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Methodology for Performing Territorial Sea Baseline Measurements in Selected Waterbodies of Poland

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Abstract: Baselines are used to establish the maritime boundaries of a coastal state which include the territorial sea, contiguous zone, exclusive economic zone and continental shelf; thus, they are instrumental in implementing state maritime policy. For Poland, as well as in other coastal states, baseline determination can be considered from both a legal and measurement-related point of view. This paper discusses an effective and optimal method of performing bathymetric measurements to enable territorial sea baseline determination in selected waterbodies of Poland. It presents a method for planning a hydrographic survey using both manned and unmanned vessels and presents oceanographic parameters that should be determined before and during hydrographic measurements, as well as a method of choosing the measuring equipment used in bathymetric measurements in ultra-shallow waters. The results of our analyses showed that using an unmanned vessel, on which a multi-GNSS receiver and a miniature MBES or SBES can be installed, is currently the optimum and the most effective method for determining the territorial sea baseline.

Keywords: territorial sea baseline (TSB); unmanned surface vessel (USV); hydrographic measurements; coastal waters

1. Introduction

According to international law, determination of the maritime boundary of a coastal state is referred to as delimitation. It allows for the establishment of four types of borders: territorial sea, contiguous zone, exclusive economic zone and continental shelf [1,2]. All of these types of borders are determined relative to the so-called baseline [3,4], which is an internal state border. For this reason, precise baseline determination is an important task for each state because it establishes the area of its sovereignty and jurisdiction.

The baseline is usually defined in two ways in the literature. In the first case, when the coastline is regular, the baseline is defined as “the low-water line along the coast as marked on large-scale charts officially recognized by the coastal state” [5]. In the other definition, the baseline is a straight line and it is applied: “In localities where the coastline is deeply indented and cut into, or if there is a fringe of islands along the coast in its immediate vicinity” and “Where because of the presence of a delta and other natural conditions the coastline is highly unstable” [5]. In such cases, adopting the baseline is a simple solution, that can be applied in cases where the land border is complex. For the majority of coastal states, the territorial sea is an integral part of the state, and it typically stretches along a belt with a width of 12 nautical miles (22.224 m) from the baseline [5].

Determination of the baseline is mainly considered in a legal sense, whereby coastal states regulate the issue through domestic legislation. In Poland, the issue is regulated by law [6,7], but the course of the baseline refers to documents from 1957–1995; therefore, considering the variability in the hydrological conditions, it is probable that the data used in the legal acts are outdated [8].

Another important issue is the methodology used to perform hydrographic measurements, which enables baseline determination. The baseline in Poland runs at a depth of approximately 1 m, so a special methodology is required for its measurement. The method for its measurement is not defined in the international IHO S-44 standard [9], which also means that the requirements regarding the accuracy of its measurement are not specified. Also, typical hydrographic vessels are frequently unsuitable for making measurements of this type due to their large draft [10]. For these reasons, alternative (precise and time-effective) methods for baseline determination are needed. There are two major trends in the research in this area—the use of GNSS network solutions or the use of unmanned surface vessels (USVs) [11]. Additionally, unmanned aerial vehicles (UAVs) equipped with LiDAR can be used for bathymetric measurements of ultra-shallow waterbodies. However, often this solution cannot be used due to the low water levels in the sounded area [12,13].

The aim of this study is to present a methodology for performing territorial sea baseline measurements in selected waterbodies of Poland.

2. Hydrographic Survey Planning

2.1. Regulations Regarding Planning of Hydrographic Survey

There are certain international standards which lay out detailed guidelines for planning hydrographic work. One of these is the standard issued by the International Hydrographic Organization (IHO), entitled "*S-44 IHO Standards for Hydrographic Surveys*" [9], which provides information on the distance between the main lines for four orders of survey and defines the nominal distances between check lines for a multibeam echosounder (MBES) and a single beam echo sounder (SBES).

Table 1 shows that no distance between neighbouring measurement profiles has been established for Special Order and Order 1a. However, a full seafloor search is required. This is only possible with a MBES. The maximum distances between sounding profiles are defined for the other two orders of survey (1b and 2). Therefore, it can be surmised that these two orders of survey apply to hydrographic work with the use of SBES. For Order 1b, the maximum line spacing should be equal to three times the average depth of the sounded area or 25 m (whichever number is greater), whereas for order 2, the distance is equal to four times the mean measured depth [9].

Table 1. List of selected requirements for hydrographic measurements [9].

Order	Special	1a	1b	2
Description of areas	Areas where under-keel clearance is critical	Areas shallower than 100 m where under-keel clearance is less critical but features of concern to surface shipping may exist	Areas shallower than 100 m where under-keel clearance is not considered to be an issue for the type of surface shipping expected to transit the area	Areas generally deeper than 100 m where a general description of the seafloor is considered adequate
Full seafloor search	Required	Required	Not required	Not required
Recommended maximum line spacing	Not defined as full seafloor search is required	Not defined as full seafloor search is required	3× average depth or 25 m, whichever is greater	4× average depth

The IHO S-44 standard also defines the minimum distances between control profiles, which are determined perpendicularly to the main profiles to control the measurements. The distance should not be greater than 15 times the distance between the main lines in hydrographic measurements with a SBES. On the other hand, control measurements with MBES should be conducted where coverage for the neighbouring swaths show considerable depth errors [14,15].

The majority of the other standards concerning hydrographic survey refer to the requirements laid down in the IHO S-44 standards regarding the planning of hydrographic surveys. However, there are differences in the requirements for determining the distance between sounding lines. For example, the standard issued by the American National Oceanic and Atmospheric Administration (NOAA) entitled "*NOS Hydrographic Surveys Specifications and Deliverables*" [16] provides information on the permissible distance between sounding profiles using a SBES. It should not be smaller than 3–5 m. The standard also defines the distances between neighbouring swath profiles using a MBES; however, the overlap zone between the neighbouring swaths are not determined. The only condition that has to be met in hydrographic work done with a MBES is that the seafloor must be fully covered by the measurements. Another standard, issued by the United States Army Corps of Engineers (USACE) entitled "*EM 1110-2-1003 USACE Standards for Hydrographic Surveys*" [17] determines the distance between neighbouring sounding lines with a MBES (L) as:

$$L = 2 \cdot d \cdot \tan\left(\frac{a}{2}\right) \cdot (1 - s) \tag{1}$$

where

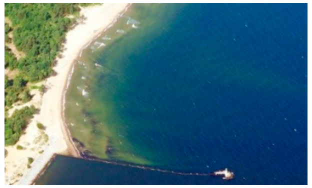
a is the angular sector of a beam of a MBES (°)
d is the depth of sounded waterbody (m)
s is the overlap zone between neighbouring swaths, which should be 20–100% (%).

None of the international standards related to hydrographic survey specify at what angle, and relative to what, the sounding lines should be designed. Information on this issue can be found in local recommendations and in books and publications on hydrography.

2.2. Planning the Hydrographic Survey to Establish the Territorial Sea Baseline

Territorial sea baseline measurements are performed in shallow coastal waters [5]. In Poland, the line is situated between several dozen and 1–2 m below the current water level, and its position depends on the day (water level fluctuations) and place along the coast (the seafloor shape varies from one waterbody to another). Therefore, several representative waterbodies were selected, to perform the baseline measurements (Table 2).

Table 2. Representative waterbodies where measurements of the territorial sea baseline were conducted. Own study based on [18].

Name of Waterbody	Features	Photograph
Waterbody No. 1: Open sea public beach in Gdynia	A typical coastline (straight line sandy section), reinforced with tetrapods and concrete wharfs. The length of the waterbody along the coastline is about 450 m.	
Waterbody No. 2: River mouth the Vistula river mouth near the National Sailing Centre in Gdańsk	A waterbody of great dynamics of hydromorphological features. It is a natural area (with no hydrotechnical structures). The length of the waterbody along the coastline is about 250 m.	
Waterbody No. 3: Exit from a large port area near the entrance to the Górki Zachodnie from Bay of Gdańsk	A waterbody with a large number of hydrotechnical structures. The length of the waterbody along the coastline is about 250 m.	

The geographic locations of the representative waterbodies (analysed above in Table 2) are re shown in Figure 1.

Figure 1. The geographic locations of the representative waterbodies.

The sounding profile arrangement differs depending on where the baseline measurements are performed. Figures 2–4 show the measurement profiles for three representative waterbodies, designed in accordance with the general principles of planning hydrographic survey. They were created using the free Google Earth Pro platform. The main sounding profiles were established perpendicularly to the coastline and it was assumed that the distances between those profiles are 5–10 m. Moreover, in order to verify the measurements, control profiles were designed perpendicularly to the direction of the main profiles while observing the rules laid down in [9]. Figure 2 shows an example of sounding plan in waterbody No. 1, adjacent to the municipal beach.

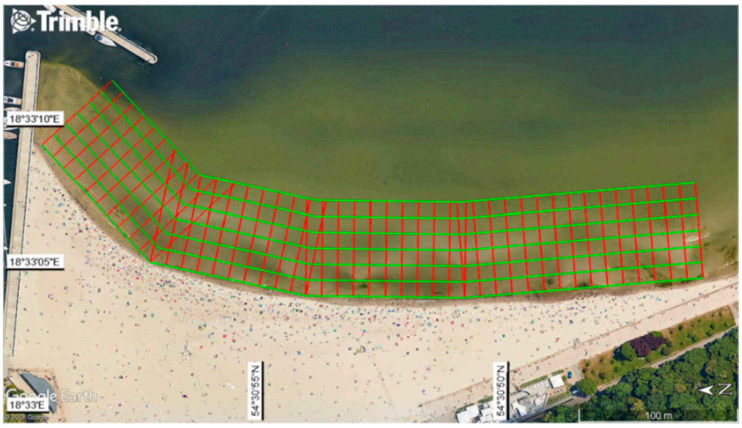


Figure 2. The system of main and control profiles in the territorial sea baseline determination for waterbody No. 1.

Figure 3. The system of main and control profiles in the territorial sea baseline determination for waterbody No. 2.

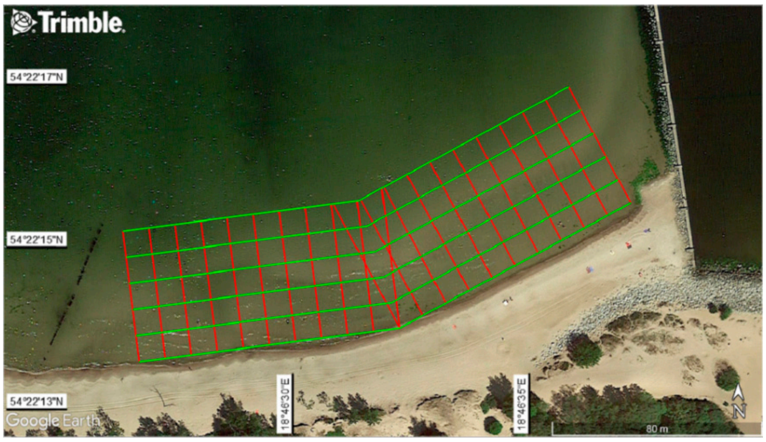


Figure 4. The system of main and control profiles in the territorial sea baseline determination for waterbody No. 3.

The systems of sounding profiles for waterbodies No. 2 and 3 (Figures 3 and 4) were planned in the same way as for waterbody No. 1, described above.

At the hydrographic survey stage, it is important to have software for planning (deploying) sounding lines and visualisation (if needed) of the position of a vessel on a map. Most programs of this type are able to design sounding profiles (directions and distances between them) based on a specific waterbody, usually on the basis of an orthophotomap from the Google Maps service (Figure 5a) [19]. Some of them also have the ability to monitor a vessel position in real time. The most popular programs used to plan navigation (inland and maritime) include HYPACK, OpenCPN, QINSy (Figure 5b) and Transas iSailor.

(**a**) (**b**)

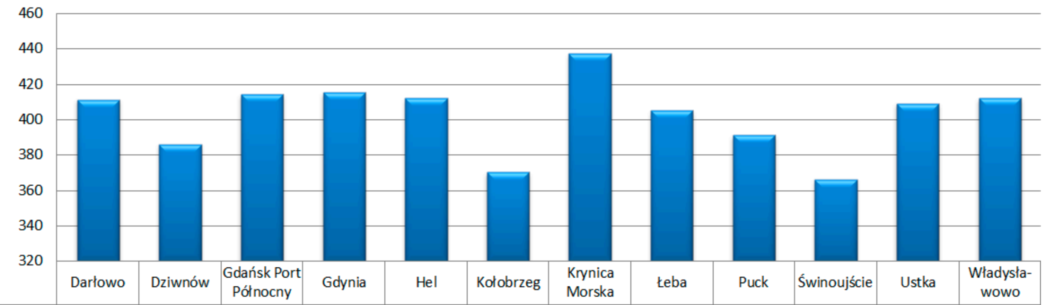
Figure 5. Applications used to plan hydrographic survey, such as AutoDron (**a**) [19] and QINSy (**b**).

3. Water Level Measurement

Considering the dynamic changes in sea water levels caused by anemobaric and hydrological factors and tidal elements, obtaining information on the current water level in the area where bathymetric measurements are performed is one of the hydrographer's most important tasks. This information allows the measured depths to be expressed relative to the reference level, referred to as chart datum. For navigation safety, the majority of national hydrographic offices and the IHO have adopted the lowest astronomical tide (LAT) as zero datum [20].

The issue of water level in Poland is managed by Maritime Branches of the Institute of Meteorology and Water Management (IMGW), which is responsible for registration, sharing and archiving information about water levels. They use gauging stations for the purpose, which are situated in marinas and ports. Each gauging station consists of a device for observing water level fluctuations (staff gauge) or a device for observing and registering measurement data (mareograph) and benchmarks, these are referenced to the geodetic height system. The staff gauge is widely used and is the simplest gauging station. A mareograph, which allows for continuous registration of water level changes, is another commonly used device. Automatic telemetric hydrological stations (ATSH) are increasingly often used to record water levels; they are fitted out with water level sensors and they are capable of data sending (GPRS or radio modem) to the IMGW databases. Owing to these functions, the results can be shared automatically in the ITC system (http://www.pogodynka.pl/). Notably, all these methods enable reading the water level with an accuracy of 1 cm, although both mareographs and staff gauges are increasingly being replaced by ATSH stations.

According to the definition in Article 5 of the UNCLOS Convention, before the determination of the territorial sea baseline is started, it is necessary to determine the lowest water level ever recorded along the coast [5]. Notably, no international legal act regulating the principles of hydrographic work specifies a method for acquiring data on the water level. However, it is possible to obtain such information from the gauging station situated nearest the site of the hydrographic measurements. Therefore, information on the lowest water levels ever recorded at gauging stations in the years 1945–2015 was acquired for this paper from the Maritime Branch of the IMGW in Gdynia (Figure 6).



	Darłowo	Dziwnów	Gdańsk Port Północny	Gdynia	Hel	Kołobrzeg	Krynica Morska	Łeba	Puck	Świnoujście	Ustka	Władysła-wowo
Lowest water level [cm]	411	386	414	415	412	370	437	405	391	366	409	412
Date of registration	14.01.2012	04.11.1979	04.11.1979	04.11.1979	04.11.1979	04.11.1979	28.11.2011	04.11.1979	07.01.1949	18.10.1967	04.11.1979	04.11.1979

Figure 6. Absolutely lowest water levels ever recorded at Polish gauging stations in the years 1945–2015.

The zero ordinate for each gauging station is referenced to the water level at Kronstadt, Russia. In Poland, it is −508 cm, except at Darłowo (−507.3 cm). With the lowest and the current water level, e.g., from the IMGW-PIB weather service (Figure 7), one can calculate the depth at which the baseline was situated at the time of measurement (d_{TSB}) from the following formula:

$$d_{TSB} = H_{CWL} - H_{LWL} \tag{2}$$

where,

H_{CWL} is the current water level in the adopted reference frame [m],
H_{LW} is the lowest water level in the adopted reference frame [m].

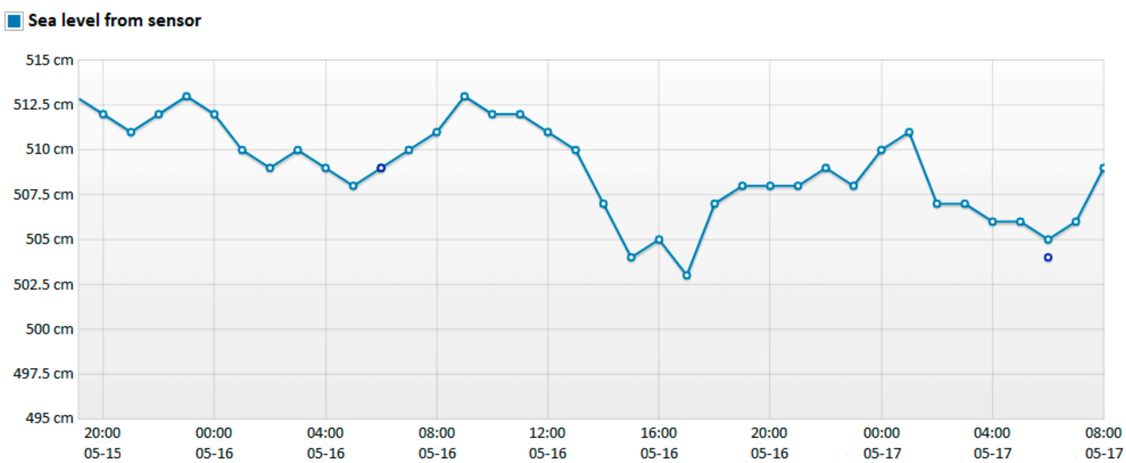


Figure 7. A diagram of sea level variability observed on a tide gauge in Gdynia according to the IMGW-PIB weather service.

However, the water levels must be reduced to a uniform reference frame valid in a given state [21]. In Poland according to the current regulations [22], water levels are referenced to the height system of Kronstadt (PL-KRON86-NH), (up to 2019) and Amsterdam (PL-EVRF2007-NH).

Based on long-term research conducted at 35 gauging stations along the Baltic Sea [23], it appears that the sea is non-tidal because the differences in water level due to the impact of the tides are small. The minimum tide was at 3.5 cm in the eastern part of the Bay of Gdańsk (Baltiysk, Russia), whereas the maximum tides were recorded at the gauging stations located in the Gulf of Finland (Gorniy Institute, Kronstadt, Russia), and amounted to approximately 18 cm. Therefore, the differences in water levels for the Baltic Sea between consecutive hours at the same gauging stations are small and amount to several centimetres (if at all). However, in order to ensure high measurement accuracy, hourly registration of water levels at the gauging stations might not be sufficient. Therefore, the current water level read from the gauging station, should be compared to the water level calculated from the Tide Tables issued annually by the British Admiralty [24]. In this way, one can determine the depth at which the baseline is situated during the measurements.

4. Other Oceanographic Measurements

Numerous long-term studies have shown that hydrophysical processes in the aquatic environment exhibit spatial and temporal fluctuations on a global scale. Therefore, both before and after each series of hydrographic measurements, one must determine precisely the inter-relationships between the phenomena and processes in the aquatic environment in their interaction with the atmosphere, land and seafloor. This issue is dealt with by an interdisciplinary science on the border between biology, geophysics, meteorology, physics, called oceanography [25]. This paper will discuss selected oceanographic parameters, without which it would be impossible to conduct hydrographic measurements. Apart from the water level, as discussed above, these parameters include the temperature of the surface and deep-water layer, salinity, hydrostatic pressure, wind wave and ocean currents.

It is not always possible to perform hydrographic measurements with an USV as scheduled. Based on previous experience, a hydrographic survey in the coastal zone using a vessel weighing about 12 kg can be performed in small waves (sea state 0–1 in the Douglas scale) and low wind (wind strength 0–1 in the Beaufort scale). Wind blowing at 10 km/h (2 on the Beaufort scale) forms small wind waves of 10–20 cm on the water surface, which can have an adverse effect on the vessel stability and on the sounding profile (with no significant heel). A short-term weather forecast shared on the Internet, e.g., http://www.pogodynka.pl/, can be used to determine the forecast weather conditions. The oceanographic parameters described above (wind wave and wind) play a key role in performing hydrographic measurements with an USV. Adverse hydrometeorological conditions make it impossible to perform such work. Therefore, short-term weather forecasts should be monitored in summer and in winter, and bathymetric measurements should be started on a waterbody when an "advantageous" weather window opens.

After an advantageous weather window is established, more oceanographic parameters must be assessed, such as temperature, pressure and salinity, which directly affect the speed of sound in water (it is the main factor affecting the accuracy of the depth measurements by a hydroacoustic device). This can be determined with an accuracy of $\Delta c = \pm 0.03$ m/s, by direct methods, such as a sound velocity profiler (SVP), which measures the actual speed of sound in water as a function of depth. There are also indirect methods, such as CTD (conductivity, temperature, depth) oceanographic sounds, which are used in measurements of ocean temperature and salinity and other physical properties of the ocean depth and surface, such as conductivity and oxygen content [26]. Subsequently, these physical parameters are used to calculate the speed of sound in water with empirical formulas developed by Wood, Wilson, Medwin, Chen and Millero, or Del Grosso. The most common is Wilson's formula, which establishes the relationship between speed of sound in water c (m/s), temperature T (°C), salinity S (‰) and pressure P (kG/cm^2). The formula has the form of a polynomial [27]:

$$c(S,T,P) = 1449.14 + \Delta c_S + \Delta c_T + \Delta c_P + \Delta c_{STP}. \tag{3}$$

The other elements of the formula represent adjustments for other non-standard conditions:

$$\Delta c_S = 1.39799 \cdot (S-35) + 1.6920 \cdot 10^{-3} \cdot (S-35)^2, \tag{4}$$

$$\Delta c_T = 4.5721 \cdot T - 4.4531 \cdot 10^{-2} \cdot T^2 - 2.6045 \cdot 10^{-4} \cdot T^3 + 7.9851 \cdot 10^{-6} \cdot T^4, \tag{5}$$

$$\Delta c_P = 1.60272 \cdot 10^{-1} \cdot P + 1.0268 \cdot 10^{-5} \cdot P^2 + 3.5216 \cdot 10^{-9} \cdot P^3 - 3.3606 \cdot 10^{-12} \cdot P^4, \tag{6}$$

$$\begin{aligned}\Delta c_{STP} = \; & (S-35)\cdot\left(-1.1244\cdot 10^{-2}\cdot T + 7.7711\cdot 10^{-7}\cdot T^2 + 7.7016\cdot 10^{-5}\cdot P + \right.\\ & \left. + 1,2943\cdot 10^{-7}\cdot P^2 + 3.1580\cdot 10^{-8}\cdot P\cdot T + 1.5790\cdot 10^{-9}\cdot P\cdot T^2\right) + \\ & + P\cdot\left(-1.8607\cdot 10^{-4}\cdot T + 7.4812\cdot 10^{-6}\cdot T^2 + 4.5283\cdot 10^{-8}\cdot T^3\right) + \\ & + P^2\cdot\left(-2.5294\cdot 10^{-7}\cdot T + 1.8563\cdot 10^{-9}\cdot T^2\right) + \\ & - P^3\cdot\left(-1.9646\cdot 10^{-10}\cdot T\right)\end{aligned} \tag{7}$$

The accuracy of the formula is estimated at ±0.3 m/s within the salinity range of $0 < S < 370‰$, temperatures $4\ °C < T < 30\ °C$ and pressures $1\ kg/cm^2 < P < 1000\ kg/cm^2$.

However, it is the authors' opinion that speed of sound in water can be determined (in the absence of velocity meters and oceanographic sounds) with oceanographic data shared in the ICT system (as long as it exists) by any institution responsible for monitoring the selected waterbody. One such service is SatBałtyk (http://satbaltyk.iopan.gda.pl), which monitors on a continuous basis and publishes information on changes in the Baltic Sea environment on its Internet website. Every six hours each day, it shares high resolution (of 1 km) and high accuracy (of the tenth part) information on the sea surface temperature, water temperature at the following depths: 0, 3, 5, 10, 20, 30 m, and sea surface salinity [28,29].

Temperature is the most variable factor and has the greatest effect on the speed of sound in water, which increases by 4.5 m/s on average when the temperature increases by 1 °C. Salinity is another factor that has a moderate effect on the speed of sound. The parameter which describes the salt content in water changes slightly, i.e., its value increases by approx. 1.3 m/s when the salinity increases by 10‰. Information about salinity (without having to use measuring equipment) with an accuracy of 1‰ can be obtained, for example, from the SatBałtyk system. The third factor, with the smallest (slight) effect on the speed of sound in water is the pressure (depth), which increases by approximately 1.6 m/s with a depth increase of 100 m. This has no practical significance in measurements performed in the coastal zone. If one assumes that the gravitational acceleration and water density are constant, then the hydrostatic pressure will depend only on the height of the liquid column. For example, a comparison of the speed of sound in water at a depth of 0 and 1 m shows a small difference of approximately 0.01 m/s [26–29].

It must be stressed that the accuracy of hydrographic measurements can be significantly affected by short-term (daily) changes in sea surface temperature. Using the information presented in [26], it can be seen that the temperature differences within a 24 h period are caused mainly by the sun warming the water surface (Figure 8). The daily speed of sound changes can reach 40 m/s in summer.

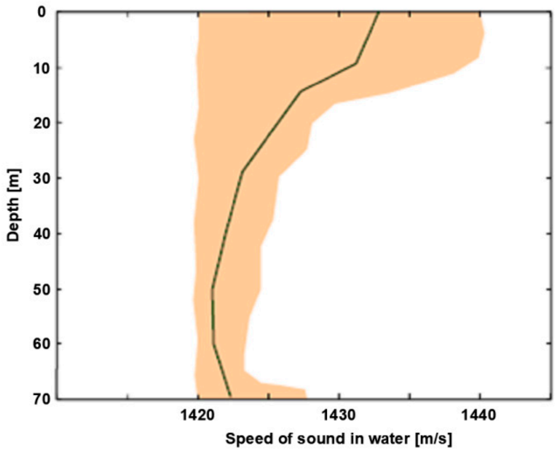


Figure 8. Daily speed of sound changes in summer in the Bay of Gdańsk. Own study based on [26].

Therefore, according to the authors, if measurements are performed with a SBES, the water surface temperature should be measured periodically, e.g., every hour with a thermometer or other equipment intended for the purpose, as mentioned earlier. The measurements can be used to determine the current calibration velocity of the sounding device.

The last oceanographic parameter discussed here is ocean currents, which can be extremely important for navigating a vessel along the established sounding profile. In some situations, it is not possible to perform bathymetric measurements with a USV (because of excessively strong ocean currents in the coastal area). As with temperature or salinity, information on the speed and direction of ocean currents can be acquired free of charge from websites run by NASA (http://oceanmotion.org/html/resources/oscar.htm), or the Institute of Oceanology of the Polish Academy of Sciences (http://www.satbaltyk.pl/en/sb_product/salinity/salinity-pm3d-model/). Maps of ocean current distribution provide graphic information (with arrows) on the direction of water flow and speed (in line with the scale provided on a graph) [30].

5. Hydrographic Depth Measurement

Bathymetric measurements are performed where the territorial sea baseline is situated, i.e., in coastal zones, which are special waterbodies from a hydrographical perspective. Their characteristic features include very small depths (less than 1 m) and high diversity of the seafloor relief. These prevailing conditions can significantly hinder or even prevent hydrographic work. Performing classical hydrographic measurements with manned vessels might prove impossible due to the excessively large draft of the vessels and echo sounder transducers installed on their bows. Therefore, according to the authors it seems optimal to use USVs for baseline measurements [31–36]. An alternative method is the use of manned or unmanned aerial vehicles equipped with LiDAR to determine the baseline. It should be remembered that this method has limited application, because it depends on the water quality classification at the place of measurement [12,13].

This section will provide an analysis of USV equipment, which will perform the planned measurement. The technical equipment used territorial sea baseline measurements (necessary on an unmanned vessel) includes [10]:

- a miniature SBES
- a GNSS receiver using a GNSS geodetic network or a DGPS receiver.

Currently, a miniature MBES or SBES is the only hydroacoustic device intended for depth measurements that can be installed on an USV. Other devices, such as a MBES or a MTES (multiple transducer echo sounder) cannot be placed on a vessel because of the considerable size and weight of the transmitting elements. The working frequency is the main factor taken into account when choosing an echo sounder. Therefore, echo sounders operating at high frequencies should be used in bathymetric measurements in ultra-shallow waters. The other (less important) requirements for SBESs in baseline measurements are described in detail in [10].

Before starting the bathymetric measurements, the measuring equipment must be calibrated to verify its operation and to eliminate errors. Therefore, two actions must always be performed when using an echo sounder [37,38]:

- measurement of the vertical distribution of the speed of sound in water
- measurement of the draft of the echo sounder transducer.

Determination of the speed of sound in water is described in detail in the previous section on oceanographic measurements. However, one must make sure that this velocity is set in the echo sounder. This can be done with the free software SonarMite App+, which can be downloaded and installed on a mobile device (laptop, tablet, smartphone). First, the echo sounder must be coupled with the mobile device by short-range wireless data transmission (Bluetooth). Subsequently, SV+ and SV− buttons can be used to set the calibration velocity in the echo sounder. The SonarMite App+ program enables displaying the results of depth measurement on the mobile device screen (Figure 9).

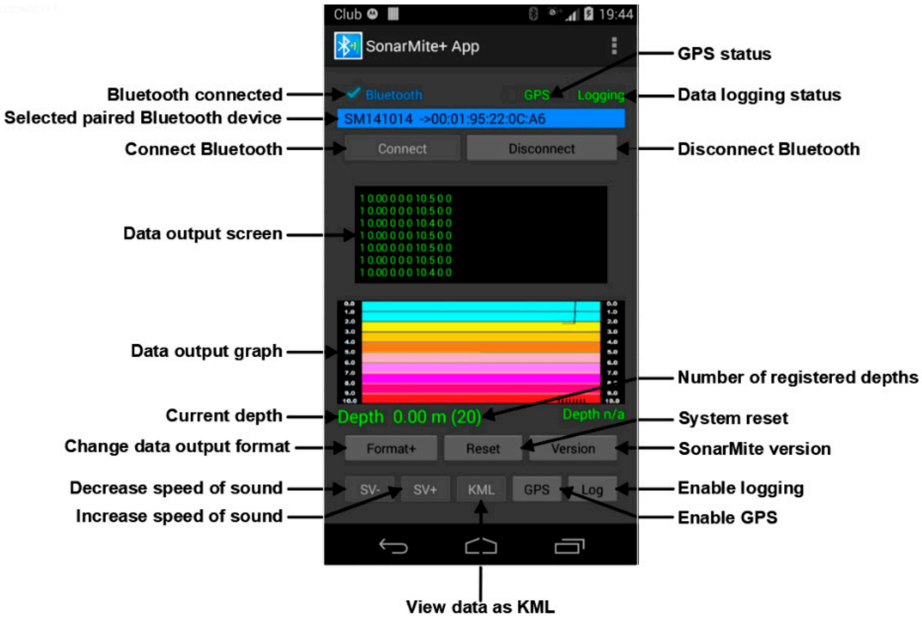


Figure 9. The application window for setting the calibration velocity of a single beam echo sounder (SBES) displaying the results of depth measurements.

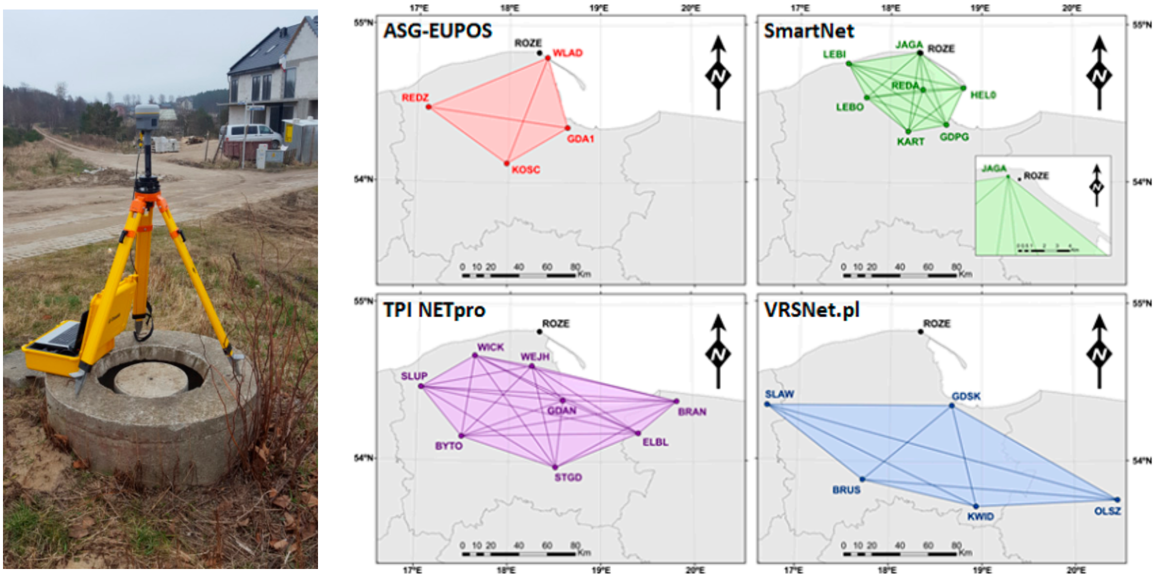
The draft of an echo sounder is another component of the depth measurement. A tape measure can be used to determine this since the draft of an echo sounder transducer installed on an USV is small (ca. 10 cm), This device will enable estimation of the transducer draft under the water surface with an accuracy of approximately 1 cm. Since it is a constant value, it must be added to the depth measured by the echo sounder during data processing.

Another measurement-related issue is the precision positioning of hydrographic measurements. Two types of receivers, which meet the requirements laid down in the IHO S-44 standard (IHO, 2008), can be used for this purpose, including:

- a GNSS receiver using a GNSS geodetic network
- a DGPS receiver.

The first of these is able to use all global navigation satellite systems (GPS, GLONASS, BDS, Galileo), satellite-based augmentation systems (SBAS) and GNSS geodetic networks. Hence, the average number of satellites available to a carrier phase receiver usually ranges from 16 to 20, which ensures a hydroacoustic device positioning accuracy of 1–2 cm (RMS). These values can be obtained only with GNSS geodetic networks, which offer paid or free services [39–43]. Network users can perform GNSS measurements with one of the two measurement methods. The first involves post-processing of observations recorded during a measurement session. The other includes real-time positioning methods, in which position coordinates are determined on an ongoing basis by a GNSS receiver. For performing hydrographic measurements, we are only interested in real-time positioning, i.e., the RTK (real time kinematic) and the increasingly common RTN (real time network) technique. The RTN method involves the generation of correction data based on observations not from one reference station, as in the RTK technique, but from at least several. Its advantages include the fact that the position error does not increase with the distance from the station (even up to 70–80 km) and the results are not inferior to classical RTK measurements.

Based on recent stationary measurements [43], it was found that reference stations at larger than dedicated (60–70 km) distances from the user performing the measurements, do not have any practical impact on the positioning error. For example, the error in the horizontal plane for the SmartNet network was 0.8 cm, with the mean distance between the reference station and the user being approximately 40 km. On the other hand, the error for the VRSNet.pl was 2.2 cm, but the mean distance between the reference station and the measuring site was nearly three times greater (ca. 120 km) than with the SmartNet network (Figure 10b). Thus, it can be stated that the difference in the positioning accuracy achieved in both geodetic networks is small.



(**a**) (**b**)

Figure 10. The measuring site (**a**) and the borders of a polygon which marks the operating range for individual GNSS geodetic networks in the province of Pomerania (**b**).

It is recommended that measurements performed by the RTK technique should use corrections transmitted by the reference station, which is the nearest to the measuring site. On the other hand, the operating range should be taken into consideration when choosing a GNSS geodetic network in the RTN technique. It can be noted that only two out of four commercial GNSS geodetic networks (SmartNet, TPI NETpro) provide coverage of the Bay of Gdańsk (where the hydrographic work will be conducted) by the network solution (Figure 10b) [44].

The DGPS system can be used as an alternative to GNSS geodetic networks. It is still, in many places, the basic positioning system used in hydrographic measurements [45–48]. Officially, the DGPS system must ensure a measurement precision (p = 0.95) of up to 10 m in a horizontal plane in accordance with a standard issued by the International Association of Lighthouse Authorities (IALA) [49]. However, in reality, DGPS users equipped with code receivers can position with an accuracy considerably exceeding the autonomous GPS positioning (5–10 m) [50].

During a recent measurement campaign, the positioning accuracy of the DGPS system in the Bay of Gdańsk was determined with respect to its application in hydrographic work. To this end, 4 h of dynamic measurements were conducted, during which approximately 11,500 determinations of position coordinates were performed (Figure 11). An analysis of the study results showed that R95(2D) and R95(3D) measures in the DGPS system were 1.42 m and 2.07 m, respectively. A comparison of the results with the minimum requirements for hydrographic measurements [9] shows that the DGPS system, like GNSS geodetic networks, meets the positioning accuracy requirements regarding all categories of work [47].

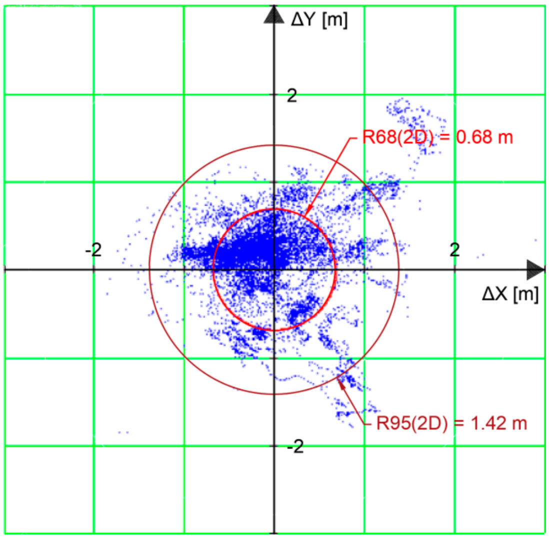


Figure 11. Horizontal position error distribution recorded by the DGPS receiver.

After the measuring equipment is completed, it can be mounted on an USV. It must be noted that a DGPS/GNSS receiver and a SBES should be fit for integration with a hydrographic vessel. It is recommended that the echo sounder transducer and receiver should be placed on a relatively short (up to 1 m long) pole, mounted in a special grip, which should be fixed firmly to the measuring vessel, e.g., on a mounting frame connecting both hulls of the vessel. It should be noted that a receiver and an echo sounder transducer should be mounted one above the other (on the same axis), in order to correctly determine the flat coordinates for the measured depths. The other devices, such as the echo sounder and the controller of the GNSS receiver should be placed in a safe place protected from water (Figure 12) [19].

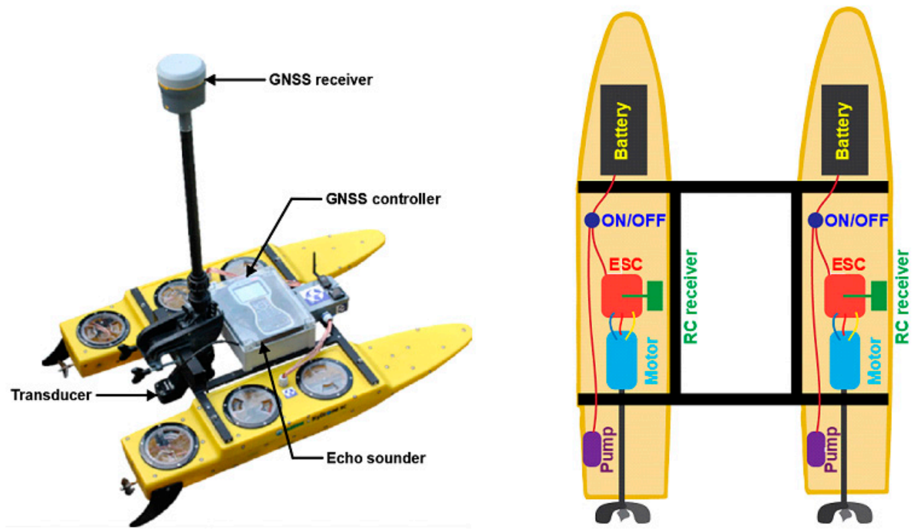


Figure 12. Unmanned surface vessel (USV) with measuring equipment mounted on it.

6. Discussions

The aim of this article is to present a methodology for performing territorial sea baseline measurements. It presents a method for planning a hydrographic survey using both manned and unmanned vessels and presents oceanographic parameters that should be determined before and during hydrographic measurements, as well as a method for choosing measuring equipment used in bathymetric measurements in ultra-shallow waters.

The analyses conducted for the study have shown that using an unmanned vessel, on which a multi-GNSS receiver and a miniature MBES or SBES can be installed is currently the optimal and the most effective method for determination of the territorial sea baseline. It is noteworthy that the measurement techniques mentioned above (unmanned vessels, GNSS geodetic networks) have been developing rapidly in recent years (the 2010s), which allows a satisfactory accuracy in measurement to be achieved. Bathymetric measurements in ultra-shallow waters were usually conducted by the tachymetric method or directly by geodesists in the sea. Unlike the proposed method, their effectiveness is low due to low measurement coverage of the terrain being measured and because of the time of the measurements.

It must be noted that hydrographic measurements with an USV can be performed in favourable weather conditions, i.e., in small waves (0–1 on the Douglas scale) and wind (0–1 on the Beaufort scale). Moreover, bathymetric measurements in waterbodies running along sandy coastal belts, e.g., beaches (such as waterbody No. 1 and 3) can be performed exclusively with such vessels. This is because manned vessels cannot conduct hydrographic measurements at depths exceeding 1 m because of their draught (0.5 m and more) and the echo sounder transducers installed on their bows.

Compared to unmanned vessels, manned vessels can perform hydrographic measurements in adverse measurement conditions, e.g., rapid current at a river mouth (such as waterbody No. 2). A small hydrographic vessel with a MBES, can be used in areas with highly dynamic hydromorphological changes. A MBES can be installed on such vessels (unlike unmanned vessels), and this ensures full measurement coverage of the seafloor.

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