

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

Andrzej Stateczny^{1,*}, Daria Gronska² and Weronika Motyl²

¹Department of Geodesy, Faculty of Civil and Environmental Engineering, Gdansk University of Technology, Poland

²Marine Technology Ltd, Szczecin, Poland

*Corresponding Author email: andrzej.stateczny@pg.edu.pl

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 where GNSS 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 (Włodarczyk-Sielicka and Stateczny, 2015, 2016; Włodarczyk-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 Włodarczyk-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.

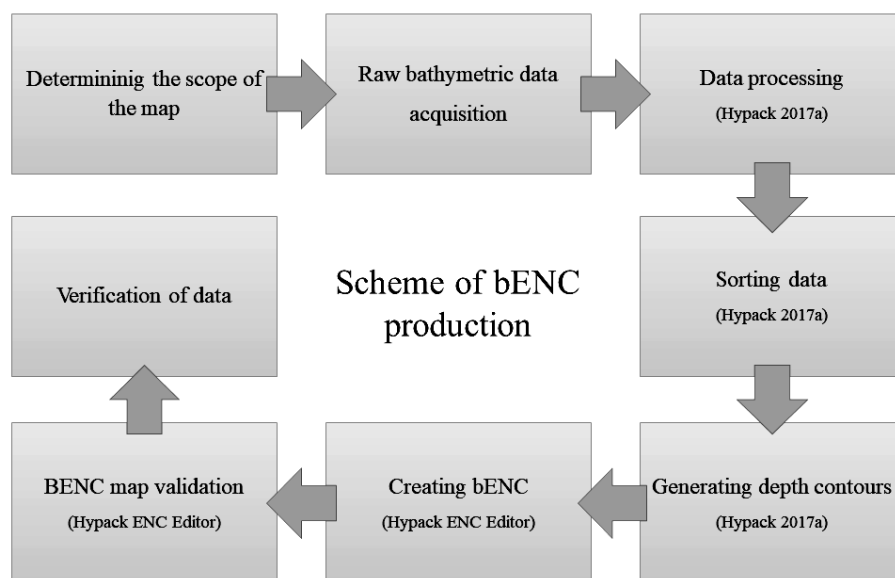


Figure 1. Algorithm for bENC production based on Hypack Max & Hysweep.

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 |
| 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 BATHYMETRIC 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.

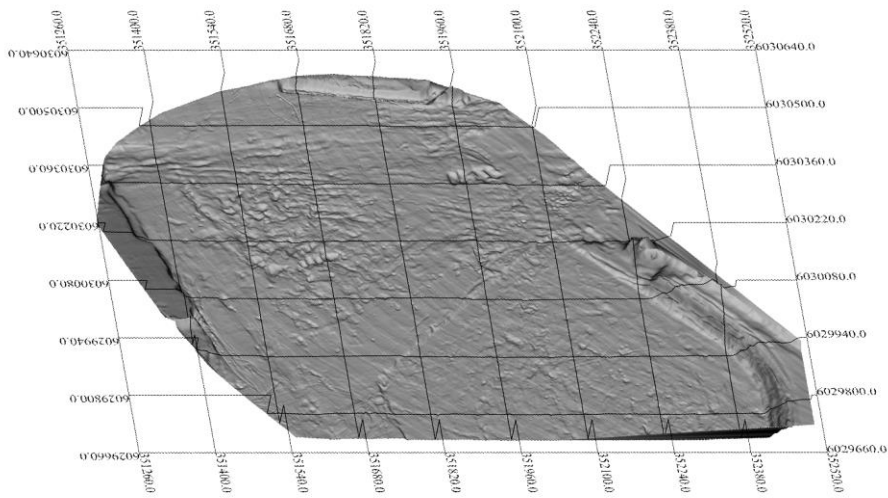


Figure 4. 3D visualisation of cloud of points of testing area.

TIN Model

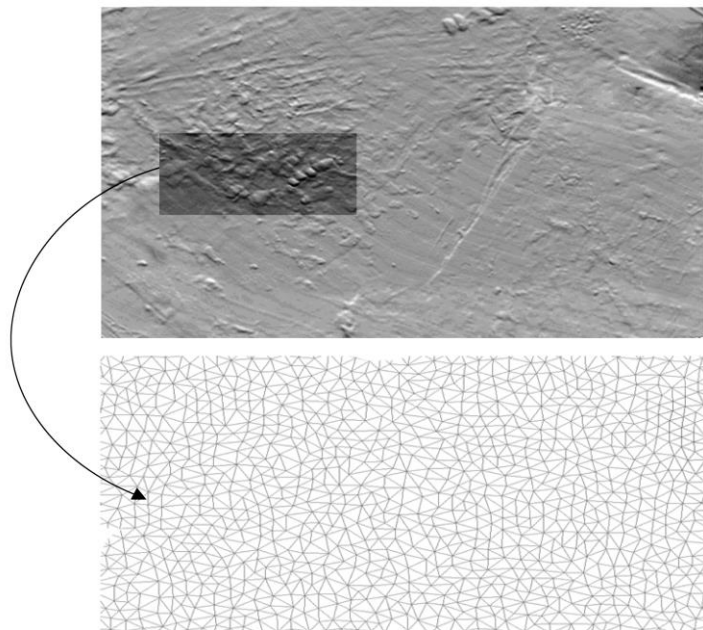


Figure 5. Generation of Triangle Irregular Network (TIN) from cloud of points.

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 ENC's 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 GNSS 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.*

REFERENCES

- Canadian Hydrographic Service (2013). Standards for Hydrographic Surveys. June 2013, Edition 2. <http://www.charts.gc.ca/data-gestion/standards-normes/intro-eng.asp>
- Chen, P., Li, Y., Su, Y., Chen, X. and Jiang, Y. (2015a). Review of AUV Underwater Terrain Matching Navigation. *Journal of Navigation*, **68**, 1155-1172.
- Chen, P., Li, Y., Su, Y., Chen, X. and Jiang, Y. (2015b). Underwater terrain positioning method based on least squares estimation for AUV. *China Ocean Engineering*, **29**, 859-874.
- Claus, B. and Bachmayer, R. (2015). Terrain-aided Navigation for an Underwater Glider. *Journal of Field Robotics*, **32**, 935-951.
- Dong, M., Chou, W. and Fang, B. (2017). Underwater Matching Correction Navigation Based on Geometric Features Using Sonar Point Cloud Data. *Scientific Programming*, article 7136702.
- Hagen, O., Anonsen, K. and Saebo, T. (2015). Toward Autonomous Mapping with AUVs - Line-to-Line Terrain Navigation. *Oceans 2015 - MTS/IEEE*, Washington DC.
- Han, Y., Wang, B., Deng, Z. and Fu, M. (2016). An Improved TERCOM-Based Algorithm for Gravity-Aided Navigation. *IEEE Sensors Journal*, **16**, 2537-2544.
- Hyla, T., Wawrzyniak, N. and Kazimierski, W. (2015). Model of Collaborative Data Exchange for Inland Mobile Navigation. In *Proceedings of Soft Computing in Computer and Information Science Conference*, Miedzyzdroje, Poland. *Advances in Intelligent Systems and Computing*, **342**, 435-444.
- Jung, J., Li, J., Choi, H. and Myung, H. (2017). Localization of AUVs using visual information of underwater structures and artificial landmarks. *Intelligent Service Robotics*, **10**, 67-76.
- Kazimierski, W. and Wlodarczyk-Sielicka, M. (2016). Technology of Spatial Data Geometrical Simplification in Maritime Mobile Information System for Coastal Waters. *Polish Maritime Research*, **23**, 3-12.
- Li, Y., Ma, T., Chen, P., Jiang, Y., Wang, R. and Zhang, Q. (2017a). Autonomous underwater vehicle optimal path planning method for seabed terrain matching navigation. *Ocean Engineering*, **133**, 107-115.



- Li, Y., Ma, T., Wang, R., Chen, P., Shen, P. and Jiang, Y. (2017b). Terrain Matching Positioning Method Based on Node Multi-information Fusion. *Journal of Navigation*, **70**, 82-100.
- Li, Y., Wang, R., Chen, P. and Zhang, Q. (2017c). Terrain Correlation Correction Method for AUV Seabed Terrain Mapping. *Journal of Navigation*, **70**, 1062-1078.
- Lubczonek, J. (2016). Geoprocessing of High Resolution Imageries for Shoreline Extraction in the Process of the Production of Inland Electronic Navigational Charts. *Photogrammetrie Fernerkundung Geoinformation*, **4**, 225-235.
- Lubczonek, J. and Borawski, M. (2016). A New Approach to Geodata Storage and Processing Based on Neural Model of the Bathymetric Surface. *Baltic Geodetic Congress (BGC Geomatics)*, 1-7.
- Maleika, W. (2015a). Moving Average Optimization in Digital Terrain Model Generation Based on Test Multibeam Echosounder Data. *Geo-Marine Letters*, **35**, 61–68.
- Maleika, W. (2015b). The Influence of the Grid Resolution on the Accuracy of the Digital Terrain Model Used in Seabed Modelling. *Marine Geophysical Research*, **36**, 35–44.
- Menozi, A., Hansen, J., Peele, G., Snarski, S. and Merrick, C. (2015). On the Development of a Framework for Underwater Localization Using All-Source Data. *OCEANS 2015*, Genova, Italy.
- Quintas, J., Teixeira, F. and Pascoal, A. (2016). Magnetic Signal Processing Methods with Application to Geophysical Navigation of Marine Robotic Vehicles. *OCEANS 2016 MTS/IEEE*, Monterey, California.
- Ramesh, R., Jyothi, V., Vedachalam, N., Ramadass, G. A. and Atmanand M. A. (2016). Development and Performance Validation of a Navigation System for an Underwater Vehicle. *Journal of Navigation*, **69**, 1097-1113.
- Salavasidis, G., Harris, C., McPhail, S., Phillips, A. B. and Rogers E. (2016). Terrain Aided Navigation for Long Range AUV Operations at Arctic Latitudes. *2016 IEEE/OES (AUV)*, Book Series: *IEEE OES Autonomous Underwater Vehicles*, 115-123.
- Song, Z., Bian, H. and Zielinski, A. (2016). Application of acoustic image processing in underwater terrain aided navigation. *Ocean Engineering*, **121**, 279-290.
- Specht C., Weintrit, A. and Specht, M. (2016). Determination of the Territorial Sea Baseline - Aspect of Using Unmanned Hydrographic Vessels, *Transnav-International Journal on Marine Navigation and Safety of Sea Transportation*, **10**, 649-654.
- Specht, C., Switalski, E. and Specht, M. (2017). Application of an Autonomous/Unmanned Survey Vessel (ASV/USV) in Bathymetric Measurements, *Polish Maritime Research*, **24**, 36-44.
- Stuntz, A., Kelly, J. and Smith, R. (2016). Enabling Persistent Autonomy for Underwater Gliders with Ocean Model Predictions and Terrain-Based Navigation. *Frontiers in Robotics and AI*, **3**, article 23.
- Wang, L., Yu, L. and Zhu, Y. (2015). Construction Method of the Topographical Features Model for Underwater Terrain Navigation. *Polish Maritime Research*, **22**, 121-125.
- Wawrzyniak, N. and Stateczny, A. (2017). MSIS Image Positioning in Port Areas with the Aid of Comparative Navigation Methods. *Polish Maritime Research*, **24**, 32-41.
- Wawrzyniak, N., Włodarczyk-Sielicka, M. and Stateczny, A. (2017). MSIS sonar image segmentation method based on underwater viewshed analysis and high-density seabed model. *Proceedings of the 18th International Radar Symposium (IRS)*, Prague, Czech Republic.



- Weintrit, A. (2005). Presentation of safety contours on electronic navigational charts in *Maritime Transportation and Exploitation of Ocean and Coastal Resources, vols 1 and 2, vol 1: Vessels For Maritime Transportation*, 1659-1666. London, CRS Press.
- Wei, F., Yuan, Z. and Zhe, R. (2015). UKF-Based Underwater Terrain Matching Algorithms Combination. *ACSR-Advances in Computer Science Research*, 1027-1030.
- Włodarczyk-Sielicka, M., Lubczonek, J. and Stateczny, A. (2016). Comparison of Selected Clustering Algorithms of Raw Data Obtained by Interferometric Methods Using Artificial Neural Networks. *Proceedings of the 16th International Radar Symposium (IRS)*, Krakow, Poland.
- Włodarczyk-Sielicka, M. and Stateczny, A. (2015). Selection of SOM Parameters for the Needs of Clusterisation of Data Obtained by Interferometric Methods. In *Proceedings of the 16th International Radar Symposium (IRS)*, Dresden, Germany, 1129-1134.
- Włodarczyk-Sielicka, M. and Stateczny, A. (2016). Clustering Bathymetric Data for Electronic Navigational Charts. *Journal of Navigation*, **69**, 1143-1153.
- Wu, L., Wang, H., Chai, H., Hsu, H. and Wang, Y. (2015a). Research on the Relative Positions-Constrained Pattern Matching Method for Underwater Gravity-Aided Inertial Navigation. *Journal of Navigation*, **68**, 937-950.
- Wu, M. and Yao, J. (2015b). Adaptive UKF-SLAM Based on Magnetic Gradient Inversion Method for Underwater Navigation. *Lectures Notes in Artificial Intelligence*, vol. 9245, pp. 237-247.
- Zhang, T., Xu, X. and Xu, S. (2015). Method of establishing an underwater digital elevation terrain based on kriging interpolation. *Measurement*, **63**, 287-298.
- Zhou, L., Cheng, X., Zhu, Y. and Lu, Y. (2015). Terrain Aided Navigation for Long-Range AUVs Using a New Bathymetric Contour Matching Method. *IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, Busan, South Korea.
- Zhou, L., Cheng, X., Zhu, Y., Dai, C. and Fu, J. (2017). An Effective Terrain Aided Navigation for Low-Cost Autonomous Underwater Vehicles. *Sensors*, **17**, article 680.
- Zhou, L., Cheng, X. and Zhu, Y. (2016). Terrain aided navigation for autonomous underwater vehicles with coarse maps. *Measurement Science and Technology*, **27**, article 095002.
- Zhu, Z., Guo, Y. and Yang, Z. (2016). Study on Initial Gravity Map Matching Technique Based on Triangle Constraint Model. *Journal of Navigation*, **69**, 353-372.



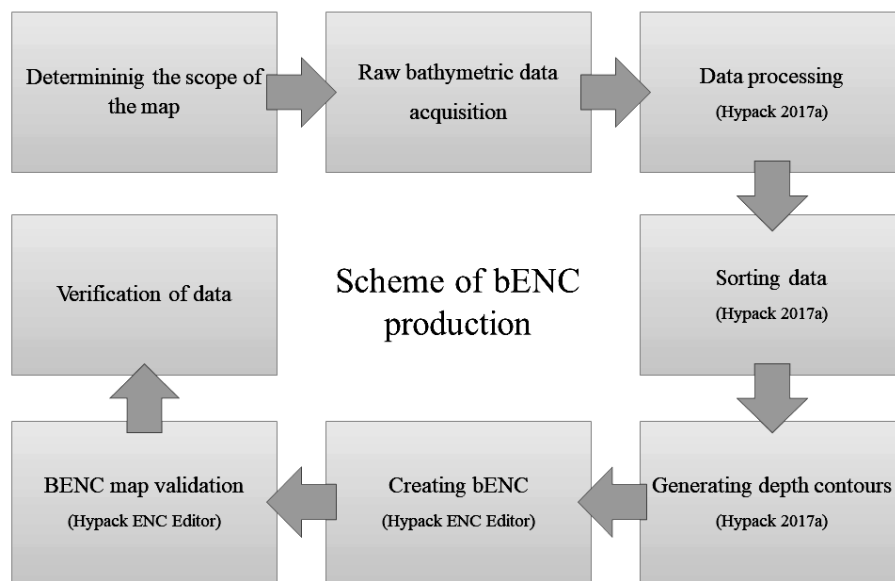


Figure 1. bENC production using Hypack software.

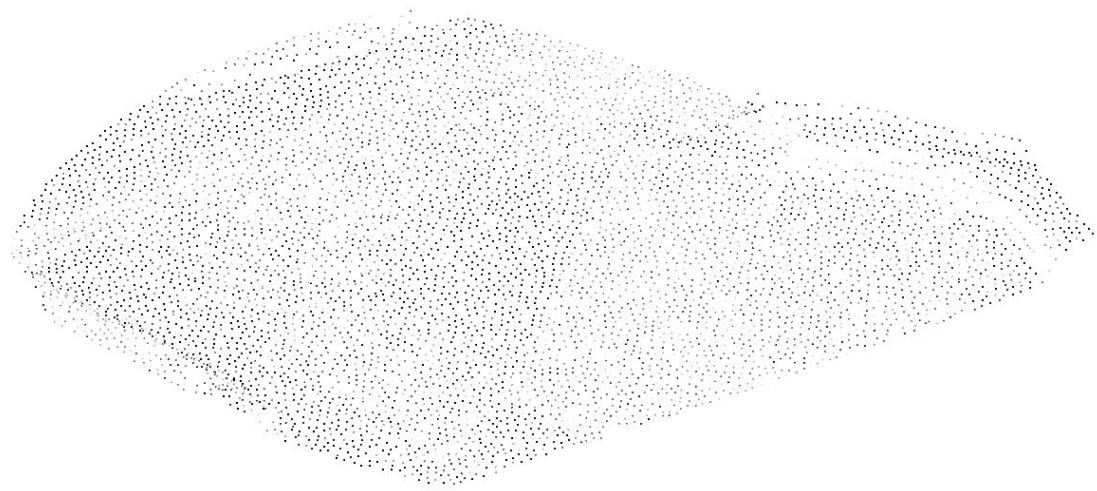


Figure 3. Cloud of points in a Hypack 3D display of the test area.

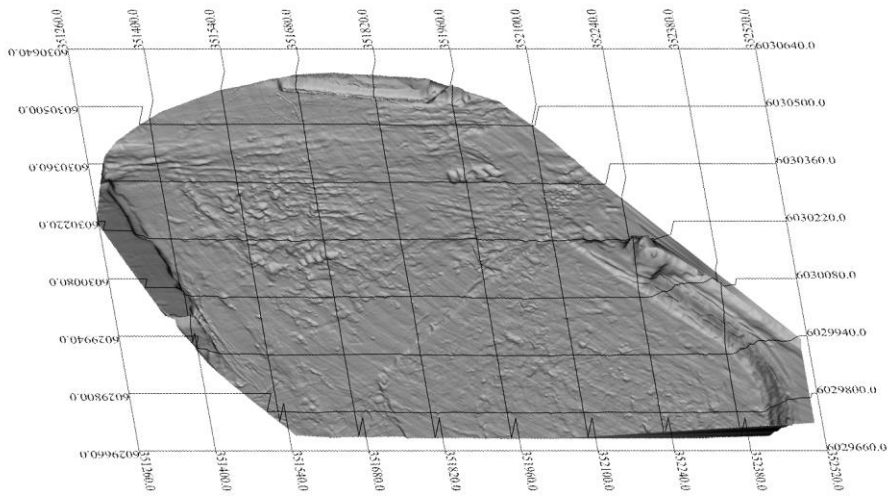


Figure 4. 3D visualisation of the point cloud of the test area.

TIN Model

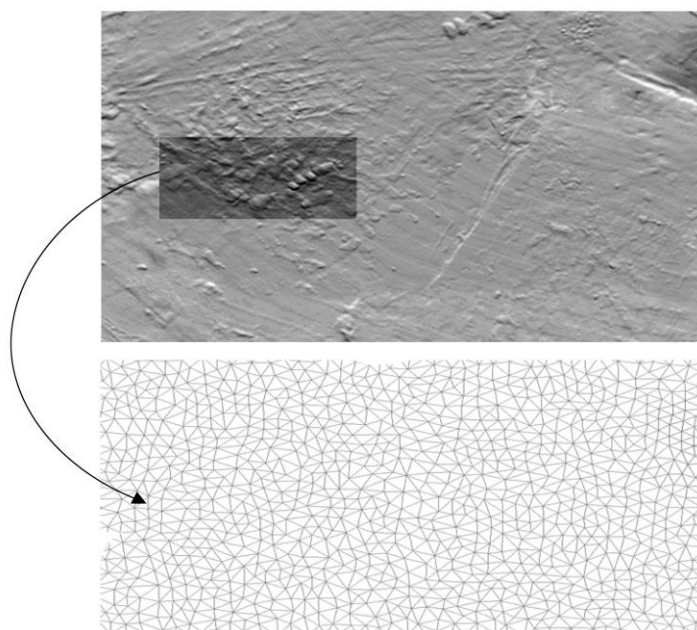
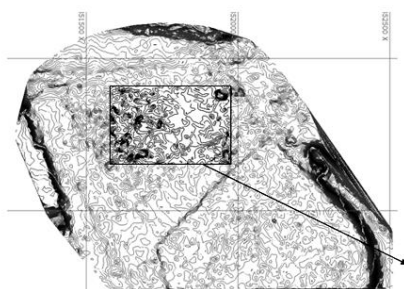


Figure 5. Generation of a TIN from a point cloud.



2D Display (Hypack)

Depth Contours

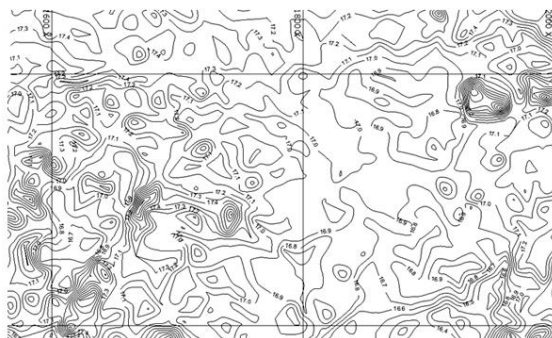


Figure 6. Depth contour generated from the TIN every 10 cm.

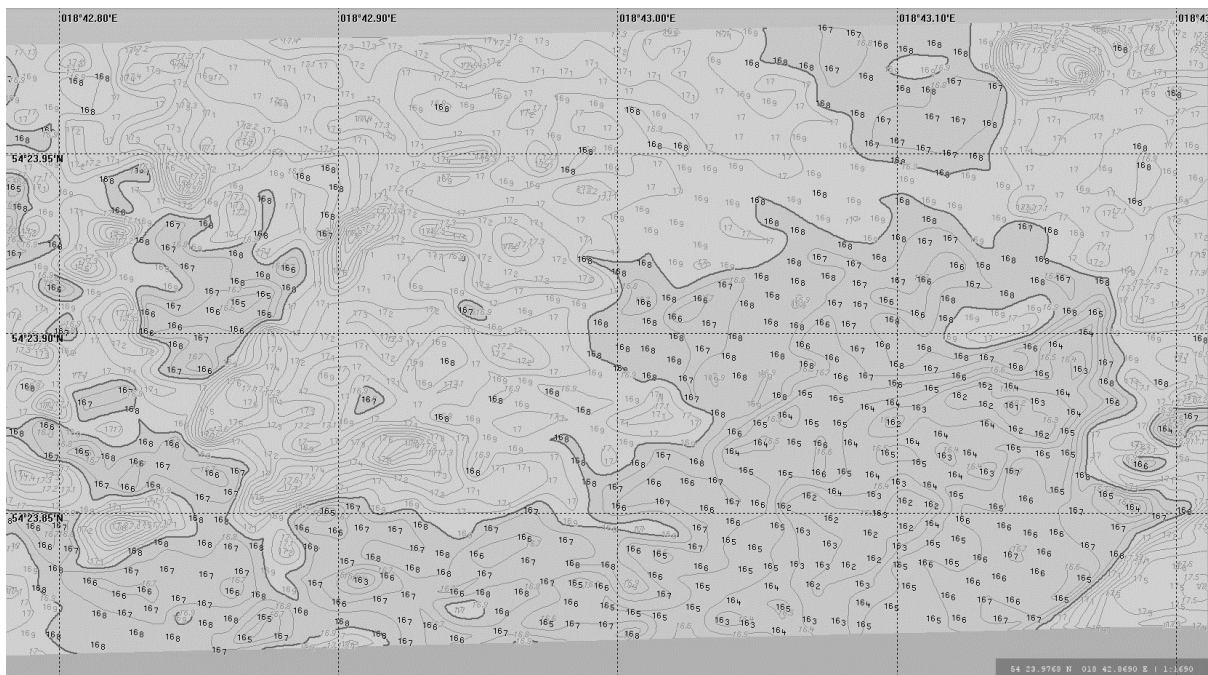


Figure 7. Part of bENC made for area of experiment (SeeMyENC SevenCs software was used for chart visualisation).

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

| Order | Exclusive | Special |
|--|---|---|
| Examples of typical areas | Shallow water in harbours, berthing areas, and associated critical channels with minimal under-keel clearances or engineering surveys | Harbours, berthing areas, and associated critical channels with minimal under-keel clearances |
| Horizontal accuracy (95% confidence level) | 1 m | 2 m |
| Depth accuracy for reduced depths (95% Confidence Level) | a = 0.15 m b = 0.0075 | a = 0.25 m b = 0.0075 |
| System detection capability | Features > 0.5 m ³ | Features > 1 m ³ |

