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Precise bathymetry as a step towards producing bathymetric electronic navigational charts for comparative (terrain reference) navigation

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Bathymetric electronic navigational charts (bENCs) contain only bathymetry data and can be used in applications such as underwater positioning, dredging, and piloting. According to International Hydrographic Organization (IHO) standard S-57, electronic navigational charts (ENCs) contain depth information with highly pure density of depth contours. Depth contours in standard solution are limited to 2, 5, 10, and 20 m. Inclusion of safety contours in bENCs could improve navigation safety, especially in restricted waters such as ports, lakes, and rivers. Another problem is non – Global Positioning System (GPS) unmanned underwater vehicle (UUV) navigation. bENCs might be used as reference data for UUV comparative navigation. This is called terrain reference navigation. This article presents the results from bathymetric data processing that was performed to convert data contained in bENCs into a reference for underwater comparative navigation. We use data obtained using a multibeam echo sounder to produce depth data with a horizontal spacing of 0.10 m that is suitable for use on restricted waters. The experimental data was collected in and around the Port of Gdansk Poland.

KEY WORDS: Electronic Navigational Chart, Bathymetry, Navigation

1. INTRODUCTION This paper's purpose is to present the concept of bathymetric data processing, which is especially useful in simplified comparative navigation – terrain (bottom) reference navigation and in production of precise bENCs. In recent years, unmanned underwater vehicles (UUVs), which are sometimes known as underwater drones or hydro drones, have become popular for hydrographic jobs and other underwater missions. These vehicles can operate underwater without a human occupant. They can be divided into two categories: remotely operated underwater vehicles (ROVs), which are remotely controlled by a human operator, and autonomous underwater vehicles (AUVs), which operate independent of direct human input.
One important problem associated with UUVs is precise vehicle positioning during movement in an underwater environment where the applicability of satellite navigation systems is limited by the need to place a receiver antenna over the water. Interactions with satellite positioning systems take place by at least partially surfacing the platform, which increases the risk of destroying it. It may be possible to position unmanned platforms that move in deep water using comparative navigation methods. In these methods, data gathered by on-board hydrographic

systems is compared to precise bENCs that include important information about the shape of the bottom.
Several underwater positioning methods have been used in modern underwater navigation. Most are based on inertial sensors that provide underwater positioning during the short time between GPS position fixing and use of underwater acoustic transponders (contact points) placed on the bottom. Some AUVs use a more independent method: terrain navigation via digital terrain models. Terrain navigation runs on any sensor that provides bathymetric data. Wider, more comparative navigation methods also use other geodata such as sonar bottom coverage, magnetometry, or gravity imaging. A comparative navigation system can be seen as an independent component of a navigation system whose primary function is to provide position measurement. In AUVs or submarines, position measurements can be integrated with an inertial navigation system in a just as they are integrated with GPS. In other systems, they can integrate with a dead-reckoning system or serve as an independent source of position information.
Comparative navigation algorithms can be conceptually divided into global correlation finding algorithms (correlation methods) and tightly integrated terrain tracking algorithms. The accuracy of comparative navigation depends on the algorithmic characteristics, sensor accuracy, map accuracy and resolution, and usefulness of the terrain. These navigation algorithms typically require heterogeneous terrain. If the terrain is flat, the algorithms can communicate only that the vehicle is over a flat area. In such cases, additional data is needed. This data can come from sonar (Dong et al., 2017; Song et al., 2016; Wawrzyniak and Stateczny, 2017; Wawrzyniak et al., 2017), magnetometers (Quintas et al., 2016; Wu M. and Yao, 2015), gravimeters (Han et al., 2016; Menozzi et al., 201; Wu L. et al., 2015; Zhu et al., 2016), or other systems (Jung et al., 2017; Ramesh et al., 2016; Wei et al., 2015).
Terrain reference navigation has been analysed by many researchers and remains a subject of investigation. Multibeam echo sounder data is commonly used, but these systems can operate on any sensor that provides bathymetric data (Chen et al., 2015a, 2015b; Claus and Bachmayer, 2015; Hagen et al., 2015; Li et al., 2017a, 2017b, 2017c; Salavasidis et al., 2016; Stuntz et al., 2016; Wang et al., 2015; Zang et al., 2015; Zhou et al., 2015, 2016, 2017).
With regard to autonomous surface vehicles (ASVs), comparative navigation methods might be used as autonomous Global Navigation Satellite System (GNSS) positioning alternatives or in areas were GNNS positioning is not possible such as under bridges or in areas covered by trees on narrow rivers and canals.
The most important problem related to bathymetric measurement gathering is that of registering large amounts of data (i.e. “big data”). The data should be reduced before processing and presentation to the user. For navigation safety it is important to retain points of minimum depth. Reduction of bathymetric geodata with a focus on minimum depth has been described in previous articles (Wlodarczyk-Sielicka and Stateczny, 2015, 2016; Wlodarczyk-Sielicka et al., 2016).
Several researchers have examined aspects of ENC production planning and navigational data evaluation (Hyla et al., 2015; Liu et al., 2014; Kazimierski and Wlodarczyk-Sielicka, 2016; Lubczonek, 2016; Lubczonek and Borawski, 2016).
Bathymetric data is typically gathered using a multi-beam echosounder (MBES). Processing of bathymetric data has been discussed by Maleika (2015a, 2015b). Some researchers have attempted to collect bathymetric data using ASVs and single beam echosounders (SBESs) (Specht et al., 2016, 2017), however the resulting data is less dense than is desired for bENC production.

The primary objective of this paper is to demonstrate the use of a bathymetric data post-processing algorithm in bENC production.

2. BATHYMETRIC DATA PROCESSING. In bathymetric data post-processing, the size of a data set is reduced with a focus on minimum depth in order to make analysis easier and more effective. It is generally accepted that acquiring depth contours every 10 cm can fulfil comparative navigation positioning accuracy requirements. Post-processing was performed using Hypack Max & Hysweep ver. 2017a software. This software is useful in data acquisition and processing. Another software system by Caris and SevenCs was used only for bENC verification.

The bENC production algorithm starts with precise bathymetric data acquisition via MBES with Real Time Kinematic (GPS RTK) positioning. Precise, accurate data is important to the goal of producing bENCs with depth contours — isobaths every 10 cm that are converted to depth information and used in charts. Raw MBES data contains spikes and other errors that should be carefully removed After the cleaning process, the data was sorted and the target density was isolated. In next step, depth areas (areas of constant depth used to generate safety contours) were generated from the depth contours created during the previous step. These were used to generate the bENCs using ENC Editor from Hypack Max. Hypack Max was used to perform validation and determine the bENCs. Finally, verification and validation were performed using Caris and SevenCs. The purpose of this was to confirm that the product was properly recognised by all standard software commonly used by national hydrographic offices. A scheme of the bENC production process performed using Hypack software is shown in Figure 1.

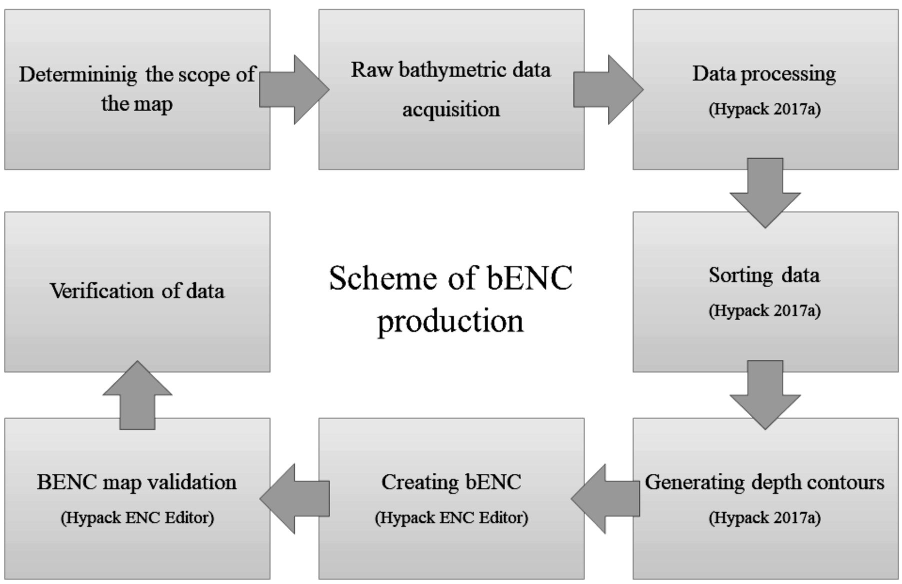

Figure 1. Algorithm for bENC production based on Hypack Max & Hesweep.

3. RAW BATHYMETRIC DATA QUALITY. Precise plan and chart production requires use of the most accurate data available. International IHO standard S-44 is not restrictive enough for bENC production. This is true even of the version designed for Special Orders intended for harbours, berthing areas, and associated critical channels with minimal under-keel clearances.

In 2013, the Canadian Hydrographic Service introduced more restrictive requirements, referred to as Exclusive Orders, for engineering surveys and shallow water in harbours, berthing areas, and associated critical channels with minimal under-keel clearances (Canadian Hydrographic Service, 2013). Exclusive Order hydrographic surveys are based on the IHO Special Order system, but require higher accuracy. Their use is intended to be restricted to shallow water areas (harbours, berthing areas, and critical channels) with optimal use of the water column and where specific critical areas with minimal under-keel clearances and bottom characteristics are potentially hazardous to vessels. Exclusive Order standards also apply to high-precision engineering surveys. All error sources must be minimized. Exclusive Orders require highly precise positioning systems, closely spaced lines (when target detection is required) and rigorous control of all aspects of the surveys (Canadian Hydrographic Service, 2013). Table 1 presents Standards for Exclusive and Special Order Hydrographic Surveys.

Table. 1. Compare Exclusive and Special Order Standards for Hydrographic Surveys (Canadian Hydrographic Service, 2013).

ORDER	Exclusive	Special
Examples of Typical Areas	Shallow water in Harbours, berthing areas, and associated critical channels with minimum under-keel clearances or engineering surveys	Harbours, berthing areas, and associated critical channels with minimum under-keel clearances s
Horizontal Accuracy (95% Confidence Level)	1m	2m
Depth Accuracy for Reduced Depths (95% Confidence Level)	a = 0.15m b = 0.0075	a = 0.25m b = 0.0075
System Detection Capability	Features > 0.5m cubed	Features > 1m cubed

To calculate the depth accuracy error limits, the corresponding a and b values listed in Table 1 must be introduced into the formula below (Canadian Hydrographic Service, 2013):

$$\pm \sqrt{[a^2+(b*d)^2]} \quad (1)$$

where:
a is the constant depth error, i.e. the sum of all constant errors in meters;
b*d is the depth dependent error, i.e. the sum of all depth dependent errors;
b is the depth dependent error factor; and
d is the depth in meters.

4. HARDWARE QUALITY CONDITIONS FOR BATYHYMETRIC DATA GATHERING.
Even the more restrictive Exclusive Standard introduced by the Canadian Hydrographic Service is insufficient for bENC production. Both horizontal and vertical accuracy should be 5 cm in order to produce precise isobaths every 10 cm. To fulfil such high hydrographic survey requirements, sophisticated MBES hydrographic equipment with external INS sensors was introduced during a research project. The project (“Developing of autonomous/remote operated

surface platform dedicated hydrographic measurements on restricted reservoirs") was supported by the National Centre for Research and Development (NCBiR) of Poland.
The goal of the project was to develop an autonomous / remote-controlled multitasking water-based platform for implementation of hydrographic survey missions around ports, estuaries, anchorages, estuaries, bays and lakes, rivers, and other restricted areas. The platform was intended to perform hydrographic survey missions using bathymetry, sonar, and other measurements in both autonomous modes that use planned trajectories and in remote control modes. It was designed specifically to operate in navigationally difficult situations. The project include six sections that comprise the overall process of implementation and platform validation, from requirement definition to specific projects: sensor deployment, hull structure, software, navigation systems, propulsion modules, and sensor integration. These sections encompass platform construction and validation, as well as development of the applicable exploitation methodology. The autonomous multi-purpose floating platform named HydroDron was developed within the framework of the project. It is equipped with Ping DSP 3DSS 450 Swath Bathymetry 3D Sidescan technology, a SBG EKINOX2-U-G4A2-EL external inertial navigation system, and an AML Micro-X SV sound velocity sensor. In addition, an AML BaseX2 sound velocity profiler with Wi-Fi was used. The hydrographic equipment was connected to a Getac s410 semi-ruggedized high performance laptop computer with Hypack Max & Hysweep. In addition, a Trimble R10 receiver was used to secure RTK corrections in difficult areas. All of the hardware specifications exceeded Exclusive Order requirements.

5. EXPERIMENT. Raw data from a survey of the area around the Port of Gdansk was used to verify the bENC production algorithm. The following figures include bathymetric data post-processing results. The data positions are given in the universal transverse mercator (UTM) coordinate system, an international locational reference system.

5.1. Sorting and reduction of depth points. The first step in data processing was point reduction. The results are presented in Figure 2. After point reduction, selected depth points were chosen for presentation to the bENC. The reduction algorithm implemented in the Hypack system was used.

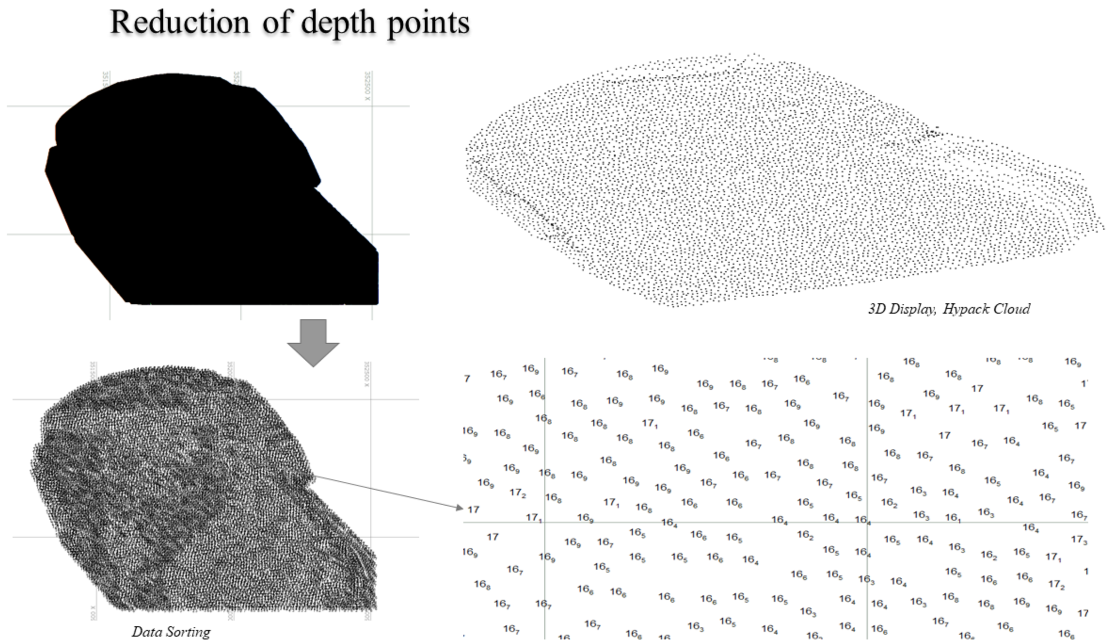

Figure 2. The process of depth points selection.

5.2. Generation of depth contours. The second step in data processing was generation of depth contours from clouds of points. A cloud of points is presented in Figure 3 and its 3D visualisation is shown in Figure 4. To calculate the depth contours, first a triangle irregular network (TIN) model is produced from a reduced cloud of points. The TIN model is presented in Figure 5. Based on the TIN model, depth contours are calculated and generated every 10 cm. The result of the depth contour calculation is presented in Figure 6.

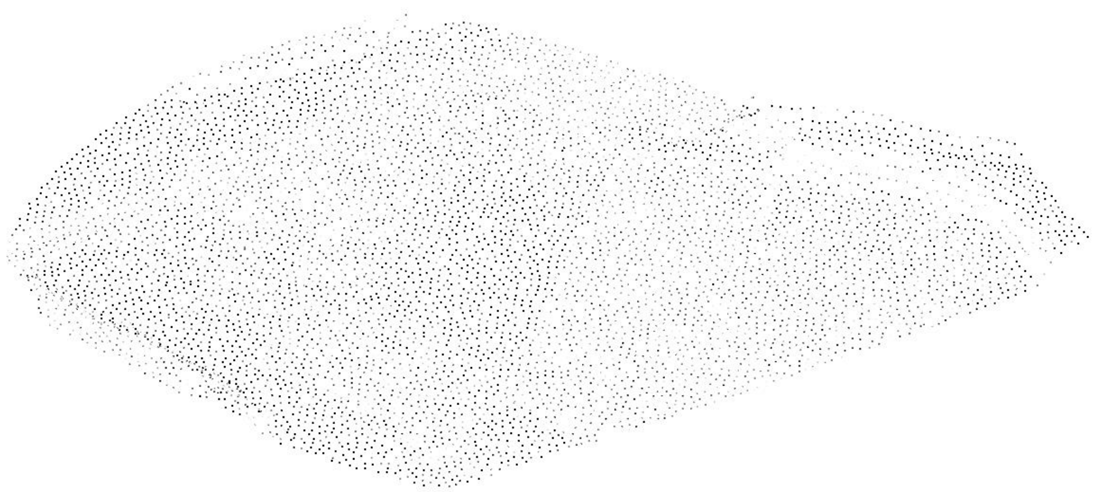

Figure 3. Cloud of points in Hypack 3D display of testing area,

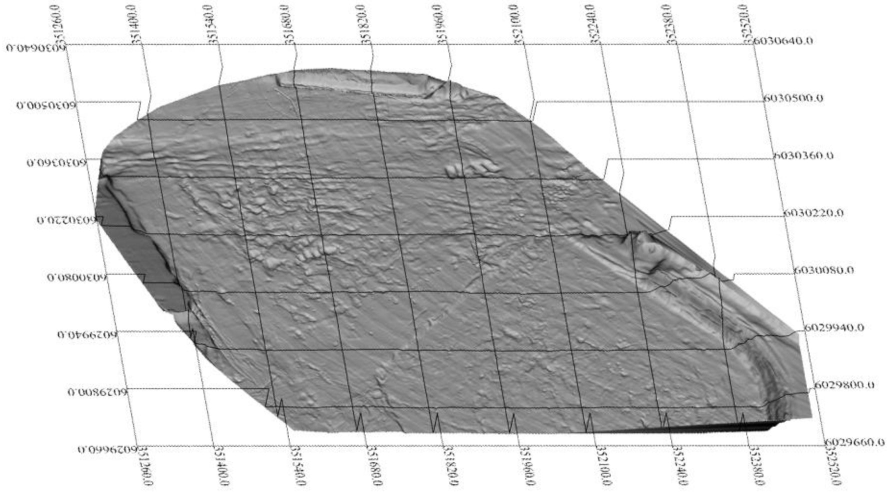

Figure 4. 3D visualisation of cloud of points of testing area.

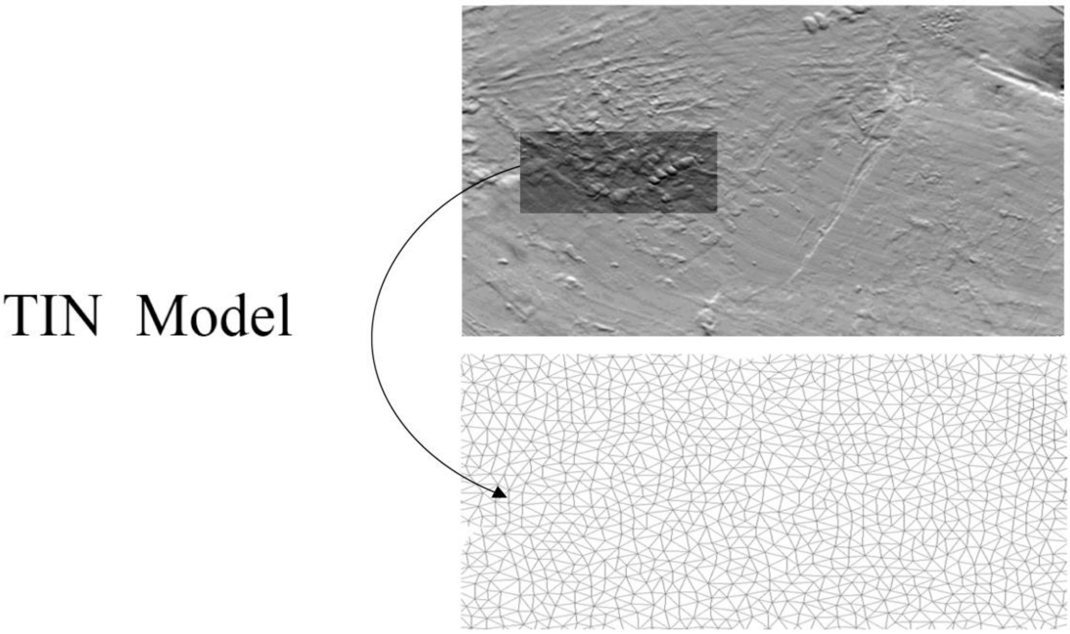

Figure 5. Generation of Triangle Irregular Network (TIN) from cloud of points.

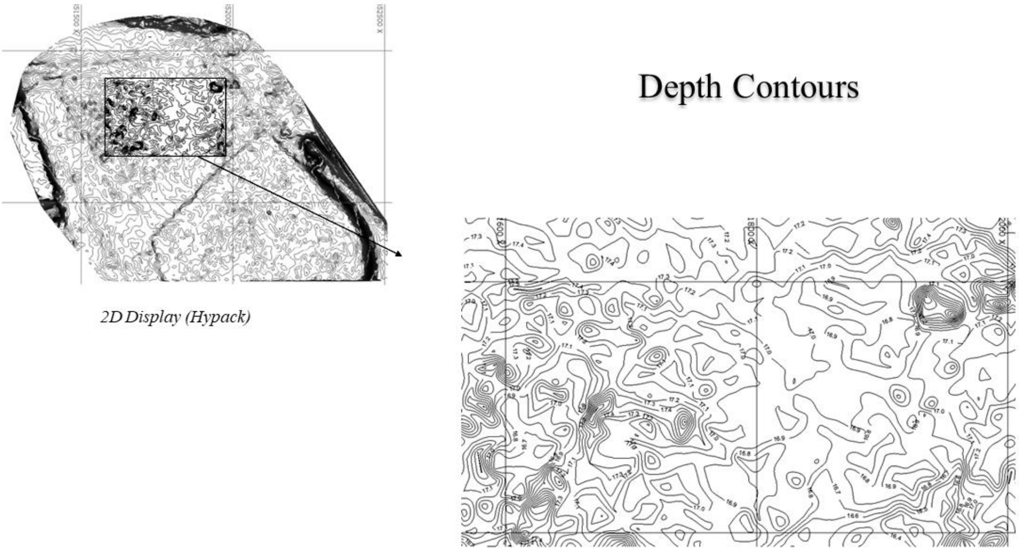

Figure 6. Depth contour generated from the TIN every 10 cm.

5.3. bENC creation procedure. Depth contours can be included in the bENC, but it is better to include depth areas converted from depth contours. Depth contours are isolines and cannot be used to calculate safety contours. Depth areas should be used instead. Figure 7 shows depth area and depth point results used to calculate the bENC of the test area.

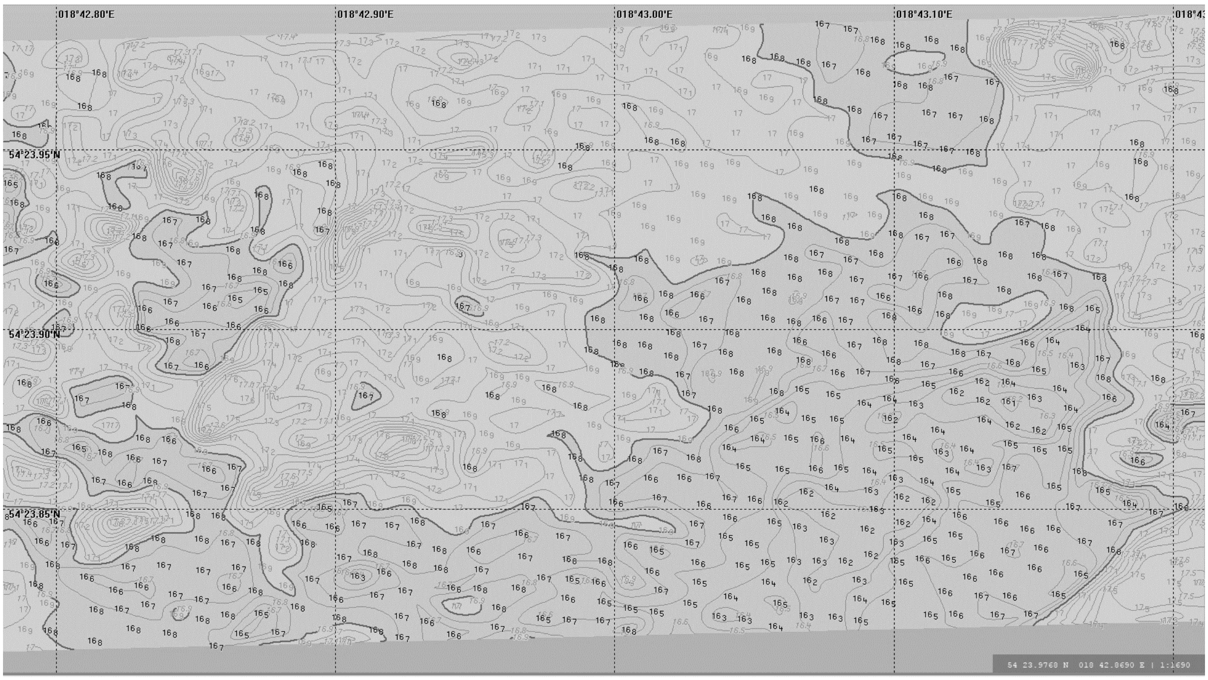

Figure 7. Part of bENC made for area of experiment (SeeMyENC SevenCs software was used for chart visualisation).

Such precise bENCs of areas described in Exclusive or Special Orders could be useful for precise underwater vehicle navigation and other tasks where precise bottom shape information is needed.

6. CONCLUSIONS. Knowledge of the depth of an area of water is crucial to the ability to navigate it safely. Bathymetric electronic navigational charts consist of precise depth information and could be part of future Port ENCs or be used for port operation, mooring, and similar tasks where precise information regarding the clearance over the keel is valuable. Comparative navigation methods based on terrain-depth information are attractive alternatives to GNNS positioning. They might also provide one of the few solutions, apart from dead-reckoning systems, for underwater vehicle navigation.

ACKNOWLEDGEMENTS. The results presented were financed from the European Regional Development Fund under the 2014-2020 Operational Programme Smart Growth. Project entitled „Developing of autonomous/remote operated surface platform dedicated hydrographic measurements on restricted reservoirs" *implemented as part of the National Centre for Research and Development competition: INNOSBZ.*

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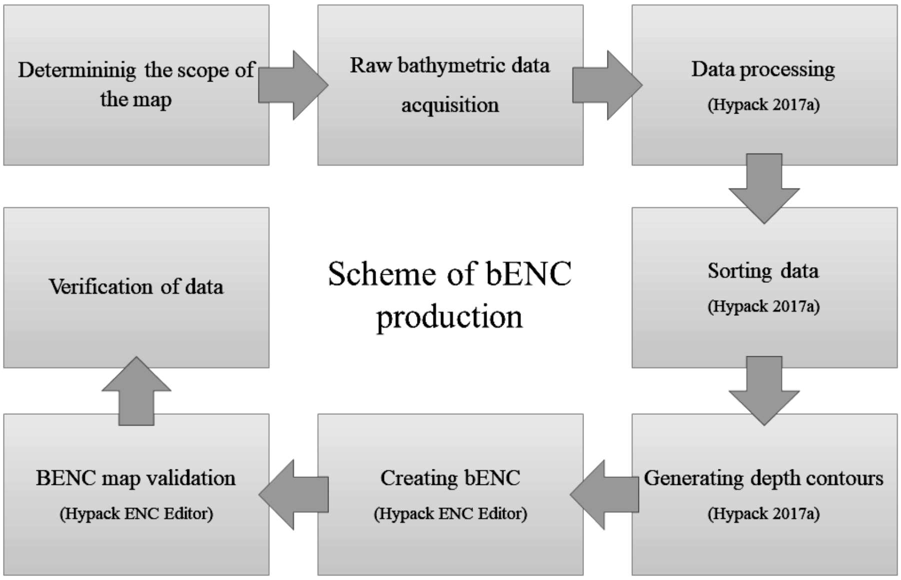

Figure 1. bENC production using Hypack software.

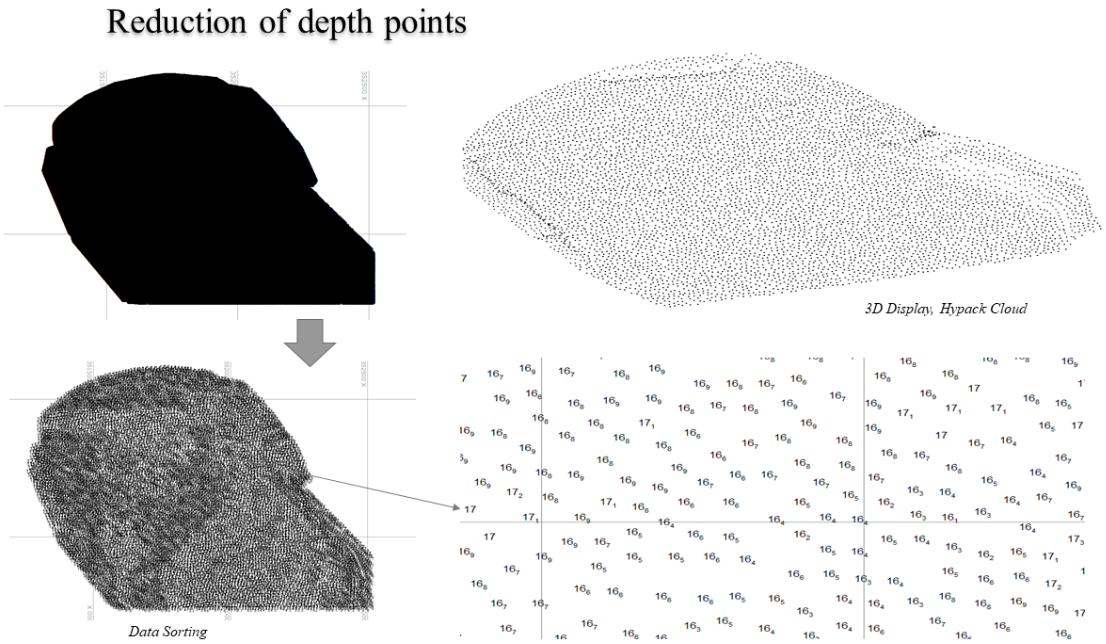

Figure 2. The depth point selection process.

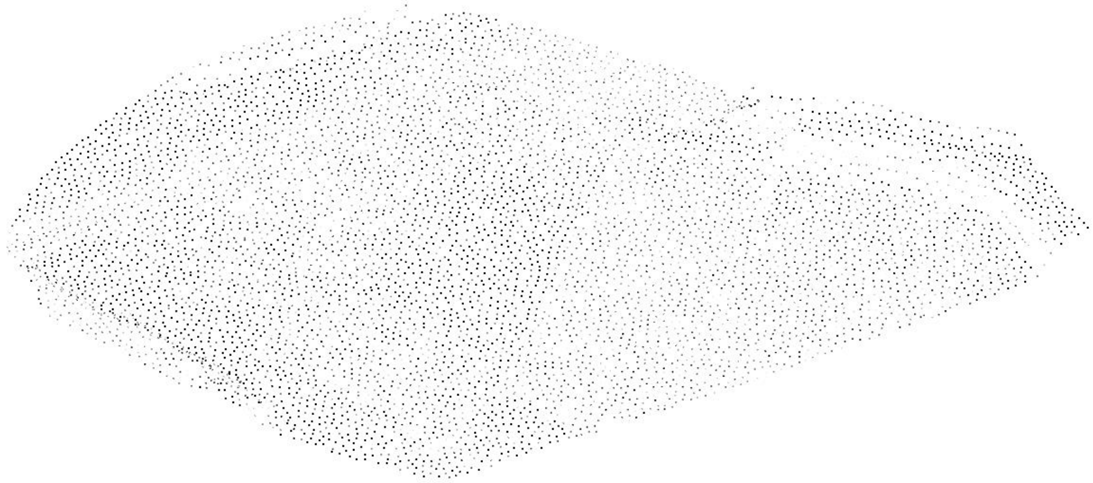

Figure 3. Cloud of points in a Hypack 3D display of the test area.

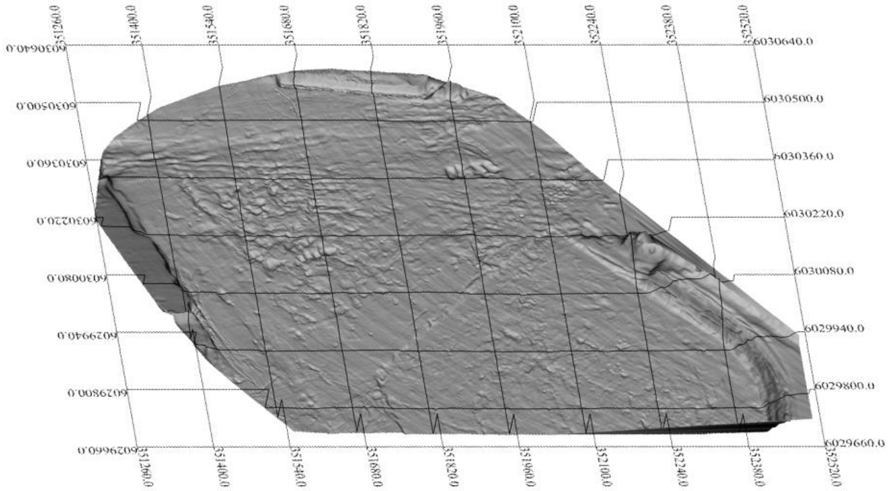

Figure 4. 3D visualisation of the point cloud of the test area.

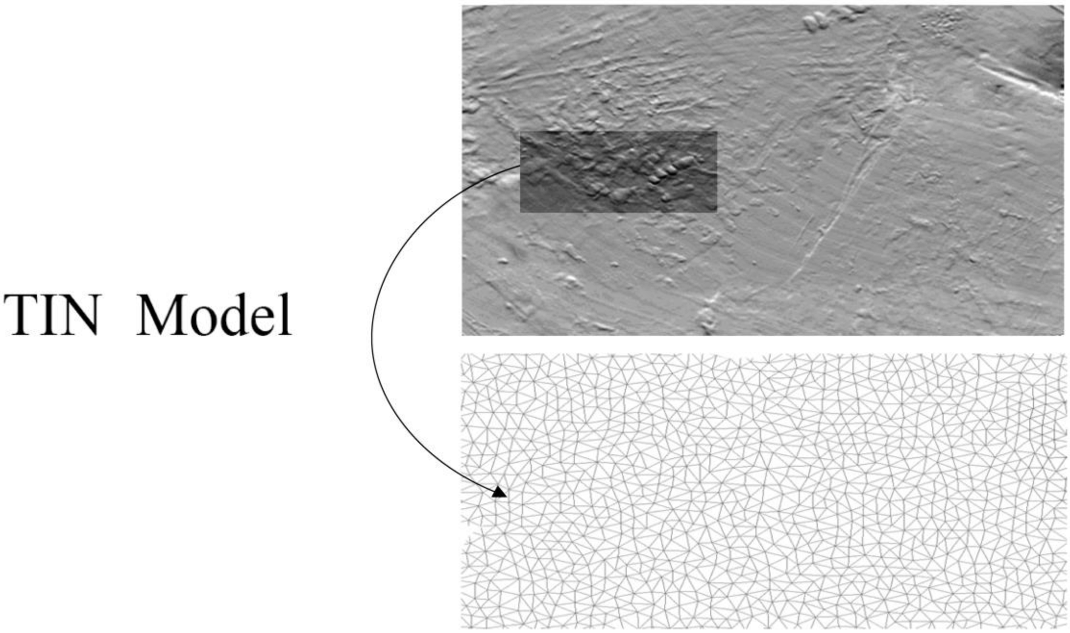

Figure 5. Generation of a TIN from a point cloud.

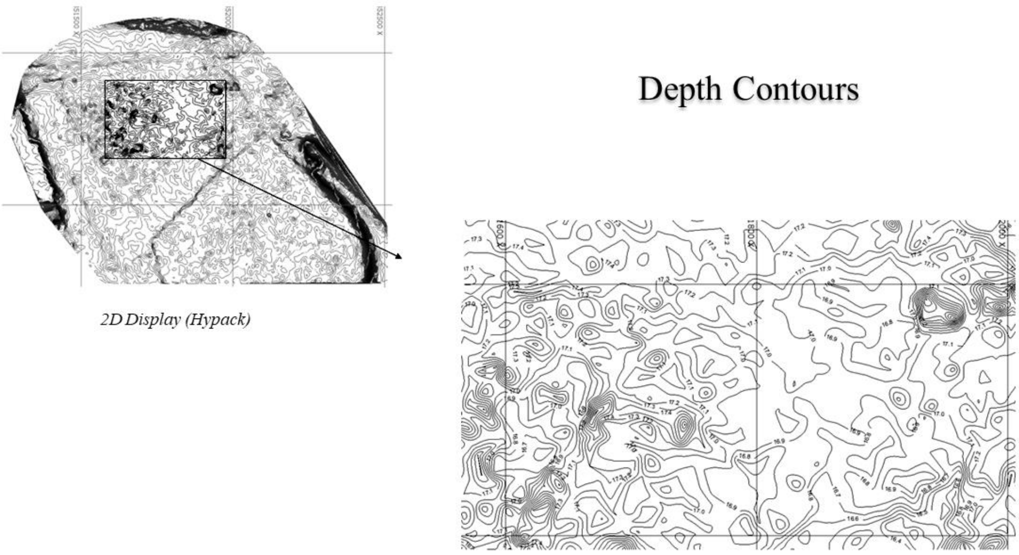

Figure 6. Depth contour generated from the TIN every 10 cm.

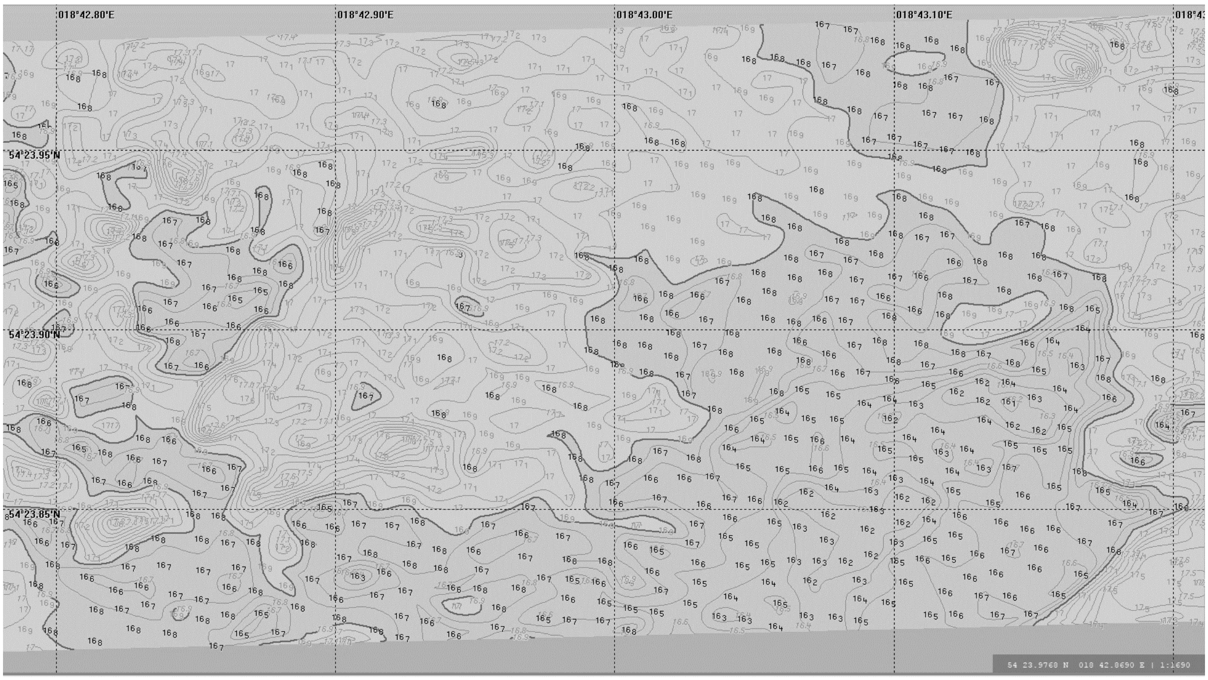

Figure 7. Part of bENC made for area of experiment (SeeMyENC SevenCs software was used for chart visualisation).

Table. 1. Comparison of Exclusive and Special Order standards for hydrographic surveys (Canadian Hydrographic Service, 2013)

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