doppler Shifts of a Continuous Wave*, 2018 Joint Conference – Acoustics, 2018. DOI: 10.1109/ACOUSTICS.2018.8502410.
17. Ostrowski Z., Salamon R., Kochańska I., Marszal J., *Underwater navigation system based on Doppler shift – measurements and error estimations*, "Polish Maritime Research", Vol. 27, No. 1, 2020, 180–187, DOI: 10.2478/pomr-2020-0019.
18. Diamant R., Lampe L., *Underwater localization with time-synchronization and propagation speed uncertainties*, 8th Workshop on Positioning, Navigation and Communication, 2011, 100–105, 2011. DOI: 10.1109/WPNC.2011.5961023.
19. Studański R., Żak A., *Results of impulse response measurements in real conditions*, "Journal of Marine Engineering and Technology", Vol. 16, No. 4, 2017, 337–343, DOI: 10.1080/20464177.2017.1378151

Wyznaczanie kąta namiaru na źródło dźwięku w wodzie z wykorzystaniem sygnału z widmem rozproszonym

Streszczenie: W artykule przedstawiono metodę oraz wyniki badań symulacyjnych i laboratoryjnych wykorzystania w nawigacji podwodnej sygnału z widmem rozproszonym bezpośrednio. Metoda została oceniona w zależności od parametrów akwizycji sygnału, wpływu zakłóceń i konfiguracji anteny odbiorczej.

Słowa kluczowe: nawigacja podwodna, widmo rozproszone, hydroakustyka, korelacja wzajemna

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