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Portable Side-Scan Sonar System for Acoustic Remote Sensing of Ultra-Shallow Seafloor: Design and Field Validation

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Highlights

What are the main findings?

- A compact inflatable-boat-based platform enables high-resolution side-scan sonar mapping in ultra-shallow and confined inland and coastal waters.
- Rigid pole-mounted SSS configuration allows reliable detection of small (<0.5 m^3), point, linear, and low-reflectivity seabed objects including artificial targets, fish and anthropogenic debris.

What are the implications of the main findings?

- The proposed system provides a low-cost, highly mobile alternative to traditional towed sonar setups for rapid hydrographic surveys in ports, lakes, and restricted areas, reducing dependence on large vessels and divers for routine seabed inspection.
- Under the tested survey configuration, the highest target detectability was observed at intermediate slant-range coverage (0.3–0.6 R), indicating a potential guideline for survey planning that requires further validation.

Abstract

Ultra-shallow and confined water environments are challenging to survey with conventional towed side-scan sonar (SSS) due to limited access and positioning uncertainties. This study introduces a portable, battery-powered acoustic survey system that integrates a pole-mounted dual-frequency side-scan sonar (600/1600 kHz) with RTK GNSS (Real-Time Kinematic Global Navigation Satellite System), deployable from a small inflatable boat. The system was validated in two settings: an inland lake and a marina. Field trials demonstrated reliable acquisition of high-resolution sonar imagery and effective detection of both natural and anthropogenic seabed features, including small and low-reflectivity objects. The high-frequency channel (1600 kHz) produced superior image quality and interpretability compared to the lower frequency. While there are limitations associated with fixed sonar mounting and limited altitude control, the system offers high mobility, rapid deployment, and operational safety. This approach represents a practical, cost-effective solution for high-resolution acoustic remote sensing in ultra-shallow water settings where traditional survey methods are ineffective or impractical.

Keywords: acoustic remote sensing; inland waters; side-scan sonar; portable survey system; seafloor mapping; target detection

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1. Introduction

Side-scan sonar is commonly used to collect acoustic images of the seafloor and underwater objects, which are used in many fields of science, in various underwater scenarios, both in deep and ultra-shallow waters, offshore and inland [1]. SSS can be considered in two categories: recreational (consumer grade) and professional (survey grade) [2]. As a hydroacoustic device, SSS is utilized to detect and determine the position of underwater objects using acoustic waves. Sonar measurement involves generating an acoustic wave and receiving an echo reflected back. The signal transmitted by the transducers and the received echo are directed perpendicular to the vessel's track.

Today, side-scan sonar is widely employed for marine and ocean exploration. This tool is indispensable for monitoring the ecological status of the marine environment. Acoustic images derived from side-scan sonar systems can be invaluable in detecting debris and other underwater obstructions on the seabed that pose a hazard to navigation [3]. Side-scan sonars are also used to find and locate marine debris from commercial or recreational fishing activities. Discarded, abandoned, or otherwise lost fishing gear is typical marine debris that significantly impacts benthic ecosystems [4]. The instrument plays an important role in fisheries research, dredging, and oceanographic surveys [5].

SSS technique is successfully applied for examining the condition of pipelines, cables and underwater marine structures [6,7]. It is crucial in operations of searching for and localizing of mines and mine-like objects (MLO) [8], as well as other objects of military origin. It is difficult to overestimate the importance of sonar in the detection of submerged human bodies [9–11], geological surveying [12], and searching for and identification of shipwrecks and aircraft wrecks [13–15]. Additionally, SSS is designed for bottom sediment classification [16,17] as well as seabed identification [18]. It is also worth mentioning that this survey technology has served marine archaeological research [19,20] for many years. Technology enables the exploration of underwater archaeological sites that were previously inaccessible, and its non-invasive nature allows the preservation of artifacts and landscapes, which is crucial for the conservation of historic locations.

Most side-scan systems are designed to operate in continental shelf areas at depths up to 250 m [21]. These are mounted on remotely operated vehicles (ROVs) or autonomous underwater vehicles (AUVs) [22], but the vast majority of SSSs are installed on a vessel or towed close to the seabed from the survey ship [23]. The side-scan sonar can be towed from the vessel's deck from the bow, off either side or directly from the stern. Linear SSS transducers are usually mounted in a streamlined housing dragged by a towing line behind the research vessel [24,25]. The technique adopted depends largely on the environmental conditions and the aim of the survey [26,27]. In general, towfish height above the bottom is governed by the effective range as well as seafloor topography [28]. The sonar's towing altitude is strictly defined and should be approximately between 8 and 20% of the range scale in use [29–31]. Towfish depth is controlled by varying the vessel speed or tow cable length adjustment. The proximity of the SSS to the bottom allows the use of higher frequencies, guaranteeing better resolution, but at shorter operational ranges.

When surveying in deep waters, the best method of using sonar is to tow it from the stern of the vessel using an electric winch and a special A-frame fitted with a pulley. Side-scan sonar operations in ultra-shallow waters (typically less than 30 m deep), ports, marinas, or inland reservoirs are demanding undertakings. Water bodies of this type pose the greatest challenge in terms of efficiency as well as high-resolution seabed mapping [32]. The survey team assigned to such tasks should select the most effective method for carrying out such a mission. Operations should be carefully planned and effectively executed. The difficulty of using scientific survey equipment in ultra-shallow waters and ports stems primarily from the accessibility of such waters, which are limited in both area and

depth, yet are highly trafficked. Therefore, there is a need to optimize both the technique and methodology for searching and locating underwater objects lying on the bottom of such reservoirs.

The development of various types of survey vehicles in recent decades has resulted in a vast variation of platforms and sensors capable of performing hydrographic measurements from the air, on the water surface, and underwater. These watercraft can conduct hydrographic surveys autonomously or with human intervention [33]. The standard classification of survey watercraft includes criteria such as medium, degree of autonomy, environment, size, or specialized sensors. Numerous hydrographic offices, training centers, and institutions providing hydrographic survey services are increasingly using unmanned and autonomous watercraft capable of conducting systematic surveys of the seafloor and inland reservoirs [34]. The usage of unmanned systems is now common in areas such as hydrographic and oceanographic research [35,36], search and rescue operations [37] and renewable energy [38].

High-resolution sonar surveys on shallow shelves and inland water bodies are becoming increasingly essential for environmental management. Despite the widespread use of side-scan sonar in marine, offshore, and inland environments, there remain significant challenges in conducting high-resolution surveys in ultra-shallow waters and confined reservoirs [39]. Limited accessibility, complex seabed topography, and vessel maneuverability constraints can hinder effective data acquisition, while conventional sonar deployment methods are often impractical in such settings. The present study addresses these limitations by developing a portable, small-scale survey platform capable of performing accurate and efficient sonar mapping in challenging shallow-water environments. We hypothesize that this system can achieve reliable seabed imaging and object detection comparable to larger, conventional sonar setups while offering enhanced flexibility and ease of deployment.

The paper outline is as follows. Section 2 describes study sites and the design of the inflatable boat-based survey system with components and outlines the process of data acquisition and processing. Section 3 presents the compiled sonar mosaics from both waterbodies as well as the results of the sonar performance test survey. Section 4 addresses the potential applications of the proposed survey system, its main advantages and operational restrictions. Finally, Section 5 summarizes the key findings and suggests directions for future study.

2. Materials and Methods

2.1. Study Sites

The first field tests using the side-scan sonar system were conducted in September 2025. Kosobudno Lake (Figure 1) was the test area, located in the Tuchola Forest, on the so-called Charzykowska Plain, in the village of Czernica, Pomeranian province.

Kosobudno Lake is a flow-through, ribbon lake with a surface area of approximately 58 hectares and an average depth of 5 m. The only deepest point is located in the western part of the lake, reaching a maximum depth of 8.2 m. The average length of the lake is over 1200 m and the average width is approximately 400 m. Based on the typical characteristics of postglacial lakes in the region, the bottom sediments are expected to consist predominantly of sands in shallow areas, with organic deposits and gyttja in deeper parts of the basin, and localized occurrences of fine-grained mud [40]. The lake is connected to Dybrzyk Lake by the Brda River and to Trzemeszno Lake by a narrow stream. Kosobudno features a poorly developed shoreline, and the lack of clearly defined narrowings means the reservoir forms a single body of water with a uniformly sloping bottom. An academic training center of the

Naval Academy is located on the northern shore, while the southern shore is less accessible, with only forest roads leading to it.

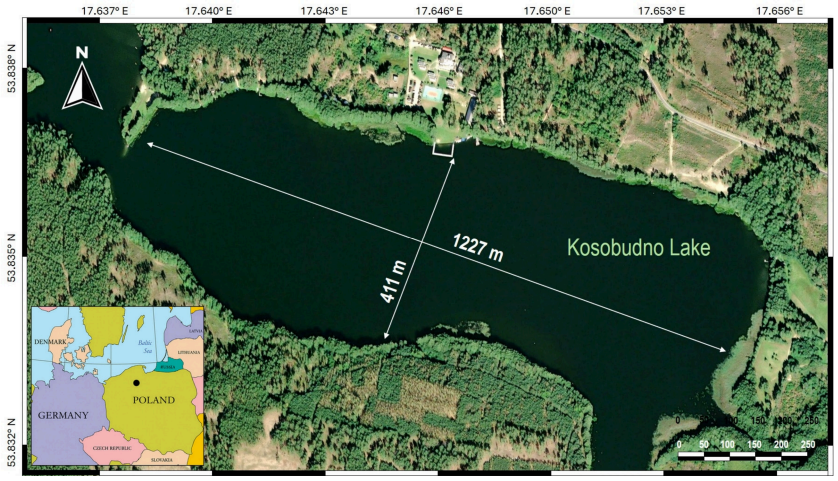


Figure 1. Kosobudno Lake study area, Tuchola Forest, Czernica, Poland.

The second test site for the side-scan sonar survey system was Marina Gdynia (yacht marina) in Gdynia, Poland (Figure 2). This test site has a trapezoidal shape, with an average length of 255 m and an average width of 129 m, and is characterized by water depths ranging from approximately 3 to 6 m. The bottom sediments of Marina Gdynia are presumed to consist predominantly of fine-grained deposits characteristic of sheltered harbor environments, including silt and sandy silt with occasional layers of fine sand. The underlying geological strata are of glacial origin and comprise primarily sand and glacial tills [41].

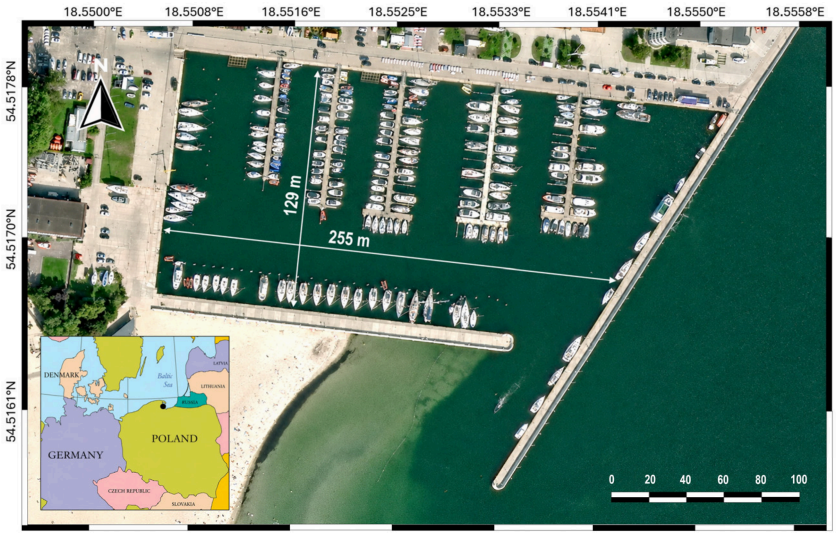


Figure 2. Marina Gdynia study area, Gdynia, Poland.

The marina offers 260 berthing places with access to water and electricity. Currently, the marina primarily provides moorings at jetties with Y-booms. The western and southern quays are equipped with dolphins. The marina is currently accessed via a short fairway bounded on the west by three red buoys and on the east by a quay head with a permanent green light.

The constraints associated with ultra-shallow water surveys differed between the sites investigated. In Kosobudno Lake, the main limitations resulted from shallow depths (typically 3–8 m), the presence of submerged vegetation and woody debris, and the need to maintain safe sonar clearance above the bottom. In contrast, Marina Gdynia posed challenges related to restricted maneuvering space, dense mooring infrastructure, floating pontoons, quay walls, and intensive vessel traffic. These factors limited survey line geometry, reduced accessibility to some areas, and increased the risk of acoustic shadow zones and incomplete sonar coverage.

2.2. Design of the Inflatable Boat-Based Survey System

2.2.1. Selection of Survey Platform

To develop a portable system for high-resolution seafloor imaging, the decision was made to use a platform up to 4 m long, which would not only be equipped with a mapping system and power supply, but would also be capable of rapid and easy transport from point A to point B. Small survey platforms, under 10 m, make it easier to work in difficult conditions like shallow or confined waters. These watercraft are adaptable and portable and may even be transported on a trailer. For this purpose, an inflatable boat for fishing was selected. The length of the pontoon is 4 m and the width is 1.9 m (Table 1). The pontoon has an aluminum floor with stringers, making the deck hard, strong, and corrosion-resistant. Furthermore, it has a non-slip surface and a porous structure that increases hardness and reduces weight. The model is equipped with an inflatable keel that provides excellent stability and balance of the pontoon, easily regulating the direction of movement over the water. To minimize the impact of the research on the environment, the boat is powered by an electric outboard motor powered by a battery. This boat can carry up to six people, and it comes with oars for propelling the boat along in calm coastal waters. The inflatable boat is one of the most affordable options. One can pick up small recreational model for a 1000–1500 EUR. The boat is transported in a folded version, and after reaching the survey area, the air chambers are inflated using an electric pump. The inflatable boat is packed in two bags that can be easily stowed in the trunk of a car. This solution makes it an extremely mobile system for rapid response and hydrographic surveys.

Table 1. Specifications of inflatable boat selected for SSS survey.

Specifications	Value
	
Overall length	400 cm
Overall width	190 cm
Number of air chambers	4 + 1
Air chamber diameter	49 cm
Weight	88.6 kg
Load capacity	700–750 kg
Number of passengers	5–6
Hull type:	inflatable
Floor	rigid aluminum
Tube material:	5-layer PVC, 1100 g/m^2

To adapt the inflatable boat for hydrographic surveying, a special stainless-steel bench was designed, mounted directly to the aluminum deck in the bow section of the platform (Figure 3). This structure served as a table for the SSS system's laptop and a mounting point for the survey pole. The entire structure constituted a rigid and stable system ensuring safety and high-quality sonar data acquisition.

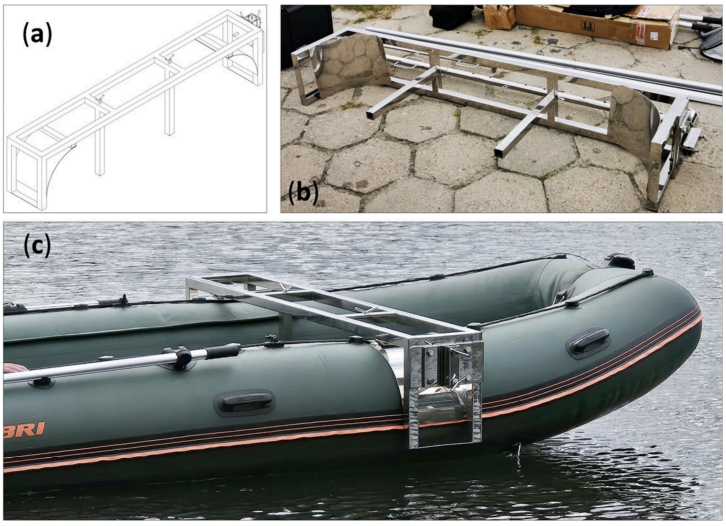


Figure 3. Deck bench as a component of a portable survey system: (**a**) construction design; (**b**) bench ready for assembly; (**c**) bench mounted to the deck of the pontoon.

2.2.2. Components of Portable Hydroacoustic Survey System

The key sensor of the survey system was the side-scan sonar, EdgeTech 4125i (EdgeTech, West Wareham, MA, USA), side-mounted using a special survey pole (Figure 4) attached to the steel deck bench on the starboard side. The pole was attached to the deck bench using a dedicated clamp-and-bolting system providing a stable mounting platform for both the side-scan sonar and GNSS antenna. Installation did not require any special tools since the connection is made with wing screws. Under normal operating conditions, the complete mounting procedure can be performed within a few minutes, while removal requires a comparable amount of time. Despite the rapid deployment and mobilization offered by the proposed configuration, immediate recovery of the sonar within a few seconds during survey operation was not possible.



Figure 4. Side-scan sonar and GNSS antenna attached to the survey pole.

EdgeTech 4125i operates simultaneously on two acoustic signal frequencies: 600 kHz and 1600 kHz. The main components include the 4125i Towfish, a portable Topside Processor, a tow cable, and a user-provided laptop with EdgeTech's Discover 4125i software installed [42]. The 4125i towfish is a lightweight and hydrodynamic sonar equipped with two transducers (port side and starboard side), a removable tail stabilizer, carrying handles, a tow arm, and a tow cable connector. The specifications of the EdgeTech 4125i side-scan sonar are presented in Table 2.

Table 2. Specifications of sonar system EdgeTech 4125i.

Specifications	Value
	
Frequencies	600/1600 kHz
Pulse-type	CHIRP
Operating range	120 m (600 kHz); 35 m (1600 kHz)
Horizontal beam width	0.33° (600 kHz); 0.20° (1600 kHz)
Vertical beam width	50°
Transducer tilt angle	Factory set at 33°, adjustable to 25°
Navigation interfaces	RS-232, NMEA0183
Depth rating	200 m
Size	114.8 cm long; 9.6 cm diameter
Weight in air	20.4 kg

The Hemisphere Vector V500 receiver (Hemisphere GNSS Inc, Scottsdale, AZ, USA), equipped with two separate antennas with 50 cm baseline, was used to position the sonar measurements, providing heading accuracy of up to 0.2° RMS. The standard V500 model tracks GPS, GLONASS, Galileo, BeiDou, and QZSS satellites and provides heading, pitch, and roll readings [43]. The V500 was mounted on the top of a survey pole, parallel to the pontoon's axis of symmetry. The GNSS receiver was interfaced with the topside laptop over an RS-232 serial port. To improve positioning quality, the V500 GNSS received RTK corrections via an NTRIP (Networked Transport of RTCM via Internet Protocol) service. ASG-EUPOS service was used to provide corrections over the Internet with access via mobile phone. The NTRIP network was developed by the German Federal Agency for Cartography and Geodesy in 2004 [44,45]. Specifications of the GNSS receiver are presented in Table 3.

Power for the entire survey system was supplied by the EcoFlow RIVER 2 Pro portable power station, whose 768 Wh lithium-ion battery met the energy needs during the survey in the most environmentally friendly way possible. The station provides fast charging in approximately 70 min. Its portable design makes it easy to carry, and the EcoFlow application allows for remote control [46]. The complete, portable side-scan sonar system together with the inflatable boat is shown in Figure 5.

2.3. Side-Scan Sonar Data Acquisition

Field tests of the newly constructed survey system were conducted in August and September 2025. To monitor and control the side-scan sonar system, Discover 4125i software developed by EdgeTech was used. Sonar data were recorded and stored in JSF format and transmitted to a Discover-enabled laptop via a wired 10/100 BaseT Ethernet connection. The sonar data were acquired simultaneously on two frequency channels, operating at 600 kHz and 1600 kHz. The side-scan sonar was rigidly mounted and positioned 1 m below the waterline. The speed at which measurements were taken averaged 2–3 knots.

Weather conditions on both Kosobudno Lake and Marina Gdynia were very favorable, with essentially no wind or waves.

Table 3. GNSS Receiver Specifications.

Specifications	Value
	
Receiver Type	Vector GNSS RTK Receiver
Signals Received	GPS, GLONASS, BeiDou, Galileo, QZSS
Channels	1059
Update Rate	10 Hz standard, 20 Hz optional
Timing (1 PPS) Accuracy	20 ns
Rate of Turn	100°/s maximum
RTK Accuracy Position	15 mm + 2 ppm
Heading Accuracy (RMS)	0.27°
Pitch/Roll (RMS)	1°
Heave (RMS)	5 cm (RTK)
Baud Rates	4800–115,200
Radio Interfaces	Bluetooth 2.0 (Class 2), Wi-Fi 2.4 GHz
Protocol	Hemisphere GNSS proprietary ROX format, RTCM v2.3, RTCM v3.2, CMR, CMR+
Data I/O Protocol	NMEA 0183, Hemisphere GNSS binary
Input Voltage	9–32 VDC
Weight	3.7 kg

Survey line planning for Kosobudno Lake and Marina Gdynia was carried out using the Discover Coverage Mapper software (EdgeTech, version 2.8.0). Survey lines were designed to be evenly spaced and arranged in parallel with predefined line spacing. In the case of Marina Gdynia, survey lines were planned parallel to the quay walls and floating pontoons. For archiving detected objects and determining their geometric characteristics, the Target Logger application—also part of the Discover software suite—was used. This application is primarily intended for cataloguing underwater objects detected by side-scan sonar [47]. All detected objects selected for further analysis were automatically saved as separate files. Before data recording began, the speed of sound in the water column was measured. For this purpose, a NORBIT SV Profiler [48] was lowered from the side of the pontoon. The sensor communicates with software loaded on a laptop via Wi-Fi. The NORBIT SV Profiler instruments are equipped with on-board GPS and GLONASS functionality.

During the field test conducted on Kosobudno Lake, an artificial object of the size 0.5 m × 0.5 m × 0.5 m was placed on the lakebed to assess the detection capabilities of the proposed survey system. The object was marked with a surface-floating buoy to indicate its position (Figure 6). The aim of this part of the experiment was to evaluate the performance capabilities of the proposed survey system solution based on a side-scan sonar, taking into account different frequencies, ranges and distances from the object placed on the bottom.

2.4. Hydroacoustic Data Processing

SonarWiz 8 (version V.8.6.0, 64-bit) software, developed by Chesapeake Technology, Inc. (New York, NY, USA), was used for the visualization and processing of side-scan sonar data. The fish position was assumed to be identical to the vessel position. No positional offsets or cable layback corrections were applied, as the side-scan sonar system was rigidly mounted on a pole with a GNSS antenna installed at the top.

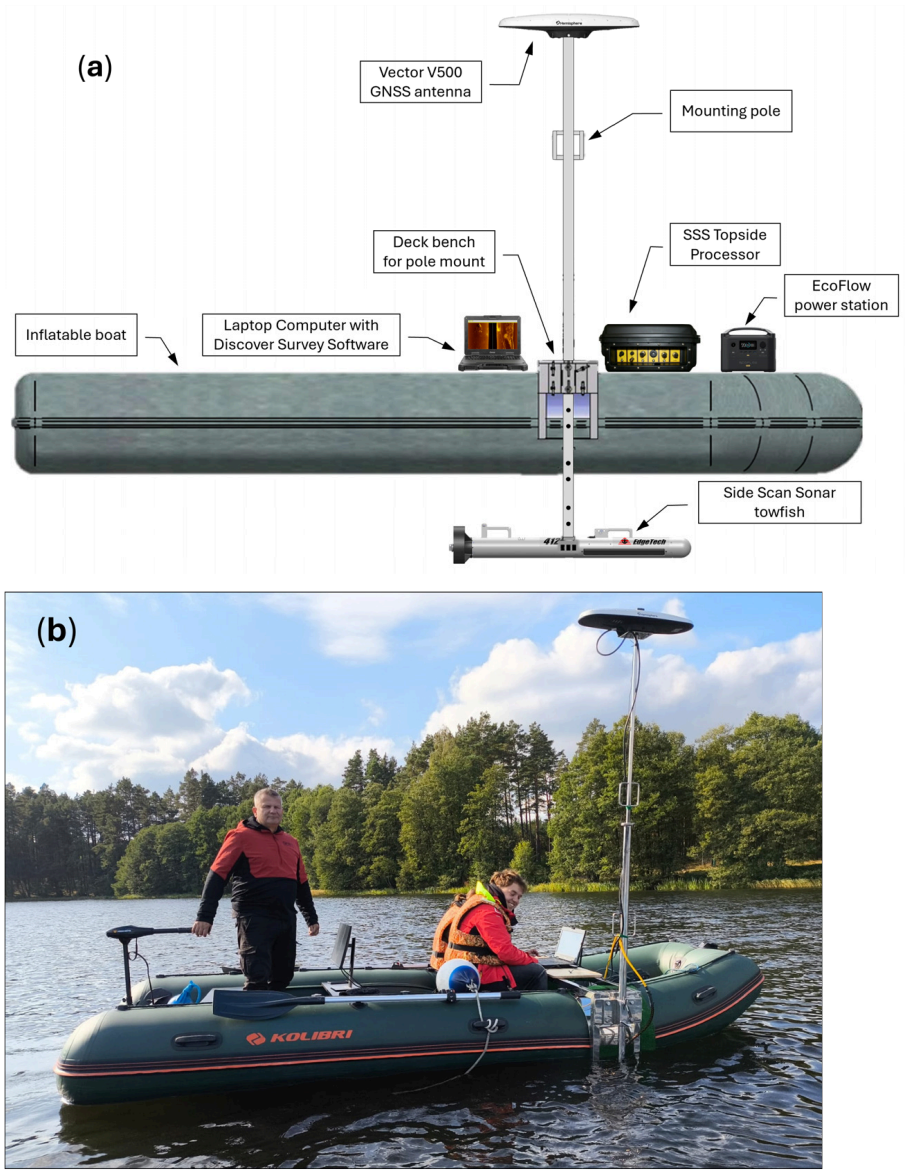


Figure 5. Design of a fully battery-powered, inflatable boat-based survey system: (**a**) system design and components; (**b**) survey boat during real measurements on the lake.

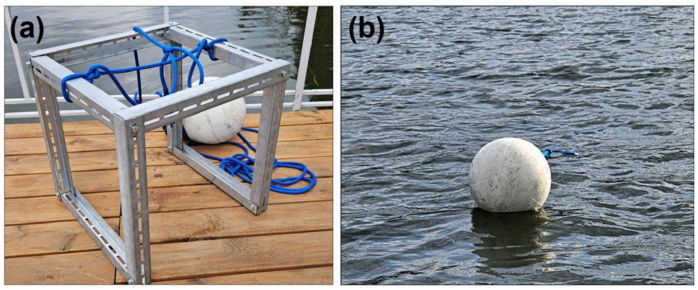


Figure 6. Components used for testing purposes: (**a**) Appearance of the test artificial object (0.5 m × 0.5 m × 0.5 m); (**b**) Buoy marking the location of the object on the lake bottom.

In the first processing step, the *Course Smoothing and Interpolation* operation was applied to individual survey lines. This procedure smoothed the raw navigation positions and interpolated the filtered navigation data onto the sonar pings, ensuring that each ping in the dataset was assigned a unique and smoothly progressing geographic position. Subsequently, all sonar data were subjected to bottom-tracking, which involved both automatic and manual detection of the seabed for each ping. In many cases, the automatic bottom-tracking algorithm did not perform satisfactorily (Figure 7). In such instances, the seabed tracking line was manually corrected. After accurate determination of the seabed line, *Slant Range Correction* (SRC) was applied to remove the water column and compensate for sonar altitude. Slant Range Correction is the simplest form of processing side-scan data [49,50]. The process of water column removal assumes the seabed is perfectly flat. The effect of SRC is to re-project the pixel from its apparent position to its actual position (in horizontal plane) by calculating the two-way travel time of the acoustic signal and return the towfish altitude. This correction ensured the proper spatial positioning of seabed features in the processed imagery.

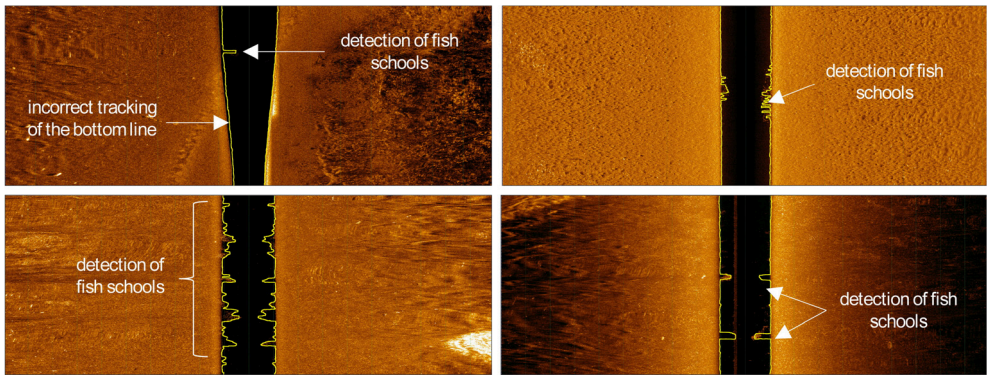


Figure 7. Examples of incorrect bottom tracking caused by schools of fish in the water column.

Raw sonar data require gain adjustment to compensate for acoustic signal attenuation resulting from sound propagation and absorption in the water column. For this purpose, gain correction was applied in SonarWiz using Empirical Gain Normalization (EGN). EGN is a function that sums and averages sonar amplitudes across all pings within a set of sonar files. The resulting EGN table is then used to characterize sonar beam behavior through empirical analysis of millions of data samples. In addition, a Nadir Filter was applied. This filter operates exclusively along the nadir stripe and is designed to reduce the intensity contrast between nadir pixel values and those immediately off-nadir. The angular width of the filtered zone can be adjusted by the operator. The final stage of data processing involved exporting the sonar data as a sonar mosaic, resulting in composite mosaic maps of the survey area.

3. Results

3.1. Survey Results on Lake Kosobudno

As a result of the survey work undertaken on Kosobudno Lake, sonar data were recorded and processed using SonarWiz software. Four sonar mosaics from four different sections of Kosobudno Lake were developed (Figure 8). The process of creating and exporting acoustic maps of the seabed involves combining individual side-scan traces from different passes into one complete image, considering geographical positions.

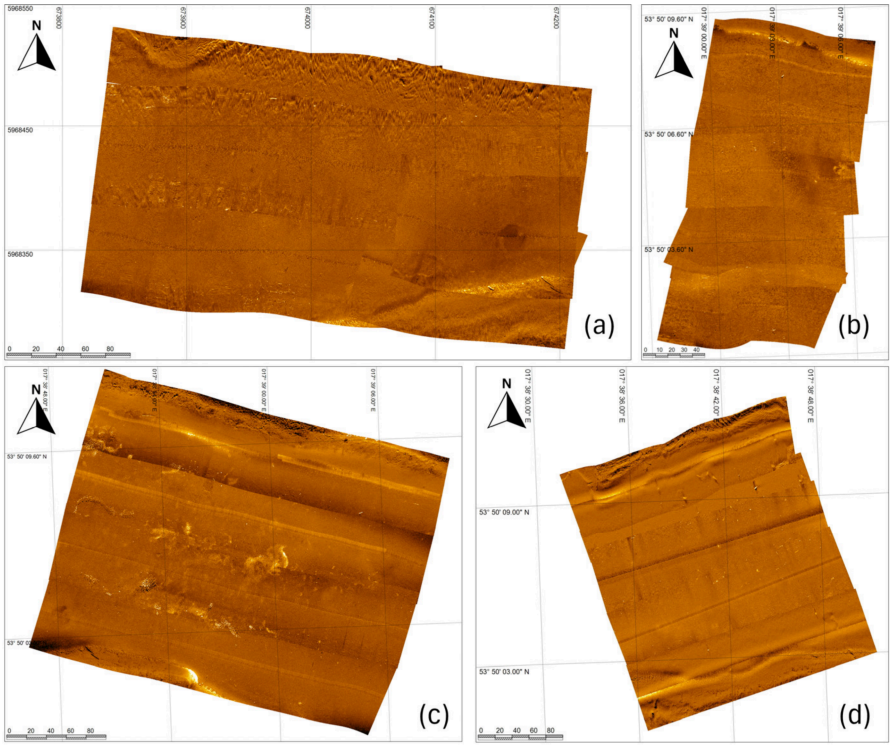


Figure 8. Side-scan sonar mosaics as the final results of the field test survey using a fully battery-powered, inflatable boat-based survey system on Kosobudno Lake: (**a**) Survey test area with dimensions 390–200 m; (**b**) Survey test area with dimensions 130–250 m; (**c**) Survey test area with dimensions 330–280 m; (**d**) Survey test area with dimensions 320–270 m.

The bottom of Kosobudno Lake is relatively flat, sandy, and devoid of interesting bottom features. Despite this, several sonograms were recorded during research conducted using a battery-powered, inflatable boat, depicting both natural and anthropogenic objects. The sonar used in the tests demonstrated good detection properties. It was capable of detecting schools of fish and even individual fish measuring several centimeters in length. Some were located right at the bottom (Figure 9b,e), while others were in the water column close to the transducer (Figure 9h). The sonar was capable of detecting and imaging narrow linear objects (Figure 9a,f,g), single car tires (Figure 9d), and anthropogenic objects such as a ladder (Figure 9c).

3.2. Survey Results at Marina Gdynia

Research at Marina Gdynia required safe maneuvering of a battery-powered, inflatable boat due to the heavy traffic of small vessels, as well as moored yachts and motorboats. A marina is a unique body of water compared to the open waters of a lake. It is bounded by quays, breakwaters, and floating jetties. Therefore, it is difficult to access every corner of the marina and cover it with sonar data. Such sensitive sites, which were not covered by sonar beams, include the corners of the quays.

Sonar data were recorded at several passes with side-scan sonar rigidly mounted to the pontoon. A bottom mosaic was created using SonarWiz software (Figure 10). The mosaic presents the bottom surface with several concrete anchors, which, using chains, stabilize the floating jetties where yachts and motorboats are moored. Also noteworthy are the clearly visible echoes from the mooring dolphins, which cast long, sharp acoustic shadows. The dual-frequency capability of the 4125i SSS model enabled direct comparison between the two simultaneously acquired frequency channels in terms of data quality and spatial resolution.

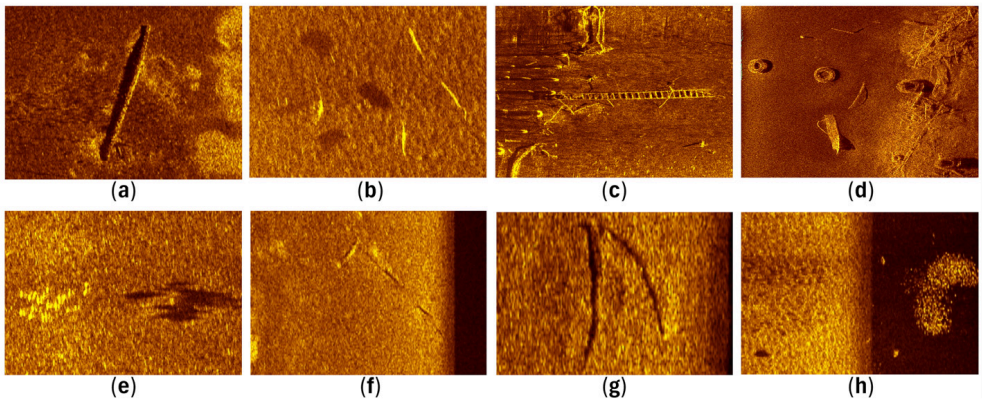


Figure 9. Underwater objects detected with side-scan sonar during the field test survey on Kosobudno Lake: (**a**) Linear object, 5.63 m long and 0.16 m high, probably a fragment of a tree stand; (**b**) School of four fish, several dozen centimeters above the bottom; (**c**) Ladder, length 6 m; (**d**) Group of point objects, car tires; (**e**) A school of fish detected at a lateral distance of 25 m, visible sharp acoustic shadows; (**f**) A barely visible underwater linear object, approximately 8.78 m long; (**g**) Linear objects, length about 2 m; (**h**) A school of small fish detected in the water column a short distance from the transducer.

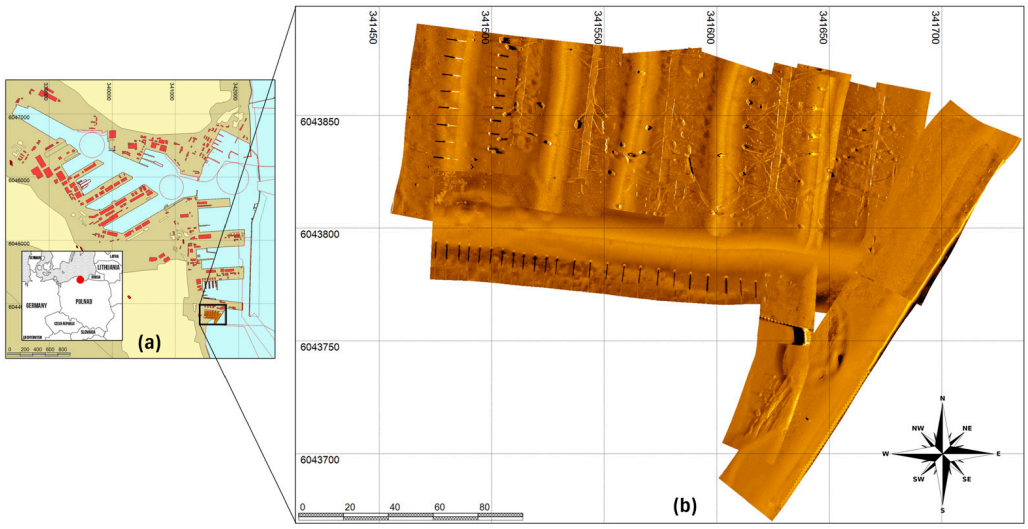


Figure 10. Side-scan sonar mosaic of the seafloor of the Marina Gdynia, Poland: (**a**) Gdynia seaport plan; (**b**) Sonar mosaic.

The sonogram in Figure 11a is characterized by a more pronounced contrast between the object and the background and has a more uniform, less grainy acoustic background. The acoustic shadow cast by the anchor and chain behind the object is continuous and well defined. The contour of the sheet pile wall is clear and sharp. Fine-grained structures in the bottom are more legible. The sonogram (Figure 11b) has more speckle noise, lower contrast between the object and the background, and a blurrier image. The sheet pile wall is darker and not as sharp as in Figure 11a. All these features make the sonogram in Figure 11a of better quality and significantly easier to interpret. Their resolution and quality are largely due to the high frequency of the acoustic signal (f_2 = 1600 kHz).

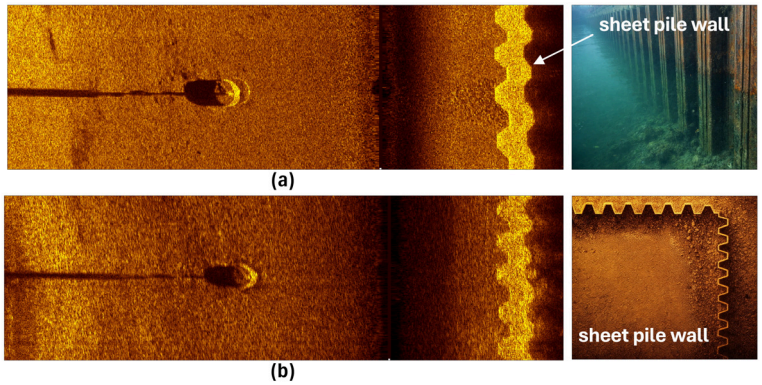


Figure 11. Sonograms with echoes from the concrete anchor of the buoy and echoes from the Larssen sheet piling: (**a**) Side-scan sonar imagery acquired with high frequency 1600 kHz; (**b**) Side-scan sonar imagery acquired with low frequency 600 kHz.

3.3. Results of the Sonar Performance Test

The sonar performance test was conducted on Kosobudno Lake. Several passes were made at different distances from the buoy to evaluate the sonar's detection capabilities. Figure 12 illustrates the test object at two different frequencies. Comparing the two images in Figure 12b with Figure 12d shows the differences. The object is clearly visible in the sonar image recorded at the higher frequency of 1600 kHz. The operator can even measure the object, which was detected at a lateral distance of 11.6 m within the sonar's operating range of R = 30 m. The sonar's height at the time of detection was F_h = 5.1 m (Fish Height).

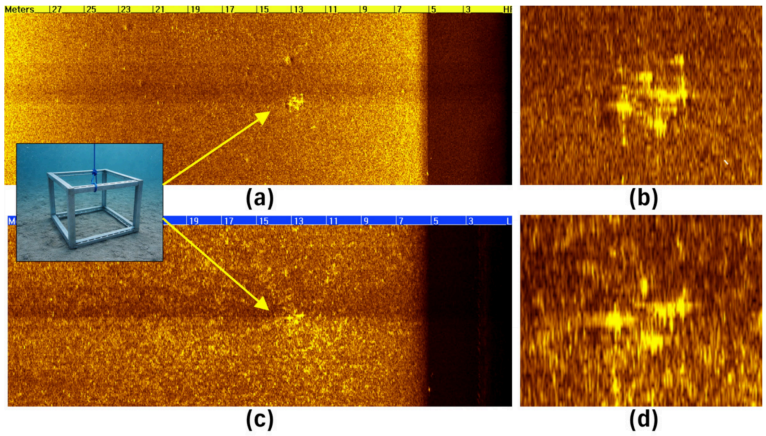


Figure 12. Detection of an artificial test object at the bottom of Kosobudno Lake at a lateral distance 11.6 m: (**a**) Part of sonogram recorded on the high-frequency channel HF = 1600 kHz; (**b**) echo of the object in magnification; (**c**) Part of sonogram recorded on the low-frequency channel LF = 600 kHz; (**d**) echo of the object in magnification.

The side-scan sonar, rigidly mounted on the starboard side of the inflatable boat, was not only capable of detecting and visualizing an object on the bottom. The sonar also detected and imaged the echo coming from a very thin line (1 cm diameter) that connected the object to a buoy on the surface (Figure 13). It is also worth emphasizing that the object constructed for testing purposes had no side walls, only aluminum profiles joined at the corners. Detecting such an object is extremely difficult due to the reduced effective signal reflection surface.

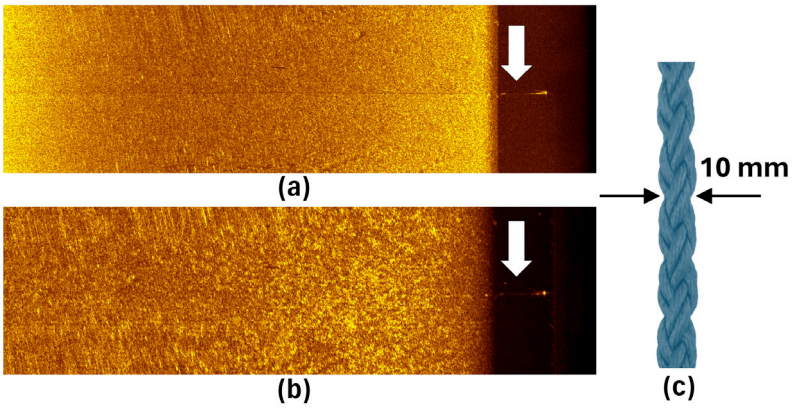


Figure 13. Detection of a thin line connecting the buoy to an artificial object on the bottom: (**a**) sonar imagery of high-frequency channel 1600 kHz; (**b**) sonar imagery of low-frequency channel 600 kHz; (**c**) sailing rope of 1 cm diameter.

During the next pass near the submerged object, at a lateral distance of R = 10.7 m, the object was detected again and recorded in the high and low frequency channels. The sonar height at the time of detection was F_H = 5.2 m (Figure 14).

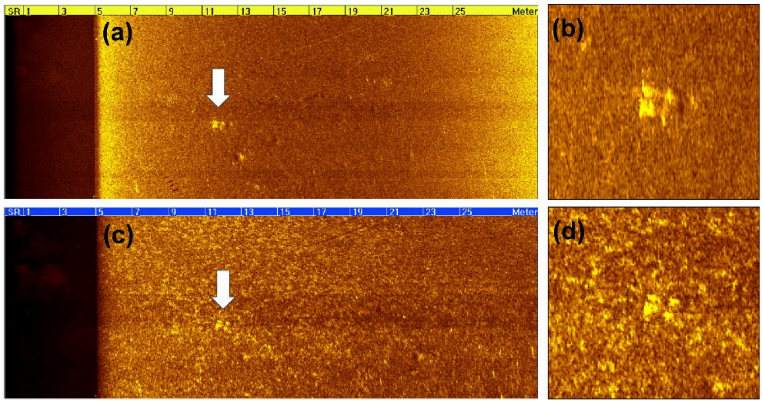


Figure 14. Detection of an artificial test object at the bottom of Kosobudno Lake at a lateral distance 10.7 m: (**a**) Part of sonogram recorded on the high-frequency channel HF = 1600 kHz; (**b**) echo of the object in magnification; (**c**) Part of sonogram recorded on the low-frequency channel LF = 600 kHz; (**d**) echo of the object in magnification.

As the lateral distance from the buoy was increased, the echo from the object was still present in the sonogram, but it was less sharp, slightly distorted, and more blurred (Figure 15b). Figure 15a shows the echo recorded at a lateral distance of R_d = 25 m. When the boat passed at distances of 5–10 m, the system either no longer detected the object on the bottom or the echo was faint, indistinct, and difficult to clearly identify on the sonar image (Figure 15c,d).

By analyzing all sonar tracks near the underwater object, one can observe differences in the quality and effectiveness of sonar echo visualization. Initial conclusions can be drawn, for example, regarding the planning of survey works using side-scan sonar. If the underwater object's position is known and the primary goal is to collect qualitative data and verify the object, the hydrographer faces the dilemma of optimally selecting the sonar operating range and distances of survey lines from the object being examined. In tests conducted on Kosobudno Lake, the clearest, and therefore qualitatively best, images of the object were obtained at distances of 0.3R–0.6R (Figure 16). The estimated values mentioned above should be verified for different sonar operating ranges and SSS heights above the bottom.

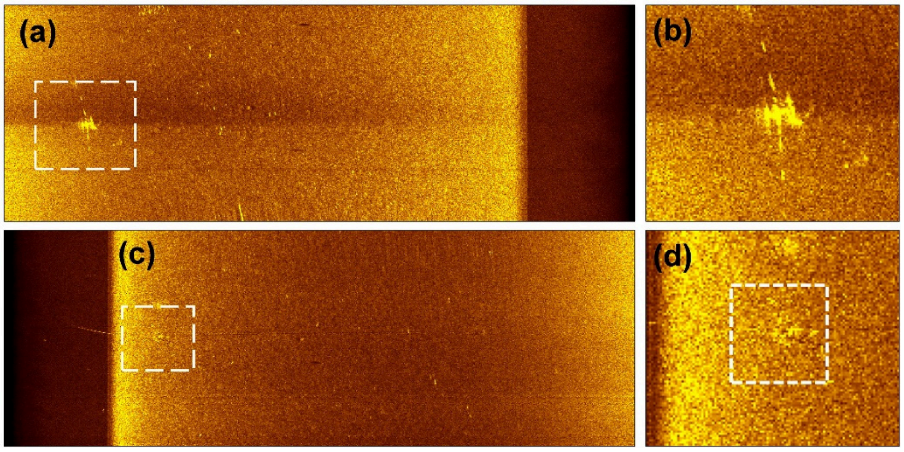


Figure 15. Detection of an artificial test object at different ranges: (**a**) Detection of an artificial test object at the distance of R_d = 25 m; (**b**) echo of the object in magnification; (**c**) Detection of an artificial test object at the distance of R_d = 5.3 m; (**d**) echo of the object in magnification.

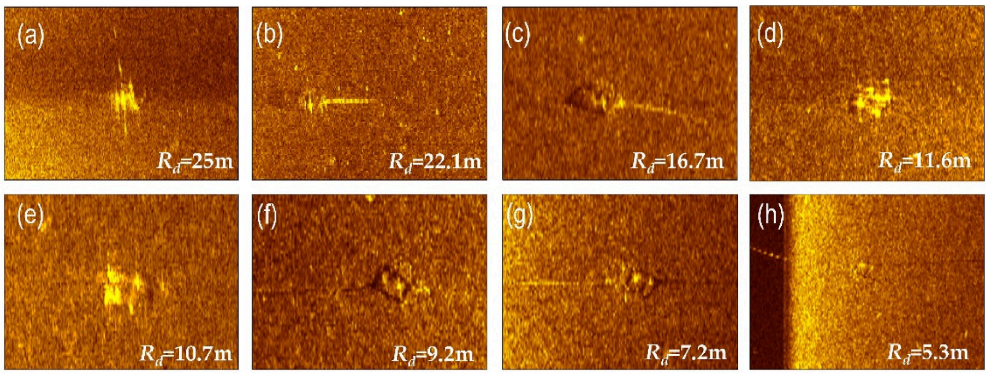


Figure 16. Sonar images of the artificial object placed on the bottom, recorded at various lateral distances from the side-scan sonar: (**a**) echo of underwater object at R_d = 25 m; (**b**) echo of underwater object at R_d = 22.1 m; (**c**) echo of underwater object at R_d = 16.7 m; (**d**) echo of underwater object at R_d = 11.2 m; (**e**) echo of underwater object at R_d = 10.7 m; (**f**) echo of underwater object at R_d = 9.2 m; (**g**) echo of underwater object at R_d = 7.2 m; (**h**) echo of underwater object at R_d = 5.3 m.

4. Discussion

The survey system, based on an inflatable boat, recorded hydroacoustic data over two water bodies: Kosobudno Lake and Marina Gdynia. The data were processed, and composite sonar images of the surveyed areas (mosaics) were ultimately generated. Experimental results demonstrate that the proposed survey system is capable of both large-scale sonar operations and the detection of point, linear and surface objects. It should be remembered, however, that survey line planning constitutes a key component that determines the efficiency and success of target search and detection [51]. Several years ago, one of the alternatives to inspecting underwater infrastructure or monitoring the bottom clearances with side-scan sonar was the use of divers. The rapid development of sonar technology allows an hydrographer to directly observe bottom objects using a small SSS mounted on highly portable craft [52–54]. In very shallow water bodies, SSS works more efficiently and safely than a diver. Underwater searches usually require well-trained and equipped divers, but they are deedless in extremely difficult conditions with limited underwater visibility.

Flemming believes [26] that in deep-water surveys, the side-scan sonar should be towed astern of the vessel. He also considers that in shallow waters, SSS can be towed from the port or starboard side, away from the propellers. However, towing a side-scan sonar from the vessel requires some caution, especially when turning or changing the survey line. The sonar can easily get caught under the vessel's hull and be damaged by the propellers. Some researchers tested the effectiveness of using a side-scan sonar but mounted on the bow of a vessel [55]. The authors obtained satisfactory results, but in the tests they used a hydrographic cutter, not a battery-powered inflatable boat. Such a solution limits the mobility of the entire survey system to some extent, due to the weight of the cutter and the possibility of its easy transport and launching in difficult-to-access inland waters.

The designed survey system, based on side-scan sonar and an inflatable boat, offers several advantages. One of them is the accuracy of positioning. The GNSS antenna and the SSS transducer are mounted on a common vertical axis, reducing potential geometric offsets in the system configuration and simplifying operational procedures related to cable deployment. The survey system is exceptionally simple to mobilize and operate. There is no need for a 300–400 m cable, winch, or A-frame. This system architecture allows for relatively quick operational readiness. Another important feature is the safety of work in shallow water areas. The pole-mounted SSS system can reduce the likelihood of the sonar contacting or becoming entangled with the bottom during normal survey operations, particularly in shallow-water environments. It also facilitates maneuvering and navigating the water among numerous vessels and between quays, piers, and other port structures.

The survey results confirmed the validity and effectiveness of using a proposed boom-mounted side-scan sonar for shallow and ultra-shallow waters, enclosed and sheltered areas, harbors, and coastal areas. This configuration is crucial in ports where underwater infrastructure inspections and seabed clearance verification are performed. However, fixed setup of side-scan sonar is associated with some drawbacks. The disadvantage of rigidly mounted sonar systems is undoubtedly poorer image quality, primarily due to the sonar's greater height above the bottom, shorter acoustic shadows, and a wider water column zone beneath the sonar (nadir zone). These factors can ultimately lead to reduced target detection and lower image resolution. The rigid mount is susceptible to longitudinal, lateral, and heave fluctuations, which are sources of various image artifacts. Fixed setups also result in a lack of operator control over the sonar's height above the bottom and the inability to achieve optimal signal geometry (10% of set range). Unfortunately, during test surveys on the Kosobudno Lake where the depth was around 5–8 m, obtaining the optimal sonar height above the bottom was sometimes impossible. As navigational depth increases and the sonar's distance from the bottom increases, detection resolution decreases, which restricts the capability of small-scale feature detection. Future studies should incorporate controlled targets and repeated observations to enable quantitative evaluation using metrics such as probability of detection, false alarm rate, and signal-to-noise ratio.

While an inflatable boat is a great choice for all types of hydrographic surveys on ultra-shallow reservoirs, it does have a few disadvantages that should be considered. These boats do not have a lot of deck space. Some models may have limited seating. Once you have mounted the survey equipment, laptops, power banks, and outboard motor, there is little space left. It is designed for short-term surveys. It does not have any overnight accommodation, unlike cabin yachts and cabin boats. The development of the proposed system required balancing portability, ease of deployment, positioning accuracy, and power autonomy. Particular attention was given to the integration of the side-scan sonar and RTK GNSS sensors and to ensuring reliable operation from a small inflatable survey platform under shallow-water conditions.

Inflatable boats are available in a wide range of lengths and widths. Hundreds of models are offered to meet the needs of every hydrographer and surveyor. This wide range and availability allow for the development of many different concepts for fast, portable hydrographic survey platforms. Water areas such as port basins or marinas, constructed with quays and floating piers, pose a challenge for sonar surveys. Corners where quays meet are a critical point in the survey area. Such areas should be additionally examined using other sonar techniques, such as stationary scanning sonar lowered to the bottom.

5. Conclusions

The study demonstrated that a fully battery-powered, inflatable boat-based side-scan sonar system constitutes an effective, flexible, and environmentally friendly solution for hydroacoustic surveys in ultra-shallow and confined water environments. Field experiments conducted on Kosobudno Lake and in Marina Gdynia confirmed that the proposed platform enables reliable acquisition of high-resolution sonar data, allowing for the detection and interpretation of both natural and anthropogenic seabed features, including small and low-reflectivity objects. Although the rigid mounting of the sonar limited the ability to maintain the optimal 10% altitude-to-range ratio and introduced certain constraints related to image quality and resolution, the system still achieved satisfactory performance, particularly at higher operating frequencies. The results highlight a trade-off between operational simplicity, mobility, and data quality, indicating that such systems are especially well suited for rapid-response surveys, environmental monitoring, and inspections in areas inaccessible to larger vessels or traditional towed configurations. Future research should focus on optimizing sensor mounting geometry, improving motion compensation, and validating performance across a wider range of depths and environmental conditions to further enhance the applicability and accuracy of portable hydrographic survey systems. The observed optimum target detectability within the 0.3–0.6R interval should be considered specific to the tested configuration and requires further validation under different sonar altitudes and operating ranges, including investigations involving targets with varying dimensions, geometries, and material properties. Although the present study focused on evaluating the operational capabilities of the proposed survey system, future work should also include sediment sampling and substrate classification to investigate the relationship between bottom type and acoustic image characteristics.

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Abbreviations

The following abbreviations are used in this manuscript:

SSS	Side-Scan Sonar
RTK	Real-Time Kinematic
GNSS	Global Navigation Satellite System
MLO	Mine-Like Object

ROV	Remotely Operated Vehicle
AUV	Autonomous Underwater Vehicle
CHIRP	Compressed High Intensity Radar Pulse
GPS	Global Positioning System
GLONASS	Global Orbiting Navigational Satellite System
QZSS	Quasi-Zenith Satellite System
ASG	Aktywna Sieć Geodezyjna
EUPOS	European Position Determination System
NTRIP	Network Transport of RTCM via Internet Protocol
RTCM	Radio Technical Commission for Maritime Services
NMEA	National Marine Electronics Association
JSF	Java Sonar Format
SV	Sound Velocity
SRC	Slant Range Correction
EGN	Empirical Gain Normalization
LF	Low Frequency
HF	High Frequency

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