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Underwater Acoustic Imaging of the Sea

Grażyna GRELOWSKA[(1)], Eugeniusz KOZACZKA[(1), (2)]

[(1)] *Gdańsk University of Technology*
Narutowicza 11/12, 80-233 Gdańsk, Poland; e-mail: grazyna.grelowska@pg.gda.pl

[(2)] *Polish Naval Academy*
Śmidowicza 69, 81-103 Gdynia, Poland

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Acoustic waves are a carrier of information mainly in environments where the use of other types of waves, for example electromagnetic waves, is limited. The term *acoustical imaging* is widely used in the ultrasonic engineering to imaging areas in which the acoustic waves propagate. In particular, ultrasound is widely used in the visualization of human organs – ultrasonography (Nowicki, 2010).

Expanding the concept, *acoustical imaging* can also be used to presentation (monitoring) the current state of sound intensity distribution leading to characterization of sources in observed underwater region. This can be represented in the form of an acoustic characteristic of the area, for example as a spectrogram.

Knowledge of the underwater world which is built by analogy to the perception of the space on the Earth's surface is to be systematize in the form of images. Those images arise as a result of graphical representation of processed acoustic signals.

In this paper, it is explained why acoustic waves are used in underwater imaging. Furthermore, the passive and active systems for underwater observation are presented. The paper is illustrated by acoustic images, most of them originated from our own investigation.

Keywords: underwater imaging, systems of underwater observation.

1. Introduction

Deep sea, though hardly accessible, becomes more and more interesting for humans for various reasons, starting with the willingness to discover more about the seabed layout for cognitive aspect (Leighton *et al.*, 2008a; Kozaczka *et al.*, 2010; Klusek *et al.*, 1995; Wunderlich *et al.*, 2003) and for the safety of sail purposes n the case of shallow waters (Kozaczka *et al.*; 2013; Kastek *et al.*, 2012).

Yet, another reason for such interest in the seabed are historical and archeological studies or the curiosity of 'treasure hunters', who spend a lot of energy searching for the objects lying at the sea bottom mostly from sunken ships and their cargo.

Another important factor in underwater exploration is the search for the natural resources which are limited on the land and seem to be indispensable at the current stage of our civilization. This refers to both, unanimated natural resources such as energy materials or polymetallic minerals, and biotic resources.

The observation of the underwater world, especially of wildlife, has two main reasons: cognitive and behavioral.

The cognitive aspect involves the willingness to get some knowledge about animals' behavior, especially of mammals and fish, their migrations, ways of communication and gaining food. Those issues are the domain of oceanographic acoustics and bioacoustics (Klusek *et al.*, 2010). The second reason is related to the necessity of going on a forage for the marine resources, mainly fish and shellfish. Such issues are the domain of fishery acoustics, which creates tools for searching for schools, or for the remote assessing of the species of fish (Moszyński *et al.*, 2006). The methods of estimation are used to assess the volumes of the underwater resources of fish and shellfish. The usage of such information enables the rational exploitation of resources and for establishing fishing limits providing the opportunity to renew the natural resources of marine animals caught by people.

The exploitation of energy materials, especially of oil and natural gas, includes the risk of leakage of those harmful substances to the sea waters. The areas of drilling and platforms, as well as underwater pipes used for oil and gas transportation, should be under continuous surveillance to reduce the likelihood of occurrence of such accidents.

Another aspect, which is related to underwater monitoring, is the protection of sea critical infrastructure objects, harbors, shipyards, farwaters or platforms. Detection of the potential danger in the underwater area is a matter of the continuous observation of the protected object. Rapid development of security systems, of which proper imaging of underwater conditions is a key element, has been observed in the recent years.

Underwater acoustical images can not only constitute a static mapping of such objects as, for instance, seabed, but can also project dynamic processes such as tracking moving objects, marine mammals, schools, divers or underwater vehicles.

Such comprehensive interest in the underwater area investigation and observation leads to the development of tools and methods specializing in the sea research. The vast majority of them use acoustical waves as an information carrier. The paper presents the latest achievements in these fields, including the methods based on a non-linear acoustic theory. The examples from the literature and the results of the own research have been included.

2. Elastic waves as an information carrier in the sea environment – possibilities and limitations

We try to systematize knowledge of the underwater world in form of images. The knowledge is being built by the analogy to the perception of the space on the Earth's surface. The images arise as a result of a graphical representation of the processed acoustic signals.

Electromagnetic waves are strongly attenuated by the sea water, while their transmission into the depth of different water basins varies according to the heterogeneity of absorption-scattering properties of the water in a given area. It has an impact on the range of underwater observation systems as presented in Fig. 1.

Another attenuation of light for different wavelengths results from the absorption-scattering properties of the sea water. Infrared light is strongly attenuated in all waters as a result of very strong absorption of this light by the molecules of H_2O. Water layers act on a daylight as the band filter of the best transmitting waves of length 400–500 nm. At depths of 100 m, even in the clearest waters, the spectrum of light is practically narrowed down to this band.

Acoustic waves, unlike electromagnetic ones, propagate in the water better than in the air. Their velocity is about 1500 m/s so it is approximately 5 times

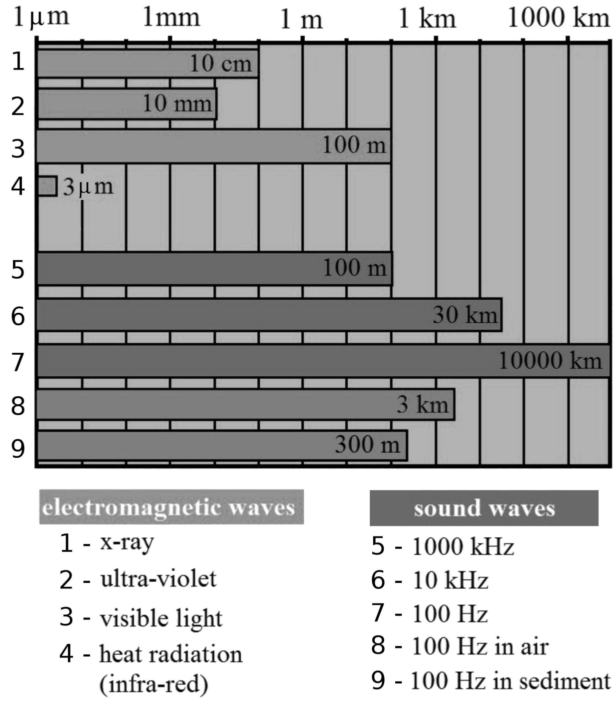


Fig. 1. Maximum ranges of underwater observation systems operating using acoustic or magnetic waves in the sea water (Wille, 2005).

greater than that in the air. The attenuation of elastic waves in the sea water is smaller than in the air and also smaller than the attenuation of electromagnetic waves in the water and depends significantly on the frequency of the wave. For water without the content of salt, the absorption coefficient α is expressed by the formula:

$$\alpha = \frac{b\omega^2}{2\rho_0 c_0^3}, \tag{1}$$

where b is dissipation coefficient, ω – angular frequency of the wave, ρ_0 – density of medium, c_0 – speed of sound in water. The value of absorption coefficient is about $2 \cdot 10^{-6}$ cm^{-1} for the wave of frequency 1 kHz and about $2 \cdot 10^{-4}$ cm^{-1} for the wave of frequency 10 kHz. The content of chemical compounds in the sea water, $MgSO_4$ and $B(OH)_3$, increases the attenuation of acoustic waves in the low frequency band (Fig. 2).

The speed of sound in water is much lower, about 200 000 times, than the velocity of the electromagnetic wave that is used as the primary carrier of information in air ($3 \cdot 10^8$ m/s). This causes a number of difficulties in a study of underwater space by means of acoustic waves. One of them is the need to wait for the echo signal while probing the sea.

While designing hydroacoustic systems, a small speed of acoustic wave in water is also a cause of the continuous search for a compromise between the range and the accuracy of mapping. The accuracy of mapping for simple antennas depends on the longitudinal and lateral resolution.

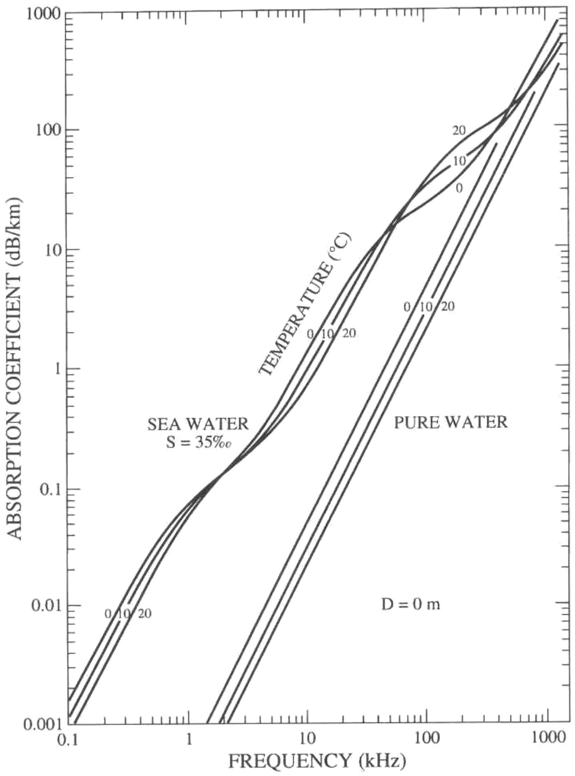


Fig. 2. Sound absorption in decibels per kilometer as a function of frequency at three temperatures at atmospheric pressure (zero depth) for $S = 35$, according to Francois and Garrison (1982).

The resolution in depth depends on the duration of the pulse:

$$\Delta R = \frac{c_0 \tau}{2}, \tag{2}$$

where ΔR is the thickness of the water layer from which the information when sounding underwater space with the pulse of duration τ is received. The pulse duration is adapted to the operating conditions of the system, nevertheless it is somehow determined by the frequency of the radiated wave. In practice, the pulse should contain at least a few or several wave periods, therefore its duration increases with the decreasing of the wave frequency, and the accuracy of mapping deteriorates.

Beam width determines the lateral resolution, expressed in angular measure and is sometimes called the angular resolution. The area covered by the beam increases with the distance from the transmitting transducer, so the accuracy of mapping decreases. The synthetic aperture systems, in which the lateral resolution is constant – not depended on the distance, represent an exception.

In summary: the range of hydroacoustic devices depends on the wave frequency – the attenuation in the water increases with the square of the frequency. On the other hand, the longitudinal and lateral resolutions increase with increasing frequency of the wave. The compromise has to be done between a long-range device with a large beam width and low-resolution operating at low frequency waves, or a device with a better resolution but a smaller operating range at high frequency waves.

Therefore, the frequency of operation of the equipment should be adjusted to the water depth. At the same time for the investigation of the underwater area and searching for the objects, the further narrowing methods of the field observation should be used. An example of the system composed of two sector sonars is shown in Fig. 3.

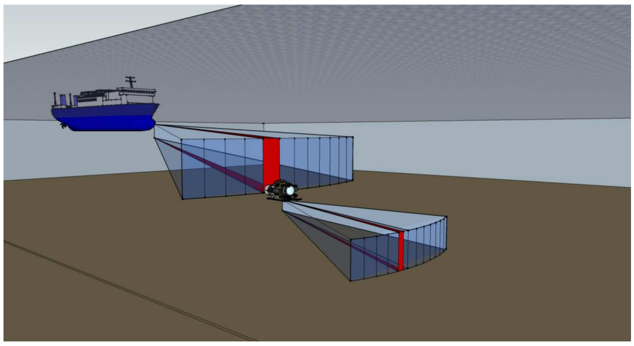


Fig. 3. Narrowing methods of investigation.

The constraints related to the physical properties of elastic waves propagation in the sea cause that different solutions used in the underwater observation systems are dedicated to a specific purpose.

3. Active and passive systems of underwater observation

In general, hydroacoustic systems that allow observation of the underwater environment and its visualization can be divided into two types: active systems that provide information based on the echo signal emitted into the water, and passive systems in which the image of the underwater world is formed on the basis of sounds received by the hydrophones only. Both types of systems provide a range of information needed to locate and identify objects and track their path, but differ from each other as to the methods of operating as well as the quality of the information. The passive systems enable direct measurement of the direction and the active ones – the direction and the distance from the sound source.

4. Stationary images

Stationary images, which characterize the underwater space, are largely the images of the seabed. The seabed, its shape, structure and objects covered with a layer of sediments are one of the main areas of interest, that is why much attention is given to the methods and devices of their visualization operating on the basis of active observation only.

There is a large variety of instruments now available, and sea bottom imaging systems can be roughly divided into three categories: single-beam echo-sounders (including parametric echosounders), multibeam echo-sounders, and sidescan sonars.

Single-beam, down-looking echo-sounders have long been the tool of choice for mapping, because they are simple to use and widespread on nearly all vessels. They transmit a single beam oriented toward the ship's nadir. The first return from the seabed corresponds to points closest to the ship, and farther as the cone spreads. Sub-surface penetration is often an issue in sedimentary areas. Echosounders are not always calibrated, but often give a very good estimate of the depth and type of seabed. The shape of the echo can be analysed quantitatively (e.g. Pouliquen, Lurton, 1992; Tegowski Lubniewski, 2000; Leighton, Robb, 2008b; Grelowska *et al.*, 2013a) to derive more information about the local habitat. Innovative techniques were also developed to extract more information from the echoes of the secondary lobes (e.g., Heald, Pace, 1996).

The examination of the surface's upper layer of the seabed requires systems with high directivity beams in order to minimize sediment reverberation. Parametric sonar systems fulfill this requirement and generate low frequency narrow beams without main lobes. Due to their comparatively small dimensions and weight, parametric systems can easily be mounted on ROVs or AUVs, thus allowing, e.g. the application as a relocalization sensor for one-shot mine disposal vehicles against buried mines.

There are various types of high resolution subbottom profiling systems, mainly varying in energy source and receiving element, with their respective merits and demerits as well as applications. One of the most popular and widely used sub-bottom profiling system is system utilizing air guns as an energy source and a separate receiving cable for recording the reflected acoustic signals. Much more precise system is based on parametric sound generation, called parametric echosounder. The most famous TOPAS that allows to penetrate sea floor up to thousands meters is a superior sub-bottom profiling system in resolution but is less common due to its high cost (Zakharia, Dybedal, 2007). There are also available mobile parametric sediment echosounder systems that allow us to carry the survey in shallow water. The ultimate objective of this technique is to provide a spatially detailed and resolved picture of the seafloor and the subsurface sediment structures. High resolution seismic surveys are primarily confined in the uppermost 80 meters of soil. This is the area where most engineering applications take place. It is estimated that about 80% of this work is done in the first 15 to 20 meters. Some typical major applications include reconnaissance geological surveys, mineral exploration, foundation studies for offshore platforms, detailed site surveys for engineering projects, cable and pipeline route investigations, harbor development and environmental studies. The technique of precise sub-bottom survey finds one more application important for safety at the sea. Presently, more and more frequently the mass destruction weapon is placed in shallow water in the very difficult way to find it. Searching for such objects in the sea requires the usage of devices that have possibility of penetration of sediment that covers the searched object.

In the most simple case, a parametric echosounder array consists of a transducer, generating high frequency waves, and the water volume, in which the parametric effect takes place. In many applications, the transducer operates in a biharmonic mode, emitting pump waves (or primary waves) with frequencies f_1 and f_2. If the intensity of the primary waves is sufficiently high, virtual secondary sources, which propagate with the speed of sound, are created in the medium behind the transducer. This leads to a significant change in the spectral composition of the emitted field. Due to nonlinear interaction of sound with the water, a part of the energy is shifted from the primary waves to secondary waves with different frequencies. The waves with the most significant energy content are waves with frequencies $2f_1$ and $2f_2$, as well as the sum frequency wave $f_1 + f_2$, and the difference frequency wave $f_1 - f_2$.

Due to the nearly quadratic dependence of the viscous absorption cross section on frequency, the high frequency secondary waves are damped much stronger than the difference frequency wave. Therefore, the difference frequency wave propagates to the longer distances compared to the region of interaction. Because of this property the difference frequency wave has drawn much attention in the field of underwater acoustic engineering.

The propagation of parametric sound beams is determined by the mutual mechanisms of nonlinearity, absorption, and diffraction. The theoretical model for this problem is based on the KZK equation which describes the balance of all three effects. We consider an axisymmetric, bounded sound beam with source radius $a$and source frequency $f = \omega/2\pi$. The KZK equation may be written in the dimensionless form (Zabolotskaya, Khokhlov, 1969; Kuznetsov, 1971)

$$\frac{\partial}{\partial\tau}\left[\frac{\partial p'}{\partial x} - \frac{\varepsilon}{\rho_0 c_0^3} p' \frac{\partial p'}{\partial\tau} - \frac{b}{2\rho_0 c_0^3}\frac{\partial^2 p'}{\partial\tau^2}\right] = -\frac{c_0}{2}\left[\frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2}\right], \tag{3}$$

where x denotes direction of wave propagation, y, z – axes perpendicular to beam axis, ρ_0, c_0 – density and sound speed, b – absorption coefficient, ε – coefficient of nonlinearity.

Here, $p' = p/p_0$ is a dimensionless pressure in terms of the acoustic pressure p and some reference value on the source p_0. Further, $\tau = \omega(t - x/c_0)$ is a dimensionless retarded time.

The second and third term on the left-hand side of Eq. (3) represent the effect of absorption and nonlinearity, and the term on the right-hand side represents diffraction respectively. In deriving Eq. (3) it is assumed that $ka \gg 1$. We restrict our analysis to the sound field of plane circular transducers. However, the KZK equation can be written in a more general form in order to treat arbitrarily shaped plane or slightly curved transducers.

For one dimensional case (right-hand side of Eq. (3) equals 0) primary wave is given in form:

$$p'(x,\tau) = p_{01}(x)\sin\omega_1\tau + p_{02}(x)\sin\omega_2\tau. \tag{4}$$

As a consequence of nonlinear interaction between primary waves, new waves occur, and it is described as follows:

$$\begin{aligned} p_2(x,\tau) = {}& \frac{\varepsilon p_{01}^2}{b2\omega_1}\left(e^{-2\alpha_{01}x} - e^{-4\alpha_{01}x}\right)\sin 2\omega_1\tau \\ &+ \frac{\varepsilon p_{02}^2}{b2\omega_2}\left(e^{-2\alpha_{02}x} - e^{-4\alpha_{02}x}\right)\sin 2\omega_2\tau \\ &+ \frac{\varepsilon p_{01}p_{02}(\omega_1-\omega_2)}{b2\omega_1\omega_2}\left[e^{-\frac{b(\omega_1^2+\omega_2^2)}{2\rho_0 c_0^3}x} \right. \\ &\left. - e^{-\frac{b(\omega_1-\omega_2)^2}{2\rho_0 c_0^3}x}\right]\sin(\omega_1-\omega_2)\tau \\ &- \frac{\varepsilon p_{01}p_{02}(\omega_1+\omega_2)}{b2\omega_1\omega_2}\left[e^{-\frac{b(\omega_1+\omega_2)^2}{2\rho_0 c_0^3}x} \right. \\ &\left. - e^{-\frac{b(\omega_1^2+\omega_2^2)}{2\rho_0 c_0^3}x}\right]\sin(\omega_1+\omega_2)\tau, \end{aligned} \tag{5}$$

where α_{01}, α_{02} are the linear absorption coefficients at angular frequencies ω_1, ω_2.

A parametric echosounder based on the wave of frequency equals to the difference of frequencies of primary waves $f = f_1 - f_2$.

The parametric echosounder utilizes the non-linear sound propagation in water. By emitting two primary beams at frequencies close to each other, a secondary beam at the difference frequency, as well as one at the sum frequency, will be generated in the water column. The sonar thus works as a virtual end-fire array with considerably larger dimensions than the physical size of the sonar. The difference frequency beam has several appealing properties:

1. No side lobes at the difference frequency.
2. A narrower beam than can be achieved by direct generation of the difference frequency at the same physical size of the antenna. This beam width is comparable with the beam width at the primary frequencies.
3. Very broad bandwidth is possible. This is because a large proportional change in the difference frequency can be achieved by making only a small proportional change in (one or both of) the primary frequencies.
4. The beam width is nearly constant in a broad frequency band.
5. Projector cavitation is not a problem (due to the transmission at high frequencies).

The main disadvantage of the parametric echosounder is the poor efficiency since only a small part of the transmitted energy appears at the difference frequency (which the system is designed to be used at).

These properties of the parametric echosounder make it a suitable instrument for the use of the proposed characterization technique. The most important factors are that the frequency band is in the kHz range and that the bandwidth is wide.

Figure 4 shows the beam pattern in the near-intermediate and far-field of the parametric array (with constant pressure distribution at the transducer surface). It can be seen that the difference frequency wave exhibits no side lobe structure. The beam width is approximately equal to the conventional far field beam width of the mean primary frequency wave.

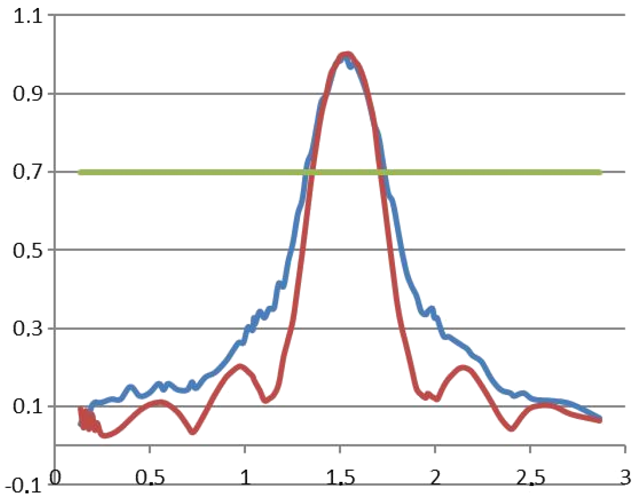


Fig. 4. Beam pattern of the primary (100 kHz) and the secondary (10 kHz) waves at the distances of 6 meters from the source.

Figures 5 and 6 illustrate the main advantage of parametric sonar – ability to penetrate upper geological structure of the sea bottom.

However, single-beam echosounders, even parametric ones, only provide information on the seabed directly just below the surveying vessel. The footprint on

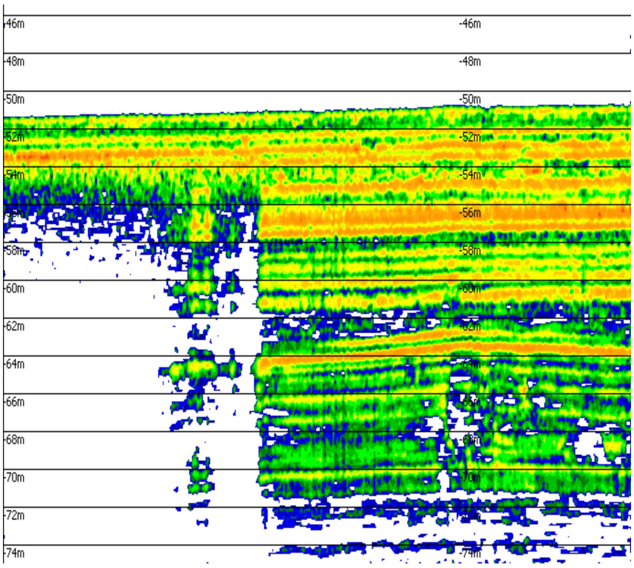


Fig. 5. Image of sub bottom structure taken in the Gulf of Gdansk; bottom at 50 m, depth of penetration 27 m.

the seabed varies in size, depending on the water depth and the local slopes, but is generally large. Seafloor coverage will therefore be variable and rather small.

This led to the design of multibeam echo-sounders. Becoming more accessible in the late 1980s, these instruments transmit several beams, covering a wide swath on each side of the ship's track (up to 20 times the water depth in some cases). These beams are narrower than single beams, and are produced with transducer arrays (made of identical transducer elements equally spaced). These systems principally acquire bathymetry measurements for each beam but, increasingly, backscatter strengths can also be derived. Targets smaller than the footprint can now be resolved by some systems, using the "split aperture" method (e.g. Lurton, 2000). Multibeam echo-sounders are particularly attractive for the mapping of Exclusive Economic Zones, and their processing is well standardized, following high standards of calibration and accuracy (e.g. IHO-S44 for bathymetry).

Multibeam sonar systems (MBSS) have been successfully used for gathering high resolution seafloor bathymetric data and acoustic imagery in shallow- and deep-water regions. With modern shallow-water MBSS detailed geomorphology and geology can be described at spatial resolutions of as little as a few centimetres (Hughes Clarke *et al.*, 1996). For that reason multibeam sonar data is considered to be a primary source of

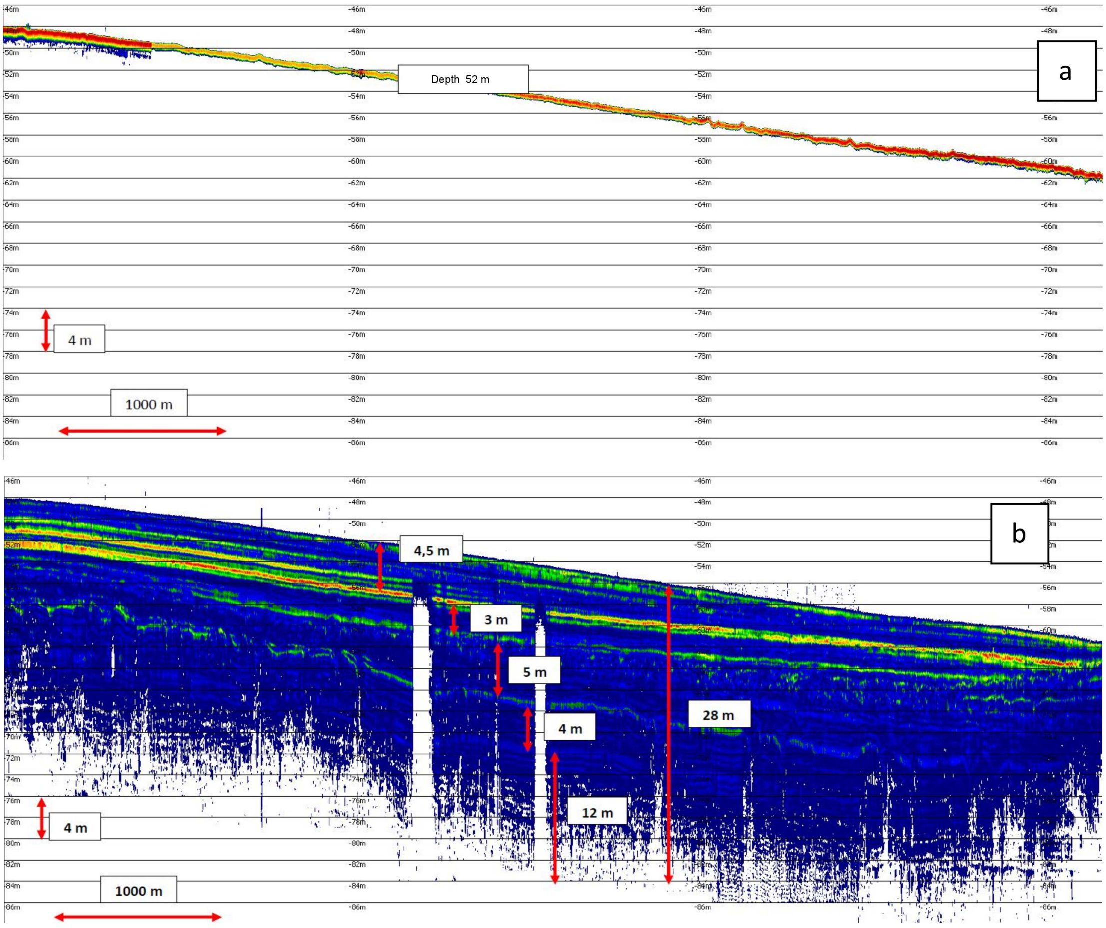


Fig. 6. Image of bottom taken in the Gulf of Gdansk using parametric echosounder; a) primary wave $f = 100$ kHz, b) difference frequency wave $f = 5$ kHz.

information for marine geologic research. The seafloor properties are related to the geomorphology (terrain relief) and the geology (sediment type).

Most shallow-water MBSS use two arrays of piezoelectric ceramics mounted in one transducer head that can be hull-mounted (fixed) or pole-mounted (portable). One array forms the transmitting acoustic signal, while the other creates a receiving one. The product of both arrays results in a fan-shaped beam set with 48 to 1440 beams in angular sectors from 90° to 180°. The operating acoustic frequencies range from 95 kHz to 455 kHz.

In general, shallow-water MBSS transmit acoustic energy in a beam-formed lobe narrow in the along-track direction (usually 1° to 5°) and wide across-track (between 100° to 180°). The receiving array is formed by a number of lobes shaped narrowly athwartships (1° to 3.3°), and usually somewhat broader in the fore-aft direction (between 3.3° to 30°). The intersection product of both beam patterns creates individual narrow beams normally spaced at 0.9° to 2.5° intervals.

The main differences between deep- and shallow-water MBSS are that the latter utilizes higher frequencies, shorter pulse lengths, and faster repetition rates. This translates into resolving seafloor features with higher resolution at higher vessel's speed, while still keeping near one hundred percent bottom coverage with a narrower swath width. However, the trade-off between the above mentioned aspects is the massive data acquisition, management, and storage requirements as well as the greater demands on the platform's attitude compensation system.

The image of part of bottom cross section through the Gulf of Gdansk taken by multibeam echosounder is shown in Fig. 7, while in Fig. 8 we can assess the depth of penetration in the same area using 10kHz waves (parametric echosounder).

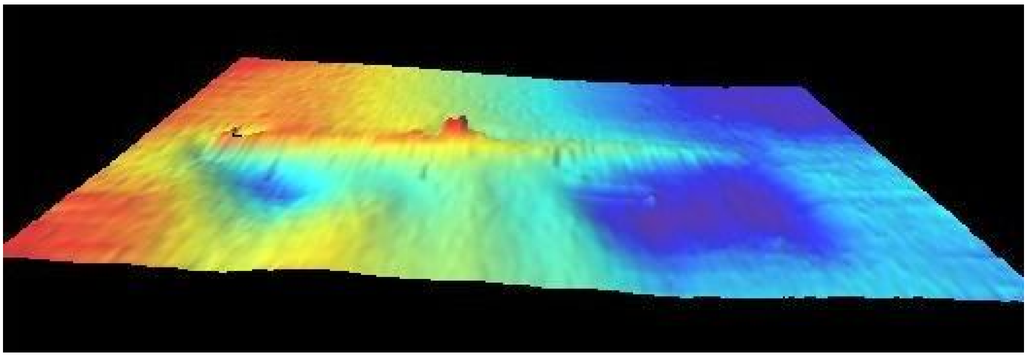


Fig. 7. Wrack on the bottom of the Gdansk Bay. Image from multibeam echosounder.

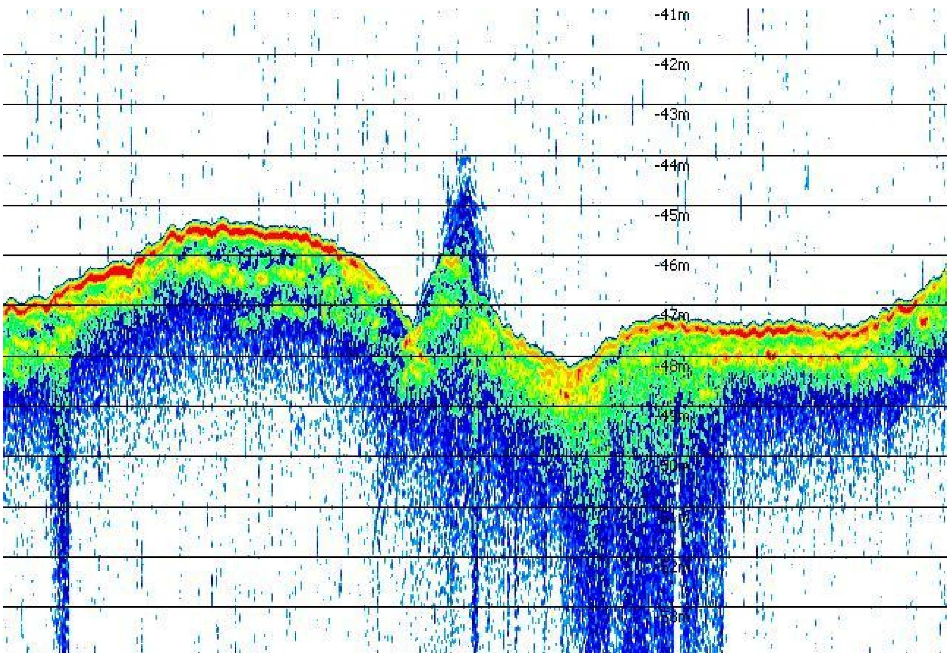


Fig. 8. Wrack on the bottom of the Gdansk Bay (the same as in Fig. 7). Image from parametric echosounder.

The images of the same object, for example a wreck lying on the seabed, created on the basis of data from different devices provide different information about the same object and are usually dissimilar. Data from a multibeam echosounder allows for the assessment of the shape of the bottom around the wreckage, and parametric echosounder data provides information about the stratification of the bottom. Simultaneous analysis of the images of both devices provides more complex knowledge of the subject, what is shown in Fig. 9.

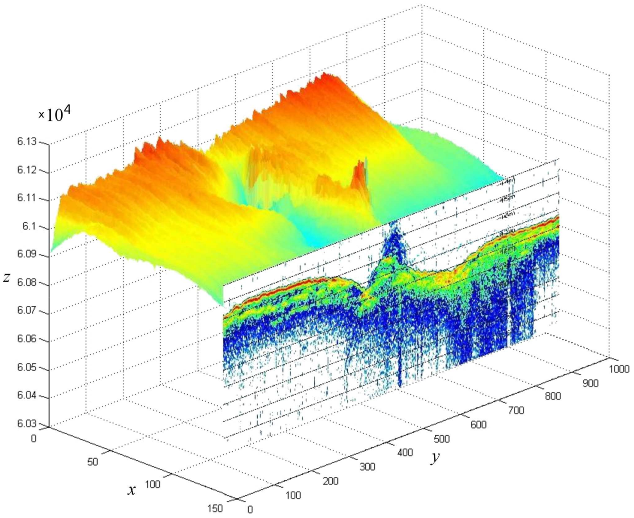


Fig. 9. Imaging of the wreckage at the seabed by means of multibeam and parametric echosounder.

Knowledge of the local bathymetry, at each point where backscatter has been acquired, can be used to correct the quality of imaging and represent it using the exact local incidence angles. Its interpretation is not too different from that of sidescan sonar imaging.

But the tool of choice for high-resolution seabed mapping remains the sidescan sonar. This instrument covers a much larger portion of the seabed away from the surveying vessel, from a few tens of meters to 60 km or more. This coverage is attained by transmitting one beam on each side (broad in the vertical plane and narrow in the horizontal plane). Using different frequencies (from 6.5 kHz to 1 MHz), sidescan sonars achieve resolutions of 60 m down to 1 cm. The processing steps are less standardized, depending on the manufacturer, despite the consensus on the types of corrections desirable.

The operating principle of sidescan sonar is illustrated in Fig. 10. A tow fish containing the physical arrays (transmitter and receiver) is towed behind a ship (an AUV, or a ROV) on a given trajectory. The acoustic observation is obtained by periodic pinging at pulse repetition frequency and is perpendicular to the array trajectory. The sound propagates along the slant

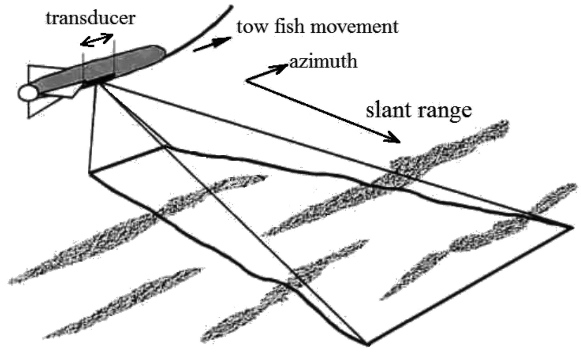


Fig. 10. Operating principle of sidescan sonar.

range axis while the arrays travel along the azimuthal axis.

Sonar images are constructed by juxtaposing the intensity of the echoes received from several consecutive pings. It is important to point out, from the very beginning, that the sonar images are quite dissimilar to standard video ones as both axis are of very different nature although they are both expressed in range (or time). One time-scale is the propagation delay of a sound pulse (travelling at about 1500 m/s) and the other one is related to the tow fish trajectory (at a few m/s).

When the bottom is flat and smooth, it acts as a perfect mirror and all the incoming acoustic intensity is reflected in the specular direction: no intensity is backscattered in the transmitter direction. However, when the bottom is rough (with respect to the wavelength), the incoming intensity is scattered in all the directions and part of it is backscattered in the transmitter direction. Apart from the vertical incidence case, the backscattered intensity is thus mainly due to the bottom roughness.

Similar observation can be made on the echo of artificial targets either in the sonar domain (mine, wrecks, containers etc.) or in the radar domain (planes, tanks, buildings etc.). A target echo is mainly due to its roughness, edges or irregularities (changing of cross-section): no significant echo is backscattered by plane or (and) smooth surfaces (except from the normal incidence case).

Whenever possible, these instruments for underwater imagining are combined (Fig. 11). The imaging can be draped over the bathymetry producing 3-D views of the seabed, and the bathymetry can be refined with seabed geological profile or detailed image of given area obtained by sidescan sonar. But they cannot be interpreted in the same way because of the significant differences in the physical processes leading to their creation. Each technique leads to specific bottom images and allows to determine only few characteristics of examined area. It is necessary to understand the basic acoustic processes leading to the formation of an image, and impacting its quality.

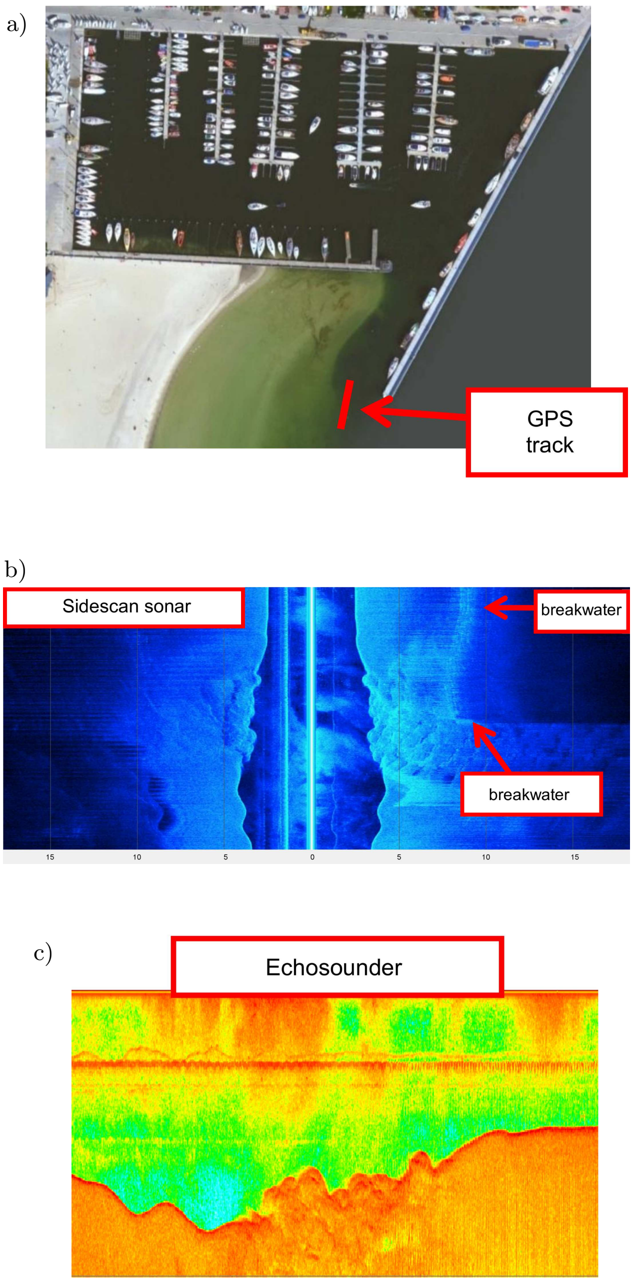


Fig. 11. Images of the bottom at the entrance to marina Gdynia: a) top view of marina, b) image of the bottom obtained by sidescan sonar, c) image of the bottom obtained by echosounder.

5. Images of moving objects

Creating images of the moving objects changing their position requires registration of data related to the distance and the bearing of the object in consecutive intervals. After processing, the visualization of the data in the form of the trajectory of the object is possible. This goal can be achieved by using both passive and active systems.

The systems of active observation are usually active sonars, omnidirectional or sector, in which the data is processed in such a way that successive images from selected sector are stored and played back sequentially, resulting in information about the change of the location of all the objects in the area of observation (Marszal, Salamon, 2012; Kozaczka *et al.*, 2007a, 2007b; Iwaniec, Wiciak, 2002). This kind of solution is very useful for underwater monitoring systems, systems of protection of maritime critical infrastructure, particularly ports and oil platforms (Fig. 12).

The passive observation systems use usually several hydrophones arranged in a determined configuration to form a receiving antenna. The receiving antenna is the most common in form of linear or tetrahedral antenna. Such antennas are designed and made especially for tracking objects moving in sea area.

For imaging systems, the angular resolution is limited by the beam divergence. The beam divergence $\theta_{3\,\mathrm{dB}}$ (beamwidth) is a function of the wavelength and the aperture size (Salamon, 2006):

$$\theta_{3\,\mathrm{dB}} = 2\arcsin\frac{0.44\lambda}{d}, \tag{6}$$

where $\theta_{3\mathrm{dB}}$ is the 3 dB beamwidth , λ – the wavelength [m], d – aperture length [m]. The use of linear antenna arrays provides the great advantages for measurements and tracking. It improves the directivity properties of antenna and allows for tracking moving objects. It is based on measurement of the difference in the phase of signals reaching particular elements of antenna (Fig. 13).

The directivity pattern of the linear antenna consisting of N elements is given as (Salamon, 2006):

$$D(f,\theta) = \sum_{n=-(N-1)/2}^{(N-1)/2} w_n(f) e^{j\frac{2\pi f}{c} nd\sin\varphi}, \tag{7}$$

where N – number of array elements, d – inter-element spacing, f – frequency, $W_n(f)$ is the complex weight of element n.

The phase shift – ψ, that corresponds to the distance $x = d * \sin\phi$ is then:

$$\psi = \frac{2\pi d}{\lambda}\sin\varphi. \tag{8}$$

Applying a linear antenna in a system tracking a tone source is described in work (Orlov and Rodionov, 2008), while in our experiment the real sources producing broadband noise are the observed objects (Kozaczka, Grelowska, 2011; Grelowska *et al.*, 2013b; Kozaczka *et al.*, 2007a, 2007b).

The main part of the measurement set-up is a linear array of hydrophones. In our experiment the distance between successive hydrophones is fixed and could be chosen in range from 0.5 m up to 6 m. At the same time, up to six hydrophones can be used in measurements. Sensors of acoustic pressure are mounted so

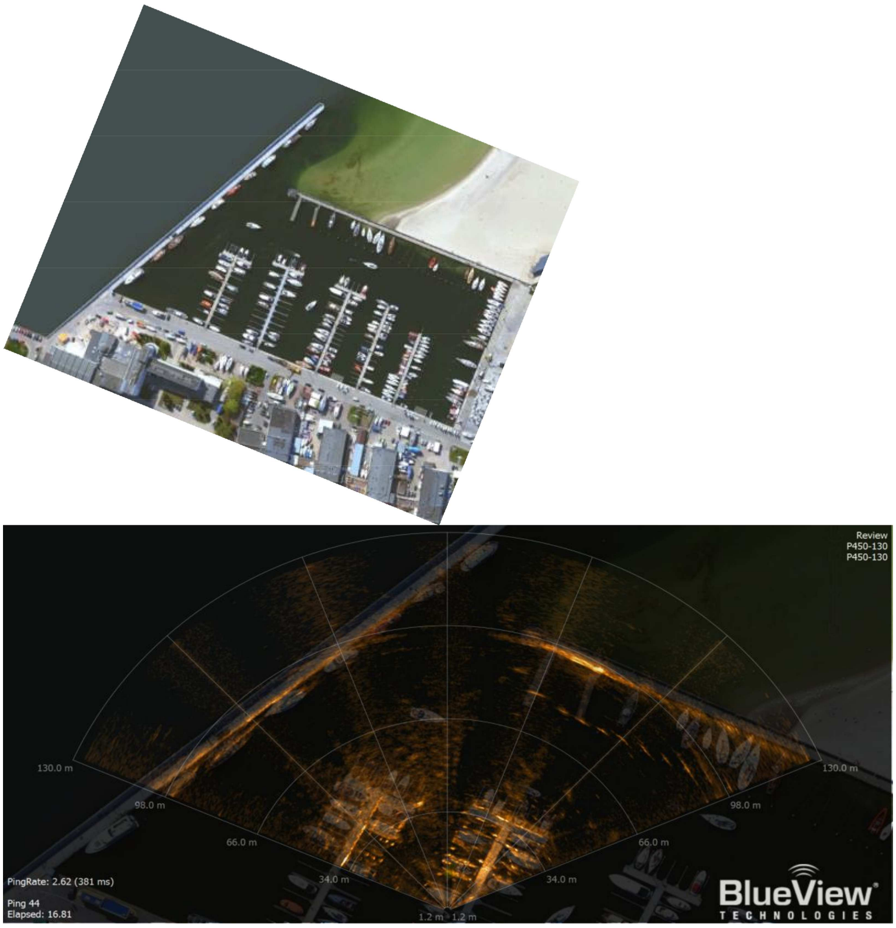


Fig. 12. Comparison of an active sonar visualisation with a yacht harbour photo.

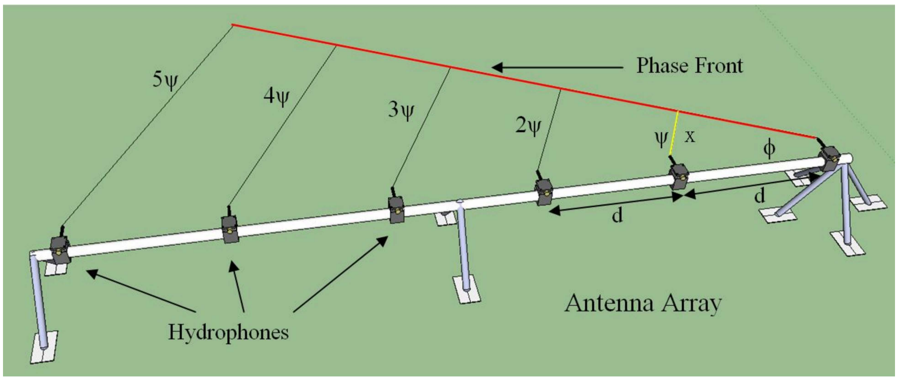


Fig. 13. Schematic diagram showing the construction used to determine the magnitude of the phase difference.

that impact of environment motion for vertical and horizontal arrays of hydrophones, especially waved sea surface, is minimized. Received signals are registered and recorded by using system PULSE – LAN XI produced by Bruel and Kjaer. The data is post processed using a prepared script in Matlab programming environment.

On the basis of the measurements, a set of characteristics is obtained, and this determines individual distinctive features of the examined sources.

The set of characteristics contains among others:

- instantaneous spectra of underwater noise of the source,
- characteristics illustrating changes in pressure level with the distance from the source at a fixed depth,
- set of correlation and coherence functions and directivity patterns.

Moreover, for each measurement are determined spectrograms that combine features of spectral character-

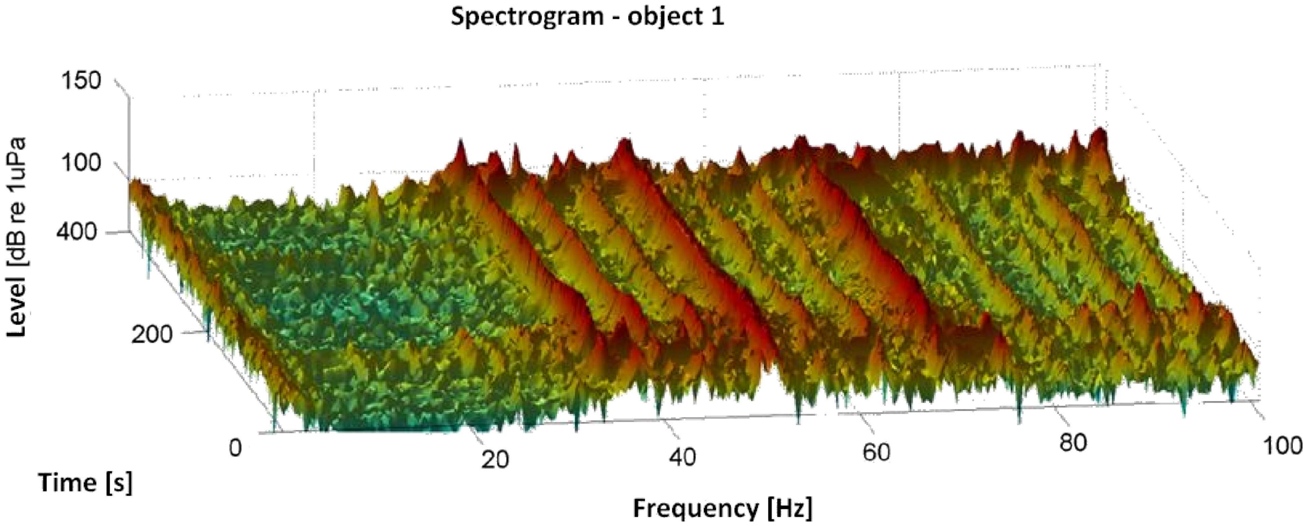


Fig. 14. The spectrogram of investigated object for frequency range up to 100 kHz.

istics and the functions connected with changing the position of the source relatively to the receiving antenna.

During the research different floating objects were measured: ships, yachts, pontoons with engine or paddles, and divers. Each object could be treated as a broadband source with spectrum in which particular components might be distinguished. The example of spectral characteristics of one of the sources is given in the form of a spectrogram for frequency range up to 100 Hz (Fig. 14).

Some characteristic components in the spectrum can be distinguished, and that data could be used to track. However, the observation basing on a wave of such a small frequency and at the same great wavelength needs the antenna of the long base. In Fig. 15

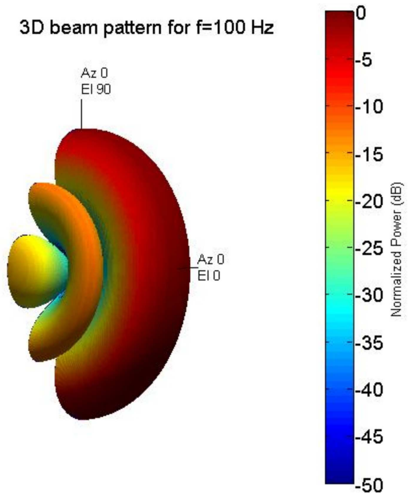


Fig. 15. Beam pattern of linear antenna of 6 hydrophones distant by 6 meters for frequency of 100 Hz.

the directivity pattern determined for linear antenna composed of 6 hydrophones distant by 6 meters is shown. Calculations are made for selected frequency of 100 Hz, well visible in the spectrum. The changes in the width of the main lobe within the frequency range up to 100 Hz are shown in Fig. 16.

Some other characteristic components can be distinguished in the spectrum of underwater noise produced by the same object in range of frequencies higher than 100 Hz, for instance 250 Hz and 590 Hz – see Fig. 17.

In this case the hydrophones of linear antenna should be placed closer than in the case discussed before.

The width of the directivity pattern is the important factor influencing the spatial resolution and it allows us to determine the direction of the source of sound, while the cross correlation function could be useful to assess the movement of the source.

Figure 18 shows the result of investigation of the source moving around the measurement range in the form of the cross correlation function of signals received by 2 hydrophones. The axis of ordinate shows the difference in time the wave needs to reach the second sensor. Basing on such data obtained for 2 pairs of hydrophones, it is possible to determine the position of the source in each moment and thus, to track it.

Moreover, the distance between consecutive maxima in time differences allows us to evaluate the frequency of the dominating component in spectrum of the signal. In this case the distance between maxima equals of about 0.004 s which corresponds to the frequency of 250 Hz.

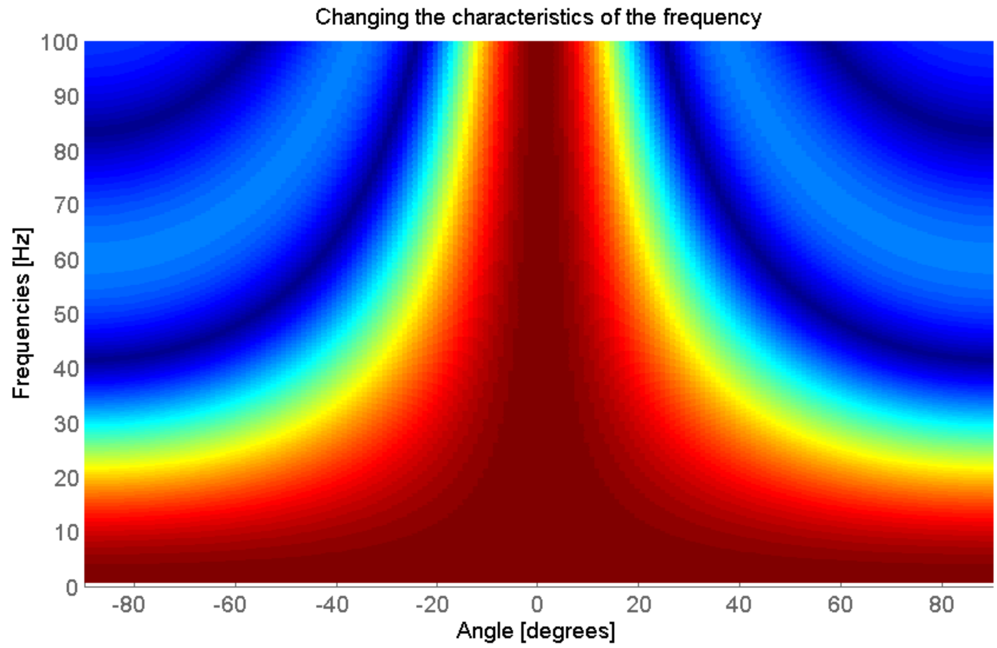


Fig. 16. The width of the main lobe of the beam pattern of linear antenna of 6 hydrophones distant by 6 meters as a function of frequency.

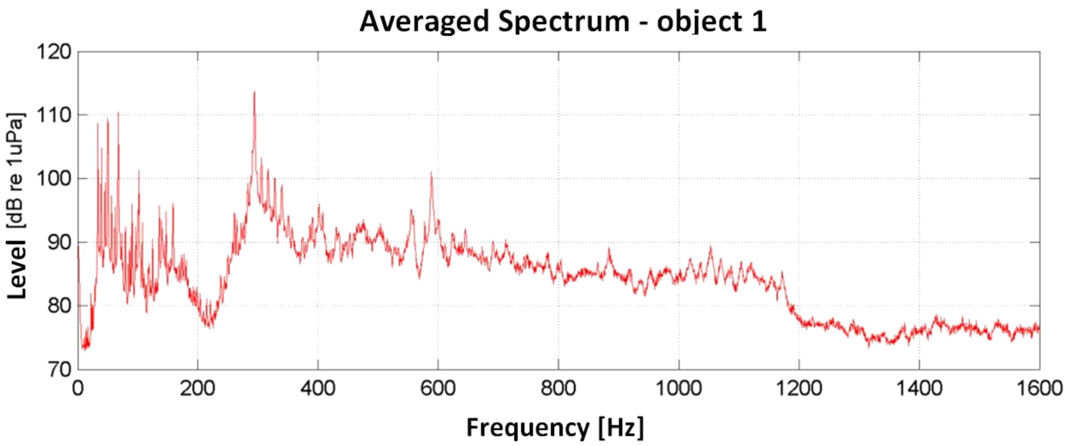
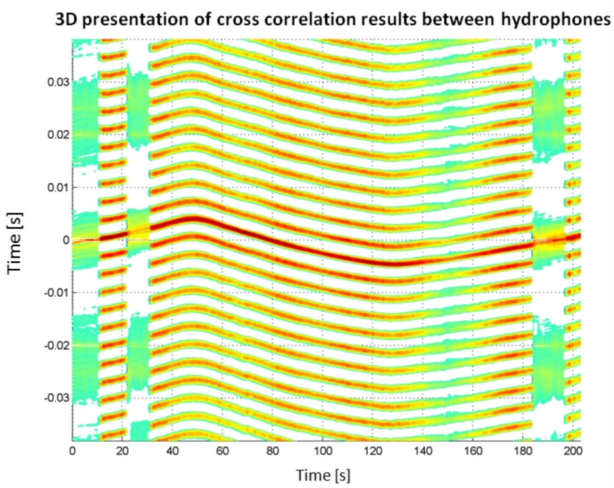


Fig. 17. The spectrogram of investigated object.



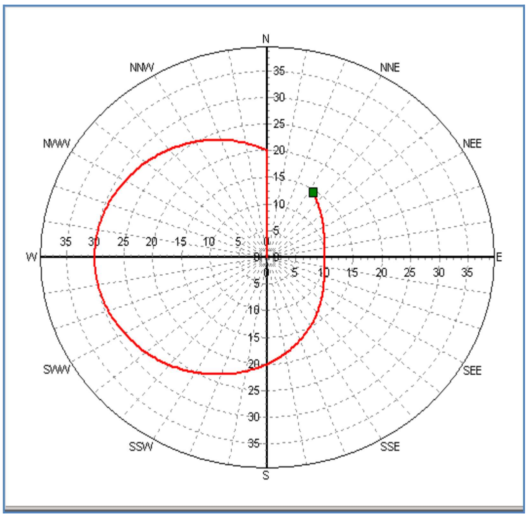


Fig. 18. Using cross correlation function of signals received by 2 hydrophones for tracking the object.

6. Final remarks

In the past decades huge progress in the research of underwater space of seas and oceans has been observed. Intensive exploration of the sea areas and its usage in a broader range is the reason.

In turn, the specification of the acoustical waves propagation in the sea water and the differences in the comparison to the frequently sought analogies to electromagnetic waves in the air, cause that various systems of underwater observation are being developed. The user has an access to a wide range of devices which differ not only in principles, range, or precision mapping but also in terms of forms of imaging the observations results.

For today, there is no universal system that would deliver all needed information about the sea environment. Learning it requires the skillful use of multiple compatible devices, often very complex ones, and a careful analysis of the data obtained. Dynamic development of electronics, IT systems and signal processing methods provides the basis to a statement that better images showing more and more details of underwater space will be possible to receive.

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