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Analyzing Depth Uncertainty of Near-Shore Bathymetric Survey Conducted by Single-Beam Echo Sounder

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Abstract: Single-beam echo sounders have gained popularity for various applications due to their compact dimensions, ease of use, and cost-effectiveness. The question that often arises among the users is whether these devices can fulfill the necessary accuracy requirements. This paper concentrates on assessing the accuracy that can be achieved using a single-beam echo sounder. An accuracy assessment was performed by comparing the depths derived from the 3D model created from the single-beam echo sounder data to those obtained through more accurate and independent method (tacheometric surveying) in the test area. Accurate depth determination was achieved through trigonometric leveling, employing a specific methodology that allows for precise depth measurements up to 4.5 meters. The assessment results were compared to the vertical accuracy requirements for surveying and mapping in shallow waters, recommended by the International Hydrographic Organization. The results indicate that, with a 95% probability, the depths determined by the single-beam echo sounder meet the total vertical uncertainty (TVU) requirements specified by the S-44 standard for Order 1a survey.

Keywords: accuracy; depth measurements; IHO S-44; single-beam echo sounder; total station

1 INTRODUCTION

In a narrow sense, hydrography involves surveying and exploring the sea to produce nautical charts to ensure safe navigation [1, 2]. The basic tasks of hydrography are positioning on the water, determining the coastline, measuring depths (bathymetry), and creating navigational information systems [3].

Modern bathymetry (Greek bathus: depth) is the science of determining depths, i. e. determining the physical characteristics of the seabed based on the analysis of data from recorded profiles [4]. Seabed research and presentation of its characteristics, in a manner similar to topographic maps of land areas, is the subject of bathymetry. There are different methods and techniques of bathymetric surveys, that depend on the complexity of the project tasks [5].

The collection of depth data aims to show the topography of the sea, river, or lake bed, including all features, whether natural or man-made [6]. The term depth measurement refers to the determination of the vertical distance from the current water surface to the bottom.

From the point of view of hydrographic measurements, the two factors that define the position of a point (on Earth) are [7]:

- The horizontal position of the point, which can be represented as latitude and longitude, or by the Cartesian coordinates (in a geodetic network), or by angle and distance from a known control point.
- The depth of a point below the surface of the water, corrected for the vertical distance between the point of measurement and the water level and for the height of the tide above the datum or reference level to which the depths refer.

The rapid technological progress, that took off in the 20th century, also left its mark on instruments for determining depths. Technological developments resulted in the emergence of acoustic sensors such as side-scan sonars and single-beam echo sounders. This was a prelude to modern instruments that are now used in hydrography, such as interferometric sonar, wide-angle multibeam echo sounder, bathymetric lidar, and various types of integrated systems that combine multiple measurement sensors [2]. Ultrasonic depth sounders (or echo sounders) are instruments that measure the depth of the seabed using sound waves. Considering the number of sound beams that they transmit simultaneously, they can be classified as single-beam or multi-beam echo sounders [8, 9]. Echo sounders are the most commonly used in the process of bathymetric measurement because they have the best ratio of price and quality of collected data [10]. Acoustic methods cover all depth ranges and meet the International Hydrographic Organization (IHO) S-44 standard for hydrographic measurements [11]. Single-beam echo sunders are an appealing solution for many users, since they cost significantly less than multi-beams, and they can be mounted on smaller vessels. The data collected by such instruments has been successfully used in studies by numerous authors, among which are [12-19], etc. Other examples of such studies include the creation of detailed digital models of the seabed [20], the determination of morphometric changes in the river bed [21], the creation of digital bathymetric models of the lakebed [22], etc. Based on 15 years of data collection with a single-beam echo sounder, [23] created a map of the seabed showing sediment accumulations at certain locations along the western coast of the Adriatic Sea.

This study examines the vertical accuracy of hydrographic data collected using a single-beam echo sounder. The location on the Adriatic Sea, in the area of the Stobreč marina in Croatia, was examined. To make an accuracy analysis, data collected by an independent, more accurate method was used. Therefore, in the area of the Stobreč marina, a reference set of measurements for analysis was collected employing the tachymetric surveying (polar method), where the electronic tachymeter Leica Geosystems TS06 was used. The results of the analysis of the accuracy of depth determination utilizing a single-beam echo sounder, regarding the depths determined by another more accurate method, indicate that the used methodology for data collection and processing gives satisfactory results

2 TEST SITE

The research site was located on the eastern side of Stobreč (Republic of Croatia, 7 km east of Split), and covered the area around the outer breakwater of the marina (Fig. 1). The measurement was commissioned by the Port Authority of Split-Dalmatia County, to create project documentation for the reconstruction of the sports and nautical port of Stobreč. According to the project assignment, the measurement had to include the mentioned breakwater and the surrounding areas. Therefore, the boundaries of the survey area were set at approx. 50 m from the planned reconstruction site. The map had to be made at a scale of 1:500, and contain the data necessary for the reconstruction project (measurements of depths, land, and overlay with cadastral map).

Figure 1 Site location in Stobreč, Republic of Croatia

3 SINGLE-BEAM ECHO SOUNDER

The single-beam echo sounder (SBES) is composed of a transducer that sends only one beam of ultrasound pulses vertically toward the seabed at a time. The depth is determined based on the time it takes for the sound wave to travel from the transmitter to the bottom and back. The time delay is calculated based on the speed of sound in the water, which depends on salinity, temperature, and pressure [24]. This principle is also used in GPR (Ground Penetrating Radar) and TPS (Total Positioning) instruments. Although ways of better physical modeling and understanding of oceanic processes are being researched [25], turbulence in ocean water is unpredictable and affects measurements [26]. Echo sounders usually work with two frequencies in the range between 12 and 710 kHz. One of them has a shorter wavelength. A shorter wavelength enables more accurate measurements, while a lower frequency allows deeper penetration of the sound pulse. Instruments are generally suitable for smaller vessels as they are portable, energy efficient, and very easy to use and maintain [27]. The transducer can be mounted on the hull of the vessel [24] or a rod (pole) [28]. Alternatively, the transducer can be towed behind the vessel [28]. Single-beam echo sounders are suitable for generating seabed profiles and are most often used for measuring depths directly below the vessel, i.e. for recording smaller parts of narrow sinkholes to determine their depth [24].

The beam width of a SBES is up to 30°. Until the mid-1980s, narrow beam echo sounders with a beam width of $\beta = 2 \cdot \theta \leq 5°$, were also used. Operations using narrow beam echo sounders require mechanical or electronic stabilization of the transmitter to reduce the rock and pitch effects of the vessel. Narrow beam echo sounders are used for:

- Measuring depths directly under the vessel, thus avoiding wide beam errors caused by a sloping seabed. These measurements are used either for the safety of navigation or for mapping the seabed.
- Improving data quality in resolution and accuracy.

To create a narrow beam, larger transmitters are needed than for a wide beam. Narrow beam echo sounders do not provide information about the topography located to the side of the vessel, but only the topography directly below the vessel. Taking this into account, they are usually used in integration with wide beam systems, as an additional data source [2]. The quality of the data collected by a SBES depends on the characteristics of the sensor, the water depth, and the adopted measurement plan [24, 10, 29].

The echo sounder used to collect the primary data set in this study is a MIDAS Surveyor, manufactured by Valeport. It is a single-beam, two-frequency echo sounder (33 kHz, resolution 0.01 m and 210 kHz, resolution 0.04 m), which can be installed on a small vessel for surveying in shallow or medium-deep waters. It has a built-in internal rechargeable battery (up to 24 hours of operation) with the option of an external power supply. MIDAS Surveyor is also equipped with an internal GNSS receiver for positioning (accuracy of 2 m with SBAS correction, WGS84, or local coordinate system), with a possibility for connecting an external RTK GNSS receiver. Additionally, the device can connect with an external sound velocity profiler, a salinity meter, and a motion sensor. Collected data is stored in the internal flash memory [30].

During the process of measurement, the internal GNSS receiver was not used. Instead, the GNSS receiver S8 Plus, manufactured by Stonex, was used. It was connected to the echo sounder via the connection for the external RTK GNSS receiver. The employed receiver was used in the RTK (Real Time Kinematic) mode of operation, for which the manufacturer states horizontal precision of 8 mm; 1 ppm RMS (Root Mean Square), and vertical precision of 15 mm; 1 ppm RMS [31].

The software package Hypack was used for the data collection, i.e. combining the data collected by the echo sounder and the GNSS receiver. It is a hydrographic application that was developed as a measurement and navigation system for vessels at sea. Hypack integrates the operation of the echo sounder and GNSS receiver, while the observed data is automatically displayed on the laptop screen, or stored in LOG files. The application allows pre-defined measurement lines to be imported. The application also has a geodetic module, in which the parameters describing the selected map projection are set.

4 MATERIALS AND METHODS

Depth measurement in practice consists of several steps, among which are the creation of a measurement plan, the calibration of the depth-measuring instrument, the measurement itself, the processing of the collected data, and the creation of the final product. An important element for bathymetric data collection is a measurement plan (Fig. 2). This plan enables monitoring the course of the measurement, as well as the organization of the measurement from start to finish. The measurement plan determines the way of working and the instrumentation that will be used, and thus the expected accuracy that will be achieved. The measurement plan for the Stobreč marina was created concerning the commissioned requests (lines spacing and orientation parallel and perpendicular to shore), in such a way that the measurement lines were placed in a grid covering the area of interest. Such arrangement of measurement lines ensured adequate data density, good distribution, and measurement control.

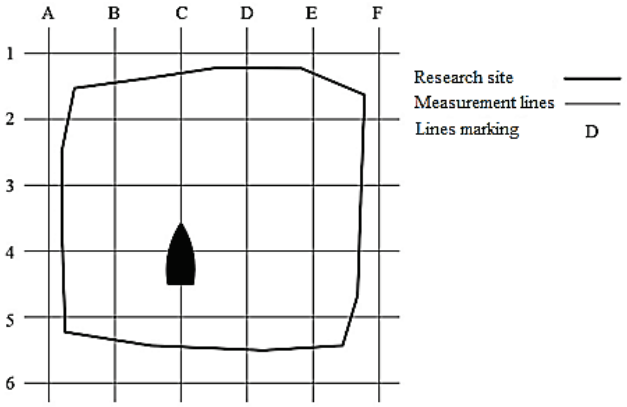

Figure 2 Sketch of the measurement lines placement

Echo sounder calibration is also an important step since different water environments affect the readings produced by the echo sounder differently. During the calibration, the readings are recorded. Based on these readings, in the data processing phase, the measurements are corrected to obtain the final product (e.g. a bathymetric map). While calibrating the echo sounder, care was taken to make the calibration at a place with a flat seabed, near the measurement site. The calibration procedure is as follows: first, an iron plate is lowered directly under the echo sounder to a shallow depth (in this case depth was 12.7 cm). The additional constant of the echo sounder was adjusted until the correct reading of 12.7 cm is obtained. After that, the iron plate was lowered to the average depth expected for the measurement and the sound speed was adjusted until an accurate reading is obtained. The procedure was repeated by returning to the initial shallower calibration depth (change in the reading is possible due to a change in the speed of sound). The additional constant of the echo sounder was set again, and with that new value, echo sounder was descended to the deeper depth, where the speed of sound was adjusted according to the value of the measured depth. Iteratively, by alternately setting the addition constant shallowly below the echo sounder transmitter and the multiplication constant deeper, the procedure was repeated until the observed values were satisfactory for both depths at the same parameters of the echo sounder constants. The vessel was acquired in the area of Stobreč, and the equipment was installed on it. Marine conditions allowed smooth navigation without requiring special adaptation; i.e., the measurements were conducted in a calm wave environment, with no wind or sea currents. The only obstacles were vessels tied up along the coast, and they were relocated upon request.

4.1 Measurement (Data Collection)

Measurements, i.e. data collection, were performed using a combination of the GNSS positioning method and dual-frequency bathymetry. As mentioned earlier, GNSS measurements were conducted using a Stonex S8 plus receiver (RTK DGP). The measurements of both systems are combined in such a way that a position obtained by the satellite positioning method was assigned to each recorded point, whose depth was measured. The GNSS antenna is placed on the mount that is attached to the side of the vessel. The transducer of the echo sounder is placed on the same mount. Since there was an offset between the phase center of the GNSS antenna and the echo sounder transducer, its value was determined on the site when the antenna and transducer were placed on the mount. All recorded measurements were corrected for the value of the mentioned offset.

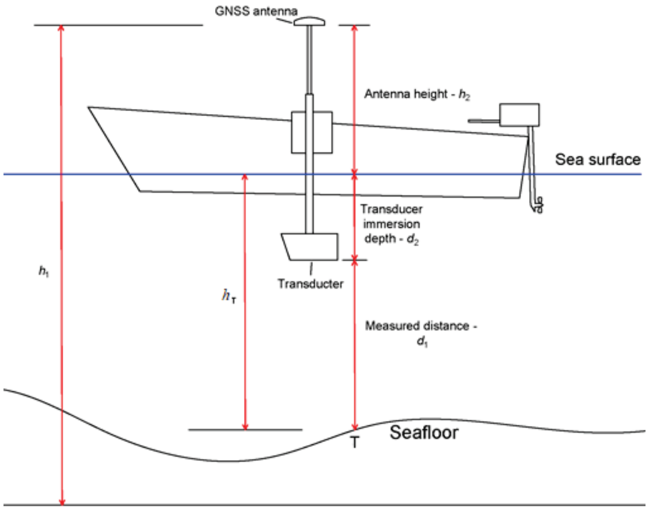

Figure 3 Schematic representation of the method of determining the depth of the recorded point

The area (about 1,5 ha) where the data was collected is on the eastern side of Stobreč, around the breakwater of the marina itself. The measurement process was conducted in such a way that the vessel, on which the GNSS system/echo sounder was installed, sailed along the measurement lines, and at predetermined time intervals (1 second) the horizontal position and depth of the submerged transducer were recorded. After that, the depth obtained by the echo sounder was assigned to each recorded point. Both devices (GNSS receiver and echo sounder) were connected to a portable computer, which synchronizes the data collected by both instruments with a control software.

The depth of the point was obtained by the following formula (Fig. 3):

$$h_{\mathrm{T}} = h_1 - h_2 - (d_1 + d_2), \tag{1}$$

where: h_1 – ellipsoidal height of the phase center of the GNSS antenna, h_2 – height of the antenna above the water surface, d_1 – depth measured by echo sounder, d_2 – transducer immersion depth.

4.2 Processing of Collected Data (Creation of a 3D Model of the Seabed)

The results of the data collection were the coordinates, i.e. the positions (E, N, h) of each recorded point. First, it was necessary to filter the data to eliminate outliers that would affect the interpolation process and creation of a 3D model of the surveyed seabed. The filtering process was performed visually, where data that deviated grossly from other surrounding values was removed. After filtering, the data was interpolated to obtain a denser, more regular mesh. Subsequently, a 3D model of the recorded seabed was created using Golden Software Surfer 11, with Kriging employed as the interpolation method. As stated by [32], Kriging is a geostatistical interpolation method, which retains the trends expressed in the input values, since it takes them as fixed during the interpolation process. The Kriging method is classified as the best linear unbiased estimator. The processing results are most often displayed in the form of contour lines (isobates) (Fig. 4) and 3D surface models (Fig. 5).

4.3 Accuracy Assessment

To ensure the quality of marine observations, it is necessary to independently validate the data [33]. The focus of the study was to analyze the accuracy of depths determined from data collected by a single-beam echo sounder. To achieve this, depths derived from a 3D model created using data from a single-beam echo sounder were compared with depths determined by another independent and more accurate method. That second (or reference) set of measurements was collected using the tachymetric (polar) method of surveying. The tacheometry is used to determine the relative polar coordinates of detailed points with respect to the instrument station, where the instrument is oriented in a known bearing toward another known point. Based on the collected measurement data (distances, horizontal and vertical angles), the coordinates of detailed points were calculated. Those coordinates are in the same coordinate system in which the control points are defined. The advantage of the polar method is the high accuracy in determining the 3D position of detailed points [34]. Robotic total stations can be used in hydrographic surveying to track and position reflectors mounted on vessels equipped with sonar and other depth-measuring instruments [35].

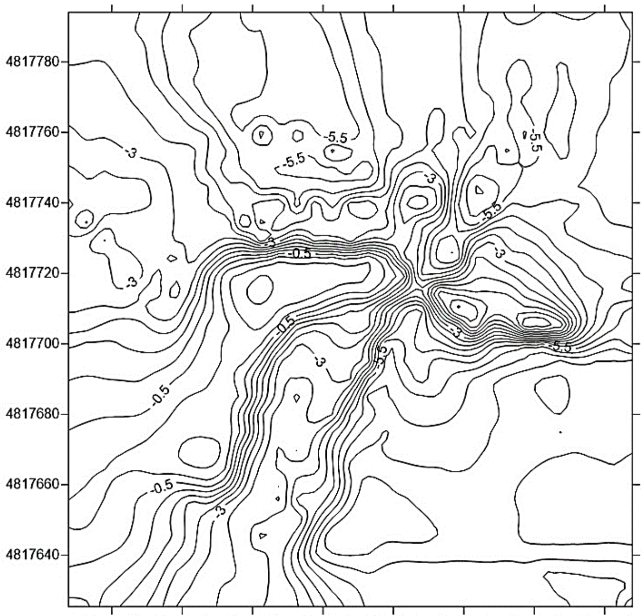

Figure 4 Representation of the seabed with contour lines (cutout)

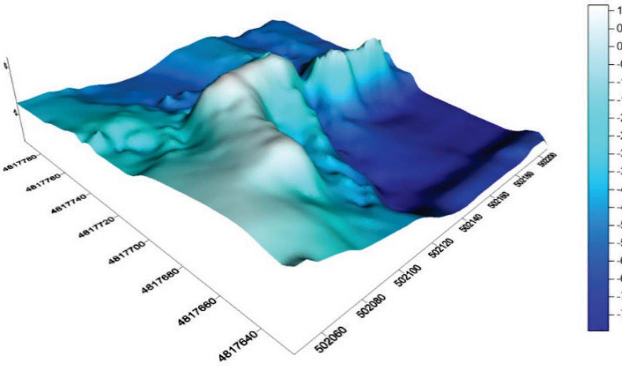

Figure 5 Representation of the seabed with a 3D surface model (cutout)

In this study, polar measurements were carried out using the Leica Geosystems TS06 total station (Fig. 6). The instrument precision according to ISO17123-3 and ISO17123-4 standards is 1 mgon for angle measurement and 1.5 mm; 2 ppm for distance measurement [36]. A custom fishing pole, chosen for its length (more than 4 m), strength, and build quality, was employed for marking the positions of detailed points at greater depths. A retro-reflective sheet was placed on the top of the pole to manually aim the instrument towards the target and for distance measurements. At the end of the pole that enters the water, a plate-shaped iron head was placed. This allowed the pole to take a vertical position, and at the same time prevented it from sinking into the seabed. The reflector mounted on a standard range pole was used in the shallower parts of the test area, and in that case the pole was held by a surveyor standing on the seafloor. In both cases (fishing pole and range pole), the surveyor holding the rod had to take special care in plumbing it, by carefully watching the circular bubble attached to the pole.

Figure 6 .Control measurements from the inside of the breakwater

The result of this type of point positioning is a set of coordinates representing position (E and N) and depth (hP). Based on collected data, coordinates for 50 detailed points were determined in the area of interest in the Stobreč marina. The calculated depths for those 50 detailed points vary from –0.7 to –4.3 m, indicating that a certain part of the test site, that exceeds this depth, was not included in the accuracy evaluation.

The vertical accuracy of detail point determination can be expressed as:

$$s_{\mathrm{h}} = \sqrt{s_{\mathrm{hA}}^2 + s_{\mathrm{s}}^2 \cdot \cos^2 z + s^2 \cdot \left(\frac{s_{\mathrm{z}}^2}{\rho}\right) \cdot \sin^2 z + s_{\mathrm{i}}^2}\,, \tag{2}$$

where: s_{hA} – standard deviation of the height of the stand point, z – measured zenith angle, s – measured slope distance, s_{i} – standard deviation of instrument height, s_{s} – standard deviation of slope distance, s_{z} – standard deviation of zenith angle, ρ - angular conversion coefficient (200 gon/π).

Due to excellent coordination between the surveyor operating the total station and the surveyor holding the rod, aiming errors can be neglected. Taking all factors into account, it can be concluded that the theoretical accuracy of determining the depths of detailed points in the Stobreč marina area is about 3 mm, if the uncertainty of holding the pole in a vertical position is 1° or better. That accuracy significantly exceeds the accuracy of depths determined using an echo sounder and RTK receiver.

The accuracy was evaluated based on the differences between the depths of points measured by tachymetry and corresponding points obtained from a 3D model (hD). The depth differences were compared with the accuracy standards defined in publication S-44 of the International Hydrographic Organization, which defines the required accuracy of hydrographic surveys. It should be noted that the 6th edition of S-44 introduced the quality matrix to provide a tool for broader classification of surveys.

The maximum allowable vertical measurement uncertainty is defined as [11]:

$$TVU_{\max}(d) = \pm\sqrt{a^2 + (b \cdot d)^2}\,, \tag{3}$$

where: a – the portion of the uncertainty that does not vary with the depth, b – a coefficient which represents that portion of the uncertainty that varies with the depth, d – the depth.

The parameters a and b to compute the maximum allowable TVU are taken from publication S-44, and in this study, they had values corresponding to the survey Order 1a, i.e. a = 0.5 m and b = 0.013. Since the test area involved shallow depths (they ranged from –0.69 to –7.27 m), it can be determined that $TVU_{\max}(d)$ is 0.50 m.

5 RESULTS AND DISCUSSION

As previously stated, the depths of 50 points obtained by the polar method were compared with the corresponding depths from the 3D model of the seabed, and the differences were calculated: $\Delta h_{\mathrm{PD}} = h_{\mathrm{P}} - h_{\mathrm{D}}$. Statistics of differences in depths are given in Tab. 1.

Table 1 Statistics of differences in depths determined by the polar method and single-beam echo sounder

Indicator		Δh_{PD}
Minimum, m		–0.53
Mean, m		–0.07
Maximum, m		0.22
Range, m		0.75
RMSE, m		0.17
Difference values, %	|0-5 cm|	26.0
	|5-10 cm|	24.0
	|10-15 cm|	14.0
	|15-20 cm|	18.0
	|20-25 cm|	8.0
	> |25 cm|	10.0

In the assessment of the quality of the depths resulting from the application of a single-beam echo sounder, the root mean squared error (*RMSE*) was used as the basic indicator of accuracy:

$$RMSE_{\mathrm{h}} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} d\Delta h_{\mathrm{PD}i}^2} = 0.17\ \mathrm{m}. \tag{4}$$

By analyzing all the points, it was found that the mean difference between the depths determined by the polar method and the 3D model is –7 cm. The maximum negative depth difference is –53 cm, and the maximum positive difference is 22 cm. Even 82% of the differences Δh_{PD} had an absolute value less than 20 cm, and only one difference exceeds the $TVU_{\max}(d)$ value, by only 3 cm.

According to the S-44 standard, the total vertical uncertainty, calculated with a probability of 95%, is determined as $1.96 \cdot RMSE_{\mathrm{h}}$ = 0.33 m. If that value is compared with the maximum allowed vertical uncertainty $TVU_{\max}(d)$, it can be concluded that the 3D model of depths created by data collected with the MIDAS Surveyor echo sounder exceeds the vertical accuracy requirements prescribed by the S-44 standard, for the Order 1a.

The results show that 92% of the points meet the TVU requirements prescribed for the class of special order of accuracy, where the parameters a = 0.25 m and b = 0.0075 are used to calculate $TVU_{\max}(d)$.

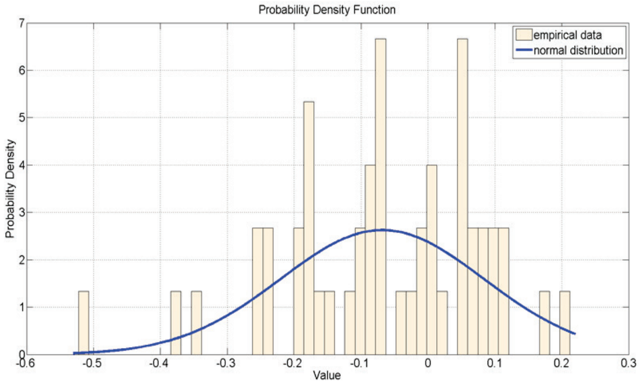

Figure 7 Histogram and difference distribution curve Δh_{PD}

Based on the available data, a histogram of the differences between the theoretical heights of the detailed points and their values obtained from the 3D model was made, as well as the corresponding curve of the standard normal distribution, which best matches the empirical data (Fig. 7). Fig. 7 clearly shows that there is no shift in the arithmetic mean $\overline{dh}$ that would be caused by the presence of significant systematic errors.

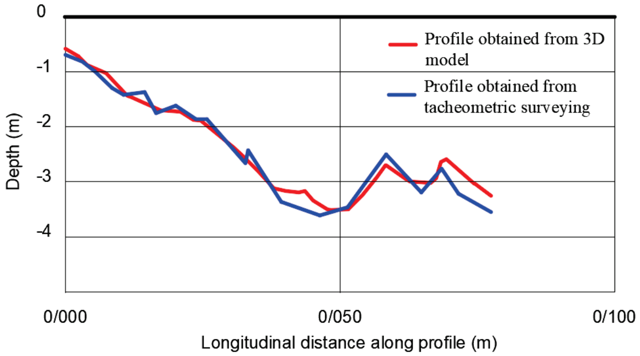

Figure 8 Comparison of two seabed profiles

In addition to a numerical evaluation of the results, visual controls were also performed. They confirmed the previous statements. To conduct a visual control, a longitudinal profile corresponding to the order of recorded points by the total station on the western side of the marina was analyzed. By comparing the profile obtained from measurements by the polar method and the corresponding profile extracted from the 3D model of the seabed, it can be concluded that the basic shape is the same, but that there are expected deviations. These deviations are not uniform, i.e. the deviations range from approx. –35 cm to +20 cm, which is visible in Fig. 8. It is evident that the 3D model produced a smoothed surface, and differences increase with the roughness of the seafloor.

6 CONCLUSION

Determining the depths is the basis for the creation of bathymetric maps, which are later used for various purposes. As different methods provide depths of different accuracy, in today's hectic pace the aim is to collect a sufficient amount of data with appropriate accuracy, in the shortest time possible. Therefore, doubts and questions often arise as to which devices can perform this task with the required accuracy. Single-beam echo sounders, compared to multi-beam ones, are cheaper, easier to operate, and have a solid data acquisition speed. However, that speed is not at the level of multi-beam echo sounders, which on the other hand, cost significantly more and in practice provide more accurate data.

This study aims to investigate the feasibility of using a relatively low-cost echo sounder for collecting accurate water depth data, which is essential for obtaining reliable bottom contour information. The research revealed that a single-beam echo sounder can indeed provide data of satisfactory vertical accuracy (referring to the S-44 rulebook of the International Hydrographic Organization for seabed surveying and mapping, TVU for Order 1a survey). The example of the Stobreč marina demonstrated that 98% of points derived from the 3D model, created from measurements collected with a single-beam echo sounder, met the prescribed vertical accuracy. The study demonstrates that there are no significant systematic errors in the depths measured with sonar. The method of control measurements with a total station gave high-quality results, but to achieve this, it was necessary to fulfill certain prerequisites. The tachymetric measurement was performed in extremely good weather conditions, to reduce the movement of the vessel at sea and thus reduce the error of non-verticality of the pole during observations. Also, good weather allowed taking observations at regular intervals at different depths. In this study, a conventional manually operated total station was used, necessitating precise coordination among the instrument operator, boat driver, and the surveyor holding the pole. It was crucial to quickly make observations, when the pole was in the vertical position. However, if this method is applied in unfavorable marine environmental conditions, with a stronger influence of waves, wind, and sea currents, it would be challenging to maintain the verticality of the pole at all points. The collection of reference data would certainly be much easier with the use of a robotic total station with the ability to automatically find, track, and aim the target. In that case, it would be necessary to mount a 360° reflector on the pole. Finally, by integrating the IMU-based tilt compensation sensor with the surveying pole, measurements can be taken with a pole tilted at any angle.

From an economic perspective, it can be concluded that measurements with a single-beam echo sounder have the full potential to be used for planning and monitoring water construction projects, as well as creating bathymetric maps and charts essential for navigation safety. Of course, S-44 defines more criteria and all of them have to be met. In this manner, it can be concluded that a single-beam echo sounder can be used for the safety of navigation purposes, but only for survey orders 1B and 2 when used as a standalone technique and for much deeper areas where underkeel clearance is not an issue. The accuracy of the bathymetric survey can be increased using a large number of survey lines as well as using the conventional base-rover RTK solution (correction services provided by the active GNSS network CROPOS were used in this study). Furthermore, better results could be achieved by integrating INS sensors within the depth measuring system to determine and reduce the heave, pitch, and roll effects in hydrographic surveying.

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