Application of Side-Scan Sonar and Multibeam Echosounder for the Investigation of Underwater Cultural Heritage – A Case Study of a Wreck in the Baltic Sea

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Abstract

As the technology of hydroacoustic sensors advances, there is a growing trend in the use of generated sonar images and point clouds in the analysis of the seabed and objects of anthropogenic origin in water bodies. In the context of cognitive and practical dimensions, obtaining data on sunken ships is of particular importance. Based on the data obtained from hydroacoustic sensors, it is possible to extract their geometric features. As a result, it is possible to develop digital repositories of wrecks, based on sonar and bathymetric data, among others, which in the future may enable the construction of integrated knowledge bases on underwater heritage. The purpose of the work was to extract the geometric features of the wreck of the Zawiszaczek located in the Puck Bay of the Baltic Sea. As part of the work, bathymetric measurements were planned, side-scan sonar and multibeam echosounder data were collected. Based on the acquired data, the geometric features of the wreck were extracted. The differences in the wreck's dimensions, as determined by sonar images obtained from different routes, did not exceed 0.25 m.

1. Introduction

The Baltic Sea, due to its historical and commercial aspects, is a unique underwater repository of shipwrecks that are an important evidence and documentation of past eras. Acquiring and interpreting data on underwater anthropogenic objects, such as shipwrecks (especially those from World War II), involves both cognitive and practical dimensions. These dimensions refer to the process of acquiring and popularising knowledge about history and technology (cognitive dimension) and specific methods and sensors for obtaining hydrographic data for the protection of cultural heritage objects (practical dimension). In the context of the cognitive aspect, wrecks are an invaluable part of underwater cultural heritage, providing knowledge about past armed conflicts and trade routes (Grządziel, 2022). It is about understanding the historical, cultural, and archaeological context and assessing the condition of the object. However, the practical aspect of underwater wreck research involves obtaining two- or three-dimensional information about these objects and extracting their characteristic features. The practical dimension includes an engineering and geometric approach. Obtaining key geometric dimensions is essential for navigational safety and planned underwater work. The practical aspect can be achieved using hydroacoustic sensors such as side-scan sonar and multibeam echosounder. Side-scan sonar is one of the most effective hydroacoustic measurement devices used for searching and measuring underwater objects (Tang et al., 2025; Zhang et al., 2024; Zieja et al., 2022). By emitting acoustic beams orthogonal to the direction of movement of the measuring unit, it is possible to obtain sonograms that precisely map the morphology of the seabed and the objects on it. The result of the measurements are sonograms, which are digital images created by digitizing the signal from the sonar system transducer. The brightness values of all points on the sonogram are proportional to the intensity of the signal reflected from the underwater object (rock, tire, wreck) or the bottom of the water reservoir. In the case of side-scan sonar data acquisition, the resulting images consist of a series of lines orthogonal to the direction of movement of the transducer, which is towed behind the stern of the measuring vessel (Chorzewska, 2013).

The main purpose of bathymetric measurements is to obtain reliable information about objects located on the bottom of the water body and their basic geometric features, such as width, length, and height above the bottom (Bodus-Olkowska, 2018). To register underwater objects in the form of three-dimensional data, a single- or multi-beam echo sounder (MBES) can be used. MBES are capable of achieving full seafloor coverage, object detection, and provide more depth information than a single-beam echo sounder (UK Hydrographic Office, 2020). All hydroacoustic methods of sea bottom recognition assume that the received echo signal contains and reproducible information about the type of bottom on which the signal was scattered (Bikonis, n.d.). As a result of the measurements, a point cloud with information about coordinates and depth is recorded for each registered profile. The principle of operation of an echosounder is based on emitting a hydroacoustic wave, recording the time of the wave's impulse, and calculating the depth from the transducer to the bottom or an object on the bottom of the body of water based on this data. The acoustic wave emitted by the transducer is subject to processes such as reflection, refraction, interference, and attenuation. The attenuation of the hydroacoustic wave is influenced by changes in temperature, salinity, pressure, and water movement. Sound waves with higher frequencies are more susceptible to attenuation. Signal dispersion is mainly associated with the presence of various objects in the water, such as vegetation, air bubbles, the type of bottom, and fish schools. The primary sources of acoustic signal interference are other moving units (screw work), waves, water conditions, air bubbles in the water, and living organisms.

With the growing technological development of sensors related to hydroacoustic seabed recognition, there is a noticeable trend of using data obtained by these sensors in automation of detection, extraction, and classification of objects of anthropogenic origin. A particularly important group of

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objects in historical terms are objects that are part of underwater cultural heritage, such as shipwrecks. Existing research related to the detection and classification of underwater objects based on SSS data concerns mines (Hożyń, 2021), generally artificial and natural objects (Kim and Yu, 2017), tires, individual stones, planks, broken moorings, and beams (Wąż et al., 2013) wrecks (Huang et al., 2022; Sheppard et al., 2025), while MBES data also concern wrecks based on backscatter (Masetti and Calder, 2012), subsea pipelines and cables (Adetunji et al., 2026). The work (Brissette and Clarke, 1999) presents the possibilities of identifying objects based on data obtained from side-scan sonar and MBES. The authors (Brissette and Clarke, 1999) concluded that sonar images complement point clouds from the echosounder, allowing for the development of comprehensive repositories of underwater objects.

Existing work indicates the need to develop methods for the automatic selection of unique and significant features of objects located at the bottom of a water reservoir. Therefore, the aim of the work was to extract geometric features of an underwater wreck located in Puck Bay (Poland) based on data obtained from a towed side-scan sonar and a multibeam echosounder. The paper presents the methodology of data acquisition and processing from these sensors and the method of extracting geometric features using the example of the wreck of the fishing cutter "Zawiszaczek" located in the Puck Bay of the Baltic Sea. Also proposed was a method for automating the processing of sonar data. The algorithm was written in Python, although the steps for processing sonar data are generally known algorithms.

2. Study site and data description

2.1 Study site

The survey area is located in the outer Puck Bay in the Baltic Sea and the western part of Gdańsk Bay. The “Zawiszaczek” (54°40′26.3″N, 18°′05″E), a fishing cutter wreck, is located at the bottom of Puck Bay at a depth of ~10 m, as shown in Figure 1.

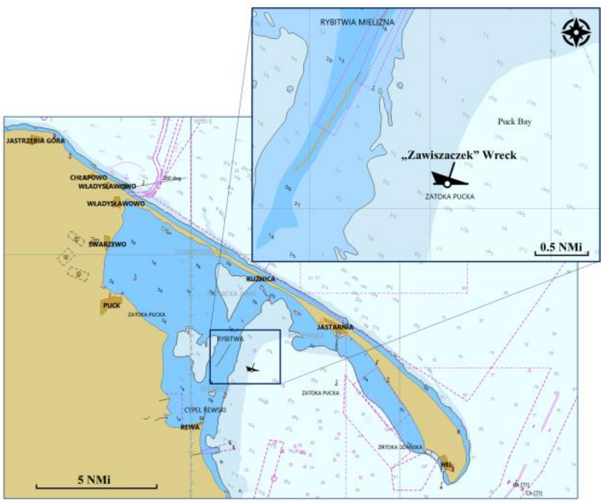

Figure 1. Location map of the wreck “Zawiszaczek”.

In regard to hydrographic surveys, water salinity is a crucial parameter that affects the formation of multibeam echo sounder receiving beams. In the case of Puck Bay, salinity ranges from 4.27 to 8.15 ‰. These values are similar to the salinity found in the surface waters of Gdańsk Bay (Klekot, 1980). Other important physico-chemical parameters of the waters of Puck Bay are presented in Table 1.

Parameter	Bay of Puck	
	Inner part	Exterior part
Temperature [°C]	9.28	7.73
Salinity [‰]	7.31	7.65
Density [g/cm^3]		
- at the surface	5.17	5.42
- over the bottom	5.35	6.62

Table 1. Physico-chemical parameters of the waters of Puck Bay (Klekot, 1980)

The parameters shown in Table 1 (temperature, salinity, water density) are influenced by various factors, such as climatic conditions, inflow of sea and land waters, and depth variation. The average depth of the outer part of Puck Bay is 20.5 m, and the maximum depth is 54.0 m. According to Bączyk (Klekot, 1980), the bottom of Puck Bay is a glacial extension of rivers. The bottom sediments of the Bay are highly diverse, with an average depth of 3 m in the inner part of the Bay. It is formed by sands of various grain sizes, silts, clays, and organic matter. A characteristic part of the Bay of Puck is the Rybitwia Shoal, a sandy embankment separating the inner part of the bay from the outer part.

2.2 Data acquisition

As part of hydrographic surveys, sonar images were acquired from a side-scan sonar (SSS) EdgeTech 4125i and point clouds from a multibeam echo sounder (MBES) Norbit Winghead i77 and an SVP profiler - AML Oceanographic. The rule for obtaining data from SSS and MBES is presented in Figures 2a (SSS) and 2b (MBES), respectively.

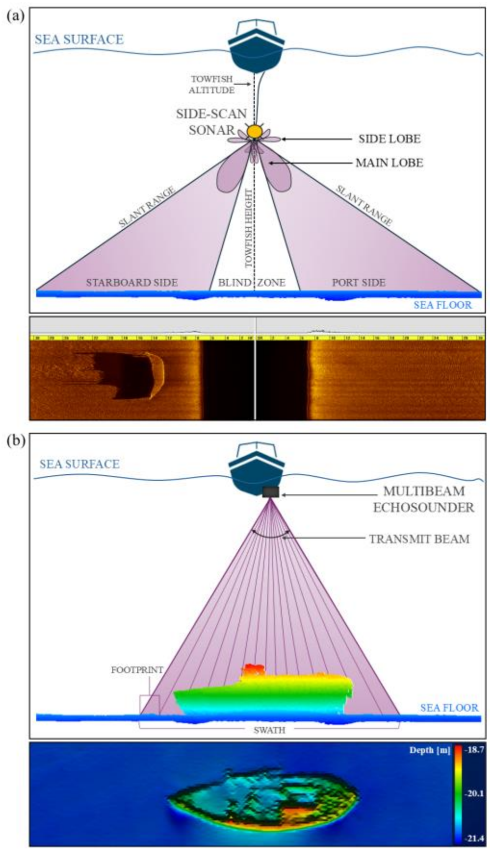

Figure 2. Flowchart for obtaining data from MBES and SSS.

Side-scan sonar data: Side scan sonar data: Data was acquired from six paths around the wreck at an average speed not exceeding 3 knots. The aim was to record the shape of the wreck from different angles on each side. Sonograms were acquired simultaneously at two frequencies: high frequency (1600 kHz) and low frequency (600 kHz). The sonar data was acquired using Discover 4125-D software. The data acquisition range was 35 m with the sonar height above the bottom at 7 m. Detailed specifications containing selected sonar parameters and measurements are presented in Table 2.

Parameter	Value
Frequency	600/1600 kHz
Survey Range	35 m
Average survey speed	3 knots
Towfish Altitude	7 m
Max range	200 m
Sensors	Heading, Pitch, Roll, Pressure (Depth)
Resolution across track	1.5 cm (600 kHz), 0.6 cm (1600 kHz)
Horizontal Beam Width	0.33° (600 kHz), 0.20° (1600 kHz)
Vertical Beam Width	50°

Table 2. Technical Specification of the side-scan sonar EdgeTech 4125i.

Multibeam echo sounder data: Data was acquired at a frequency of 550 kHz using Hypack software. The transmit beam width of the transducer was: 140°. Distances between measurement profiles ranged from 5 m to 20 m. Detailed specifications containing selected sonar parameters and measurements are presented in Table 3.

Parameter	Value
Frequency	550 kHz
Resolution (across x along)	0.4° x 0.7°
Depth range	0.2 – 400 m
Ping rate	up to 60Hz
Number of beams	1024 EA & ED
Heading Accuracy	0.02°
Pitch/Roll Accuracy	0.01°
Swath coverage	5-210°

Table 3. Technical Specification of the multibeam echosounder Norbit Winghead i-77.

3. Methods and overall workflow

The methodology proposed in this paper presents the process of extracting geometric features of anthropogenic underwater objects from data obtained using a towed side-scan sonar and a multibeam echo sounder. The presented methodology consists of a few stages. The first one is the preliminary processing of the acquired data, the stages of which are different depending on the type of data (subsections 3.1 and 3.2). Based on the processed measurement data, the geometric features of underwater anthropogenic objects were determined (subsection 3.3). A diagram of the processing of data obtained from sonar and multibeam echo sounder is shown in Figure 3.

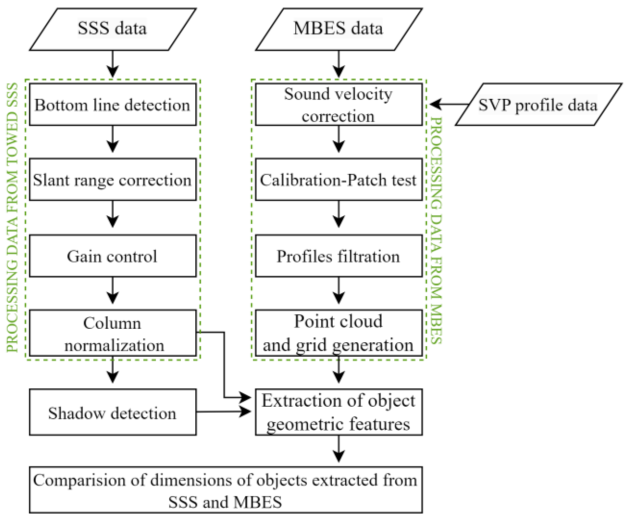

Figure 3. Flowchart of sonar and echosounder data processing.

The values obtained for these objects were determined on the basis of data acquired from both the towed side-scan sonar and the multibeam echo sounder. The dimensions obtained for the object were compared with each other and were summarized in table in the chapter Results and discussion.

3.1 Data processing from SSS

The sonar data was processed using Hypack and Python software. The first stage of processing raw sonar data (*.xtf) is first bottom line detection, which determines the height of the sonar above the bottom - h_f. This line was determined based on the automatic determination of the T threshold value based on the mean (μ) and standard deviation (σ): sigma threshold → adaptive threshold based on signal statistics. Due to interference (local noise occurring in sonar data), smoothing filtration was applied to the detected line (smooth). A part of the pseudocode for the proposed method of partial sonar data processing is shown in Figure 4.

```
# Input: raw sonar data (*.xtf file)
# Output: corrected – slant-range-corrected amplitude image

# Bottom detection
search_range←bottom_search_range[side_name]
bottom_bins←detect_bottom_first_return(amp,med_filter_size=median_filter_size,
threshold_method="sigma",σ=2.5,search_range=search_range,smooth_line=True,
smooth_size=11)

# Remove nadir zone (mask nadir using detected bottom)
(ampmasked, nadir_mask) ← remove_nadir_zone(ampraw, bottom_bins,
buffer_bins=buffer_bins)

# Slant Range Correction (SRC)
ampsrc←slant_range_correction(ampmasked,bottom_bins,range_bin_size)

# Time Varying Gain (TVG)
amptvg←apply_tvg(ampsrc,range_bin_size,α=tvg_alpha,b=tvg_b)

# Column normalization (optional stripe removal)
if normalize_remove_stripes_axis0=True:
ampcolnorm←normalize_remove_stripes(amptvg,axis=0)
else: ampcolnorm←amptvg

# Visualization results
# Display intermediate images with bottom overlay:
ampraw, ampmasked, ampsrc, amptvg, ampcolnorm
```

Figure 4. Pseudo code for part of sonar data processing.

With the knowledge of the sonar height above the bottom (h_f) and the slant range (R_s), the horizontal range (R_H) can be determined. Based on the detected first bottom return line, a correction of geometric distortions of the sonar image was performed (ang. *Slant Range Correction* – SRC). This correction consists in compensating for the signal propagation time relative to the side distances from the sonar.

The following stage involves compensating for the loss of acoustic energy, which increases with distance traveled, caused by geometric spreading and absorption. In order to amplify the time-varying acoustic signal TVG (ang. *Time Variable Gain*) is used. This process aims to reduce the dynamic range of the acoustic signal. The value of acoustic signal loss (TL), caused by spherical dispersion and corrected for attenuation, is determined using formula 1.

$$TL = 20 \cdot log10(R + 1.0) + \alpha(R) + b, \quad (1)$$

where R = sonar side range [m]
α = attenuation coefficient [dB/m]
b = shift constant [dB]

The next stage of processing is column normalization. This process is based on determining the average value of each ping (each column) and then subtracting it from all values in that column. As a result, the column bands visible on the acquired sonograms are removed. The sonar image (sonogram) in the form of intensity (reflection strength) shows the bottom and all objects within the field of view of the acoustic beam. Figure 5 shows the wreck of the "Zawiszaczek" captured on sonar images from several profiles. The object was recorded simultaneously at two frequencies: 600 and 1600 kHz.

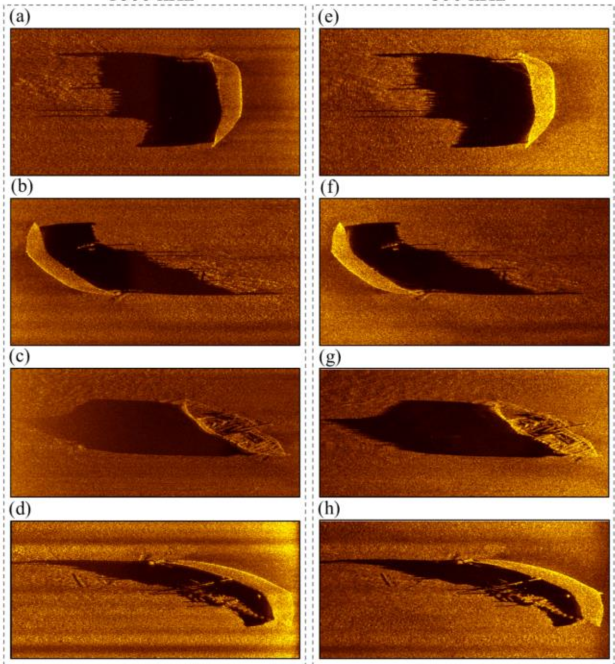

Figure 5. Wreck recorded on sonar image on several profiles.

A crucial part of the sonogram is the acoustic shadow. By the analysis of its shape, it is possible to determine the physical condition of the object, e.g. to notice a break in the hull or net. The acoustic shadow introduces a three-dimensional character to the sonar image, and its measurement makes it possible to estimate the height of an obstacle located at the bottom of the water. The above sonogram fragments (Figure 5) show both the wreck and its shadow, on the basis of which the height of the object can be estimated using formula 2 (Bodus-Olkowska, 2018).

$$H_t = \frac{h_f \cdot L_s}{R_s \cdot L_s}, \quad (2)$$

where H_t = height of the object above the bottom
h_f = sonar height
L_s = acoustic shadow length
R_s = slanted distance to the object (the point casting the longest shadow)

The sonar height (h_f) and slanted distance (R_s) to the object are known from the metadata of the recorded measurement file. In order to determine the height of a wreck or other object, the only feature that needs to be measured on the sonar image is the length of the recorded acoustic shadow (Bodus-Olkowska, 2018). Analysis of the shape of the object on the sonogram allows for the identification of its characteristic geometric features. Basic features, such as width, length, and height, may indicate the anthropogenic (wreck) or natural (rock) origin of the object. However, it is not always possible to measure these parameters on the recorded data. An example of this is shown in Figure 6, where the wreck of the "Zawiszaczek" is partially recorded in the sonar blind zone.

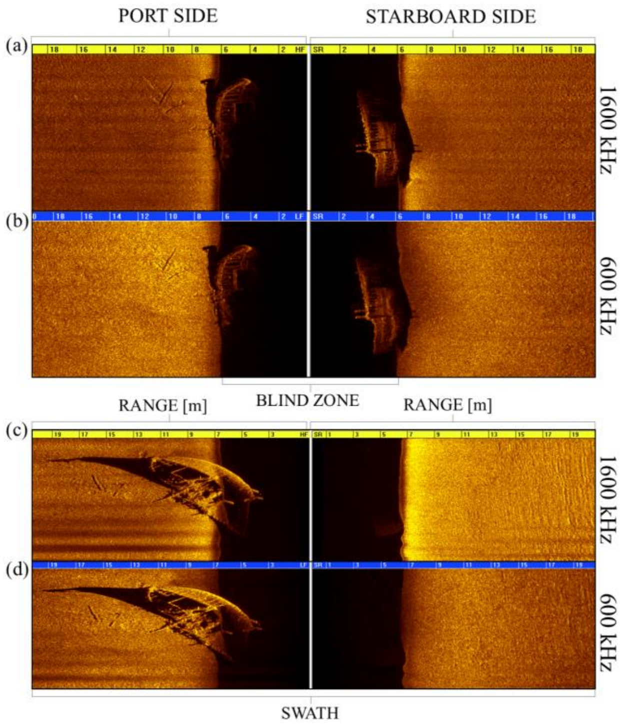

Figure 6. Wreck on sonar image captured in sonar blind zone.

Underwater objects recorded in the sonar blind zone should not be analyzed or identified, as the acoustic data obtained from this range is incomplete and underwater obstacles may be invisible in this area.

3.2 Data processing from MBES

The data was processed using Hypack software. The standard procedure for processing MBES data sets consists of the following stages: acquisition of 3D data sets, pre-processing (filtering, noise reduction), main processing (NMT generation, bathymetric map development) (Stateczny et al., 2019). The following processing steps were performed: (1) import of data from SVP, (2) calibration of data obtained from MBES, (3) filtering of MBES data on individual profiles. The receiving beams formed by the multibeam echo sounder were corrected using data obtained in the sound velocity profile in water. SVP measures the sound velocity in the vertical distribution of water. Recording this data is crucial due to errors in depth or distance measurement caused by sound wave deflection, dispersion, and attenuation due to the thermocline, changes in salinity, and water density.

The collected raw bathymetric data is subject to noise associated with the recording of points representing fish, seaweed, air bubbles in the water, and other factors affecting the signals. Next, as part of the multibeam echo sounder calibration, a patch test was performed to determine calibration corrections for: latency, pitch, roll, and yaw/heading. Latency time (Δt) determines the difference between the time of determining the position using the positioning system and the time of determining the depth using the echo sounder. The latency time value should not exceed 0.5 s. Pitch defines the angle between the motion sensor (MRU/IMU) and the echo sounder swath line in relation to the bow-stern direction of the measuring unit. Roll is the angle between the motion sensor and the echo sounder swath line, referring to the starboard-port direction of the measuring unit. The course indication (yaw/heading) determines the angle between the course indicator line and the echo sounder swath line. Echo sounder indication control (Cross Check) should be performed before and after bathymetric measurements. The method of recording data for the purpose of calibrating a multibeam echo sounder in post-processing for the calibration corrections discussed is shown in Figure 7.

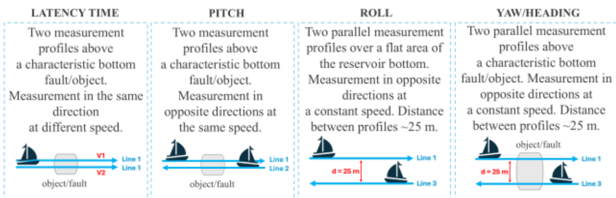

Figure 7. Method of measurement for calibrating a multibeam echo sounder.

In order to correctly record the geometry of the wreck, the measurement lines should be designed in a central position along the wreck and parallel on both sides of the object. Next, measurement lines should also be designed at right angles to the previously planned lines. Measurements planned in this way form the basis for a comprehensive representation of the geometry of the recorded wreck.

3.3 Extraction of object geometric features

In the context of obtaining information about the geometry of underwater objects, a key stage is the correct identification and extraction of relevant attributes from different types of data. This stage involves extracting new features from the input data. The study (Grządziel, 2022) compared the geometric features of the wreckage of a Szcze-2 transport aircraft from World War II, obtained from sonar and multibeam echo sounder data, with reference data. The extraction of object features should also include the analysis of the wreck's surface topography, characteristic structural features (i.e., the presence of hulls, towers, antennas), hull shape, angles of inclination, bends in the object, and damage.

4. Results and discussion

The data obtained from the SSS and MBES systems were subjected to comparative analysis in terms of the interpretability of the wreck elements and their dimensions. Selected parts of the wreck, recorded by two sensors, are shown in Fig. 8.

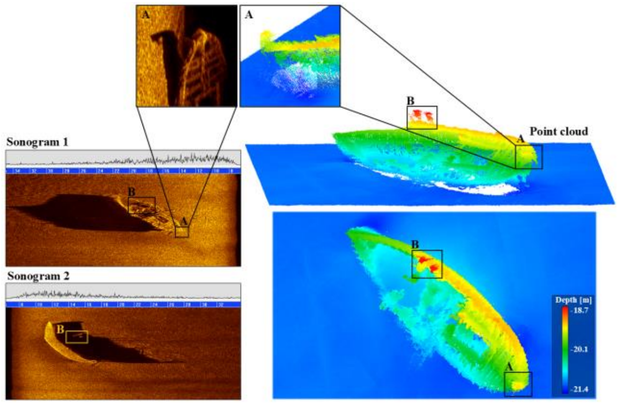

Figure 8. Comparison of the wreck based on SSS and MBES data.

Both the SSS and MBES data show elements such as the hull, the location of the superstructure (empty space), and the rudder. The object's mast was recorded in the sonar data, but not in the point cloud. The sonar data clearly shows the frames of the cutter. One sonogram even recorded the rigging. The average density of the point cloud obtained from MBES is shown in Fig. 9. The density output is the number of neighbors divided by the neighborhood surface = *N / (Pi.R2)*.

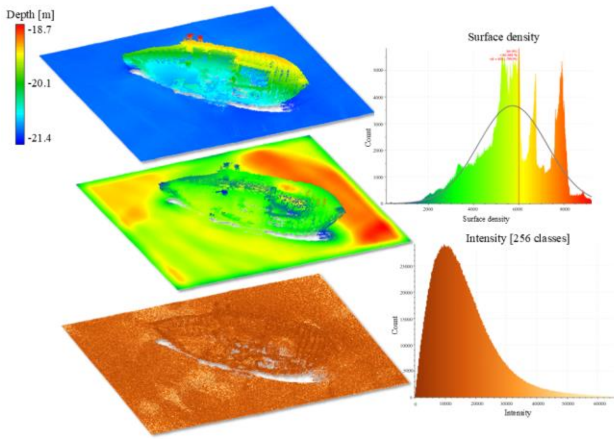

Figure 9. Density of the wreck point cloud acquired.

Based on the point clouds, profiles were generated along the object to determine the geometric features of the object (length, width, height) – fig 10.

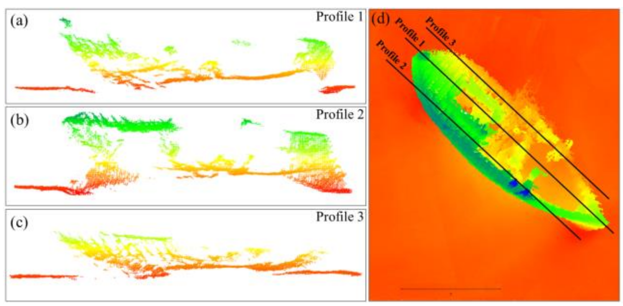

Figure 10. Profiles generated from the point cloud acquired by MBES.

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Based on data obtained from towed side-scan sonar and multibeam echosounder, the dimensions of the wreck were extracted and compiled in the following table 4.

Sensor	Product	Length [m]	Width [m]	Height [m]
MBES	point cloud	15.45	4.80	2.86
SSS	sonogram 1	14.75	4.30	3.00
	sonogram 2	14.65	4.05	2.80
	sonogram 3	14.75	4.20	2.90
	sonogram 4	14.60	4.20	2.75
	sonogram 5	14.65	4.30	2.80

Table 4. Wreck dimensions obtained from the multibeam and sonar.

The differences in the determined dimensions from SSS data do not exceed 25 cm. The differences in dimensions obtained from SSS and MBES are within the range of 0.70-0.80 m. Due to the lack of reference data on the unit's dimensions, the dimensions from the echo sounder (pc) were compared with the dimensions obtained from the sonar (s1-5), as shown in the graphs in Fig. 11.

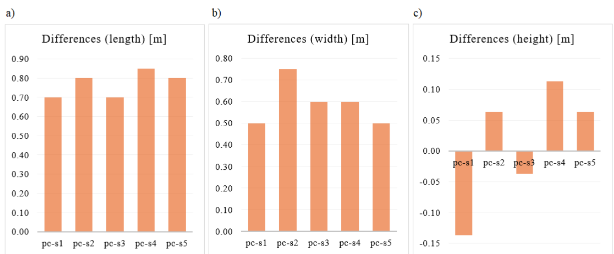

Figure 11. Differences between wreck dimensions obtained from MBES (pc) and SSS (s1-5).

The along-track and cross-track resolutions of the echo sounder were 0.38 m and 0.26 m, respectively. The sonar resolution in the along-track direction was 0.63 m (for a frequency of 600 kHz) and 0.38 m (for a frequency of 1600 kHz), and in the cross-track direction it was 0.45 m. However, the resolution of the recorded data alone is not the only parameter influencing the discrepancies between the MBES and SSS results. In addition, MBES dimensions are obtained from a point cloud, while sonar data is obtained from two-dimensional images. Data from the sonar and multibeam echo sounder clearly indicate that the wreck of the cutter is tilted. The amount of tilt of the wreck to one side is 55°.

5. Conclusion

This article presents a method of obtaining and processing sonar and bathymetric data, as well as a method of extracting the geometric features of an object, using the example of the wreck of "Zawiszaczek", located in the Puck Bay of the Baltic Sea.

Developing digital repositories of wrecks, based on sonar and bathymetric data, enables the construction of integrated knowledge bases about underwater heritage. These repositories can be a key tool not only for maritime administration and hydrographic services (e.g., in the area of maritime safety and maritime spatial management), but also for scientific communities dealing with history, archeology, and geoinformatics.

The acquisition and processing of sonograms and bathymetric data enables detailed reconstruction of the geometry of underwater objects, including shipwrecks, which forms the basis for further morphometric analyses and archaeological interpretations. The use of towed side-scan sonar to supplement MBES data for the detection of underwater objects is necessary until the detection characteristics of underwater objects are improved.

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