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ORIGINAL RESEARCH PAPER

The influence of the grid resolution on the accuracy of the digital terrain model used in seabed modeling

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Abstract Modern digital terrain models (DTM) are widely used in the exploration of water areas. The models are often based on bathymetric data from a multibeam echosounder. DTM creators should properly select model parameters, firstly the grid resolution. High grid resolution enables creating very accurate models, however, they require high computing power and the data gathered in the grid occupy much more memory space. Low grid resolution means significantly less data describing the model, but, naturally, its accuracy will also be lower. The author proposes a method permitting to examine the accuracies of DTMs that depend on adopted grid resolution. Further the article will present search for an accurate grid resolution for three selected real surfaces of the seabed. The obtained results were visualized and interpreted. The author also proposes tips to be used while creating DTMs. Conclusions from the research may be helpful in digital terrain modeling of the seabed.

Keywords Digital terrain model · Grid resolution · Bathymetric survey · Accuracy of DTM

Introduction

The use of water areas in most cases requires the knowledge of detailed bathymetric data. This type of information is more and more frequently visualized and processed with geoinformation tools, so that more profound and comprehensive analyses can be made. At present, sounding by a multibeam echousounder (MBES) is one of the most effective and most accurate methods of depth measurements, yielding a set of measured points covering the entire seabed. As a rule, multibeam echosounder data recordings consist of a huge collection of measurement points, characterized by irregular spatial distribution. Such data, due to their large quantity and irregular distribution are not suitable for direct processing, such as visualization or analysis. For these reasons sounding data are processed into more ordered structures, such as grid (regular square network), that describes a digital terrain model (DTM) (Gaboardi et al. 2011; Hamilton 1980; Maleika 2012, 2013; Stateczny 2000). Grid structures are created through interpolation of measurement data (Gao 2001; Hammerstad et al. 1993; Lubczonek and Stateczny 2003).

The selected grid size is one of the key parameters in this process, directly affecting grid resolution, understood as a distance (expressed in metric units) between neighbouring points in the grid in the X and Y axes. For instance, grid = 1 m means that two adjacent points are 1 m apart. Thus, the overall number of points describing a given area, and consequently the model description accuracy, depends on grid resolution. High grid resolution offers a potentially high accuracy of the model, at a cost of huge quantity of data that have to be processed and recorded on mass storage. A lower grid resolution requires definitely less data for terrain description, but also lower accuracy of a created model (Calder and Mayer 2003). Therefore, it seems purposeful to seek such grid resolution for which the least quantity of data will produce a description with assumed accuracy. It is obvious that in practice the selection of grid resolution depends on a number of factors—primarily on the achievable resolution of the measurement instrument, and on the level of representation accuracy that the user needs to maintain for the given purpose. Other minor

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factors are: measurement class (defined by IHO), expected accuracy and quantity of measurement data.

This article proposes a method (algorithm) enabling estimation of the accuracy of created DTMs for various grid resolutions. Then research is presented which allows to estimate the impact of grid resolution on the accuracy of created DTMs. The performed experiments are of empirical nature. The data used are real measurement data from three surveys of varying relief. Test data were processed by computer methods using advanced numerical methods suitable for working with great data sets.

Similar studies, examining the influence of TIN (triangulated irregular network) on the accuracy of created models, were described in publication (Agugiaro and Kolbe 2012; Isenburg et al. 2006; Arge et al. 2010). However, for large data sets it seems more justified to use grid (Brasington and Richards 1998; Falcao et al. 2013; Jalving 1999; Luo et al. 2014; Yanalak 2003).

IHO standards in DTM

Worldwide organizations involved in hydrographic survey comply with IHO Standards for Hydrographic Surveys, issued by the International Hydrographic Organization—IHO (IHO 2008). The basic aim of that publication is to establish minimum standards for hydrographic surveys so that the data collected in compliance with the standards are sufficiently accurate. The standards also enable the determination of spatial uncertainty of data, which will allow users of the information to use the survey results safely (merchant fleet, the navy, GIS users, etc.).

Standards described in IHO S.44 should be treated as a kind of suggestion (and not a requirement) regarding the expectations of the accuracy of created seabed models and as a certain reference point for assessing the obtained inaccuracies in the research described below. Certainly, different hydrographic offices reinterpret IHO standards to make their own specifications.

In order to approach in a systematic manner different requirements on accuracy of measurements of diverse terrains, the following four classes of measurements are distinguished:

- Special—areas where under-keel clearance is critical ($a = 0.25$ m, $b = 0.0075$),
- 1a—areas shallower than 100 m where under-keel clearance is less critical but features of concern to surface shipping may exist ($a = 0.5$ m, $b = 0.013$),
- 1b—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 ($a = 0.5$ m, $b = 0.013$),
- 2—areas generally deeper than 100 m where a general description of the sea floor is considered adequate ($a = 1$ m, $b = 0.023$).

The formula below is to be used to compute, at the 95 % confidence level (CL), the maximum allowable TVU (total vertical uncertainty):

$$TUV = \sqrt{a^2 + (b \times d)^2} \quad (1)$$

where a represents that portion of the uncertainty that does not vary with depth, b is a coefficient which represents that portion of the uncertainty that varies with depth, d is the depth, $b \times d$ represents that portion of the uncertainty that varies with depth.

The total modeling error is influenced by individual errors that occur during the consecutive modeling stages, i.e.:

- depth reading errors caused by measurement devices—dependent on device type, depth, type of bottom,—significant, given by producers of MBES (Hare 1995; Hammerstad 2001; Lurton and Augustin 2010; Maleika et al. 2011; Maleika 2013),
- errors resulting from adopted survey parameters (such as measurement unit rate, track configuration and multibeam echosounder parameters;—hard to estimate, generally neglected),
- errors in determining the position, dependent on the positioning and motion systems (Hare 1995; Morton et al. 2010),
- errors that occur during the interpolation process (so far these have been difficult to assess and are hence omitted by device operators),

Additionally, we can distinguish the following sources of errors in DTM modeling process:

- errors occurring during the surface interpolation/creating process (so far omitted by operators),
- errors due to the use of grid model of a specific resolution (which is the subject of research described in this paper).

Measurement data processing, DTM modeling and data analysis make use of advanced numerical algorithms that enable both effective data processing (important feature due to great amount of data) and high 'quality' of modeling.

Importance of grid resolution in DTM modeling of sea bottom

At present a DTM of sea floor is mostly based on the regular square network, referred to as grid and is a

Table 1 Number and size of a 1 km^2 area covering data located in grid structures of various resolution

	Grid resolution (m)	No. of points	Size (MB)
1	10	10×10^3	0.04
2	5	40×10^3	0.15
3	2	250×10^3	0.95
4	1	1×10^6	3.81
5	0.5	4×10^6	~15
6	0.25	16×10^6	~61
7	0.1	100×10^6	~381

principal model representing the terrain relief. The resolution is essential from the viewpoint of data quantity used to describe the terrain surface (Brasington and Richards 1998). Higher grid resolution gives a more accurate model, which, however, is burdened with a huge amount of data describing it (number of data gathered in the grid structure grows quadratically along with resolution increase). A large amount of data significantly hinders their further processing, i.e. interpolation, volumetric computations, data compression, creation of contour maps, as well as recording and archiving (particularly when larger areas are modeled).

In the described research the data obtained using Simrad EM 3002 echosounder were used, and the survey was performed in shallow water (approximately 5–20 m depth). The distances between neighbouring measurement points varied from 5 to 20 cm. In the case of the 'wrecks' surface, 3 overlapping profiles had been carried out, which additionally increases the data density—the distances between points lie within 3–10 cm.

Given the above properties it can be assumed, that the highest useful grid resolution is equal 10 cm (used only in special cases, describing small areas, e.g. wrecks, underwater constructions, small untypical objects). For shipping lanes and port basins the grid within 0.5–2 m is most often used, and for large areas (e.g. lakes, gulfs, sea subareas), due to data amounts, the grid of 5–100 m is used. A significant difficulty when creating a DTM lies in the issue of describing large areas with as high accuracy as possible. The subjective decision of the user of hydrographic software determines the selection of the "optimal" grid size.

Table 1 presents the number and volume of data covering an area of 1 km^2, described with the use of grid structures of varying resolution (it was assumed that a recorded depth is recorded with a number of 4 byte length).

Modern geoinformation systems (including hydrographic and GIS systems) face a problem of simultaneous processing of great quantities of data. For this reason the examined area is often divided into smaller portions, and each is processed separately. We may assume that it is possible to reduce the number of data describing a DTM by decreasing grid resolution, and at the same time maintain a sufficient accuracy of the created model.

If so, it will be desireable to be able to choose such grid structure that will minimize, with an expected accuracy of the model, the number of included data.

The algorithm

In order to estimate the accuracy of a created model described by a grid structure, we have to be able to compare the model to a reference surface. The author proposes to create from measurement data a terrain surface of very high grid resolution, thus very accurate. To minimize errors made during interpolation, reference surfaces for the research were formed by three common interpolation methods: Moving Average, Kriging, Inverse Distance to a Power (2nd degree), and the obtained models were averaged and adopted as reference DTMs. Those interpolation methods were selected, since according to published research results they give good results (low errors) when creating DTM (Maleika et al. 2012; Kidner 2003; Su et al. 2008).

Then we create a DTM from the same measurement points, based on a grid of any resolution. To get a precise quantitative determination of the created DTM accuracy (for a chosen grid resolution) all we have to do is compare the obtained surface with the reference one. To make it possible, the DTM surface has to be converted to a network with the same grid resolution as the reference one. This can be done through fast interpolation algorithms based on splines. This method results in small errors and is commonly used in many solutions related to creating and modeling data for changing the resolution of the signal/model (Jiang and Xu 2011; Lee et al. 1997; Unser et al. 1991). The obtained surface can then be compared to the reference surface. By subtracting one surface from the other, we get a matrix of error distribution. Analyzing this matrix we can determine, maximum error, mean error, standard deviation, root mean square error or errors at a specific confidence level. A lot of information can also be derived from visual analysis of spatial distribution of errors. Analyzing the above parameters we can assess the accuracy of the examined model and to estimate the conformity with current standards, model application and expected accuracy.

Schematically, the proposed method for examining accuracy of created models of any grid resolution is presented in Fig. 1.

The experiments

Three test surfaces were formed to verify the proposed method and to test practically the influence of grid structure

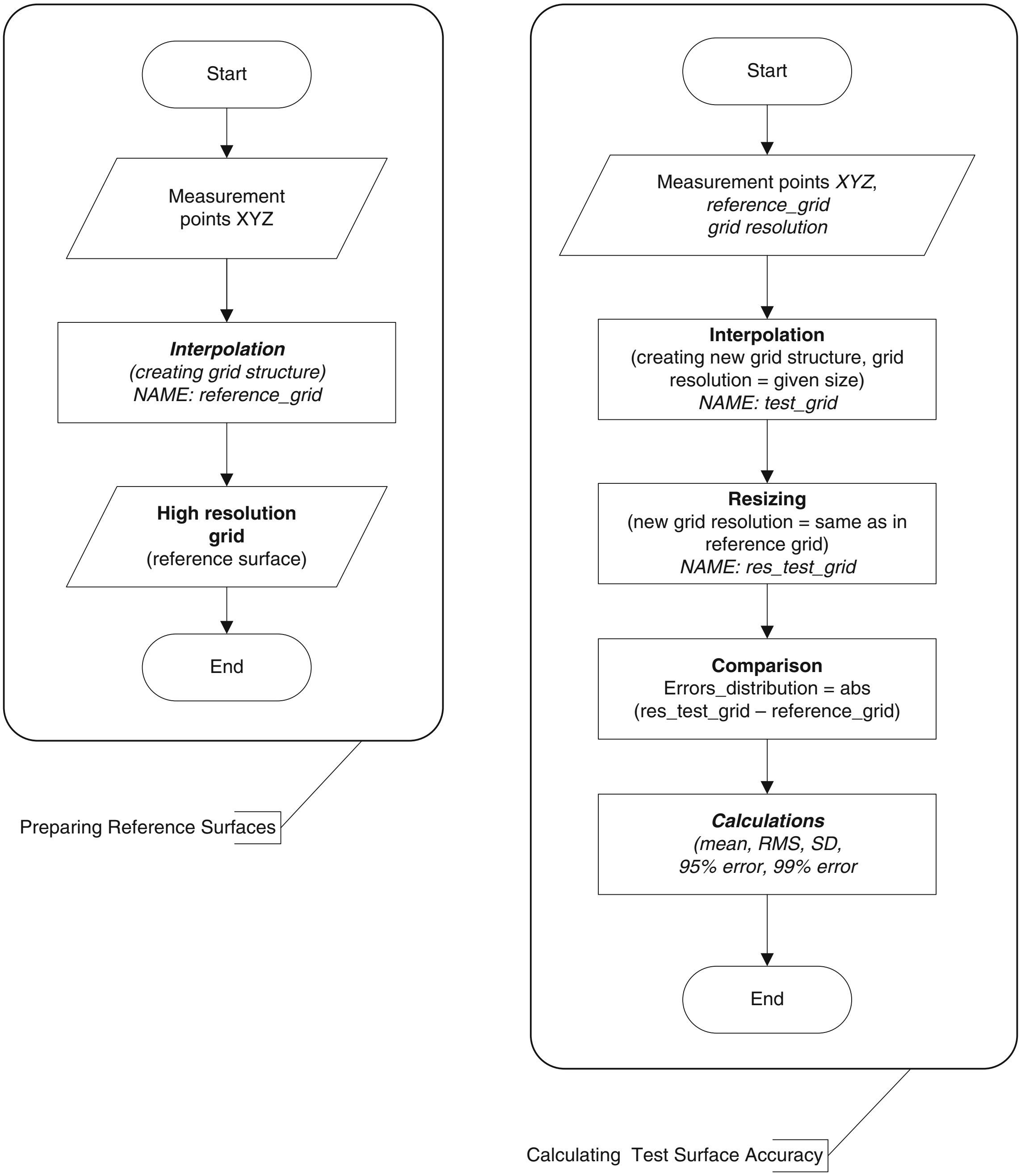

Fig. 1 Algorithm describing the method for testing the accuracy of a DTM of any resolution

size on the accuracy of a seabed model made from real measurement data. These test surfaces, named '*gate*', '*rotator*', '*wrecks*', with very high resolution, are reference surfaces (see Fig. 2).

The resolution of these surfaces is, respectively: 0.25 m ('*gate*' and '*rotator*') and 0.01 m ('*wrecks*'). Then we created several models, using the same measurement points, described in grids of varied resolution. The properties of those models are shown in Table 2 (grey background indicates reference surfaces).

Each of the created DTMs describes a selected area with different accuracy (with different number of data contained in the grid structure).

Figures 3, 4, and 5 present test surfaces described by means of grid structure of various resolution.

An essential objective of the research is to examine how the decreasing of data amount (by reducing grid resolution) affects the inaccuracy of the created model. To this end, all created surfaces were compared with the reference surfaces (previously the resizing of data was made to obtain

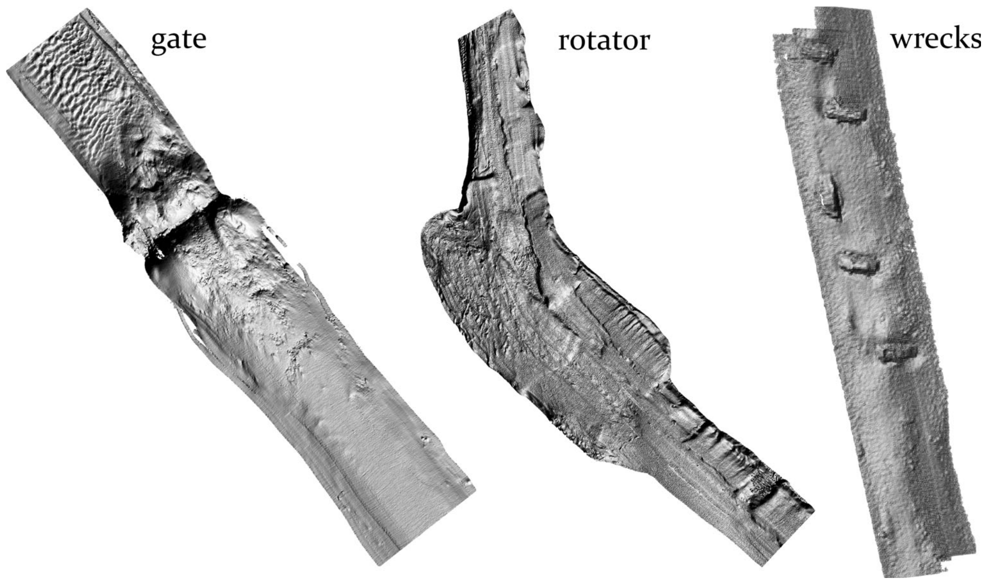

Fig. 2 Three test reference surfaces: ‘gate’, ‘rotator’, ‘wrecks’

Table 2 Properties of models created using grids of various resolutions

Surface name	Grid resolution (m)	Grid size	Total nodes	Size (MB)
Gate	0.25	3,826 × 3,226	12,342,676	98.7
Gate	0.5	1,914 × 1,614	3,089,196	24.7
Gate	1	957 × 807	772,299	6.2
Gate	2	479 × 404	193,516	1.5
Gate	5	192 × 162	31,104	0.24
Gate	10	97 × 82	7,954	0.06
Rotator	0.25	7,419 × 5,256	38,994,264	312
Rotator	0.5	3,710 × 2,628	9,749,880	78
Rotator	1	1,856 × 1,315	2,440,640	19.5
Rotator	2	928 × 658	610,624	4.9
Rotator	5	372 × 264	98,208	0.79
Rotator	10	186 × 132	24,552	0.20
Wrecks	0.01	7,074 × 2,525	17,861,850	142
Wrecks	0.02	3,537 × 1,263	4,467,231	35.7
Wrecks	0.05	1,416 × 506	716,496	5.7
Wrecks	0.1	708 × 253	179,124	1.4
Wrecks	0.25	284 × 102	28,968	0,.23
Wrecks	0.5	142 × 51	7,242	0.058
Wrecks	1	72 × 26	1,872	0.015

matrices of the same size). While comparing, we determined maximum error, mean error, root mean square error (RMS), standard deviation (SD), and an error at the confidence levels 95 and 99 %. Besides, a spatial error distribution was determined (depth differences between tested and reference surfaces at a specific point) marking particularly those areas where IHO standards were exceeded.

The results

Table 3 and Fig. 6 presents the results obtained in the process of comparison of test surfaces with reference surfaces.

Analyzing the results we can easily notice that along with a decrease in grid resolution the model accuracy also decreases. However, it is worth indicating the resolution for which we can recognize a model as having ‘sufficient’ accuracy. Optimizing the grid size will permit to reduce the amount of data and accelerate subsequent processing.

In the case under consideration the sufficiently accurate grid resolution for ‘*Gate*’ and ‘*Rotator*’ areas is 2 m. The mean error of the model in this case is, respectively, 1.42 and 1.75 cm, while the respective model errors at the confidence level of 99 % are 10.14 and 8.66 cm. Higher grid resolution for these surfaces (e.g. 1 or 0.5 m) increases model accuracy by approx. 50 %, simultaneously raising data amount four or eight times. Lower resolution than the suggested one, e.g. grid = 5 m or 10 m, makes the model rather inaccurate, so it cannot be accepted (and fails to satisfy S.44 Special Order). When we deal with larger sea areas of special class (high accuracy required), and the survey data will be visualized and used for making maps of small or medium scale, it seems that assuming 2-m grid resolution is optimal and enables creating accurate models of the seabed (at confidence level = 95 % the error is about 5 cm while 20 cm, which seems acceptable).

However, there exist situations where a model is expected to have a relatively high accuracy, for instance, when untypical small objects are found on the seabed. In such cases grid resolution is much higher, so that we are able to describe the bottom more precisely (by using high resolution networks). In the presented case the ‘*wrecks*’ surface with a few car wrecks illustrates such an example.

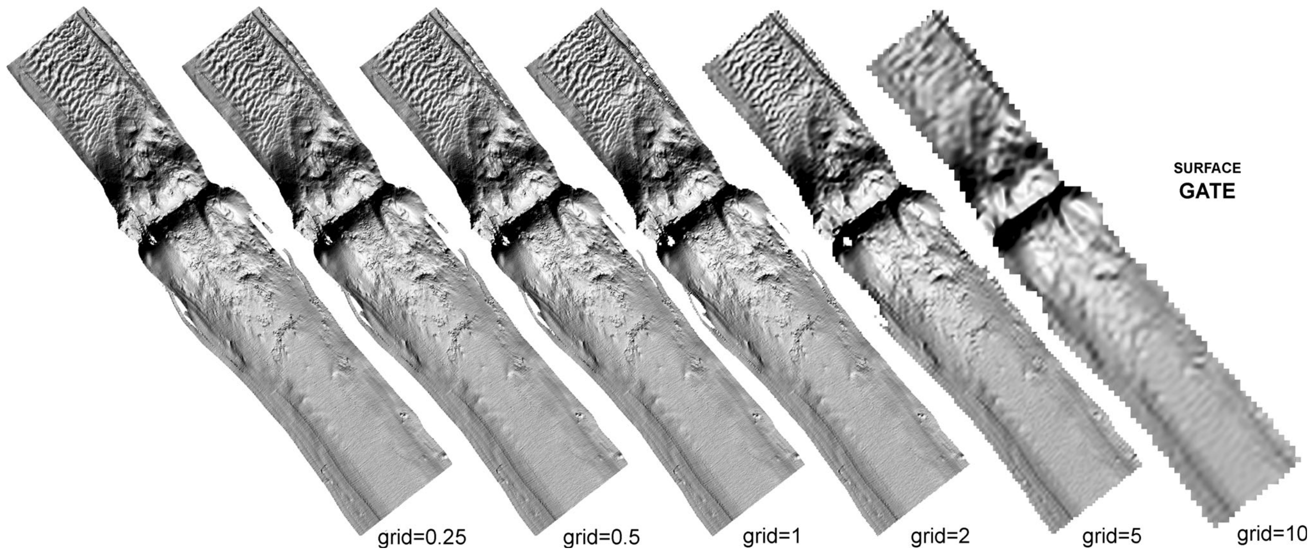

Fig. 3 'Gate' surface described by means of grid with different resolution

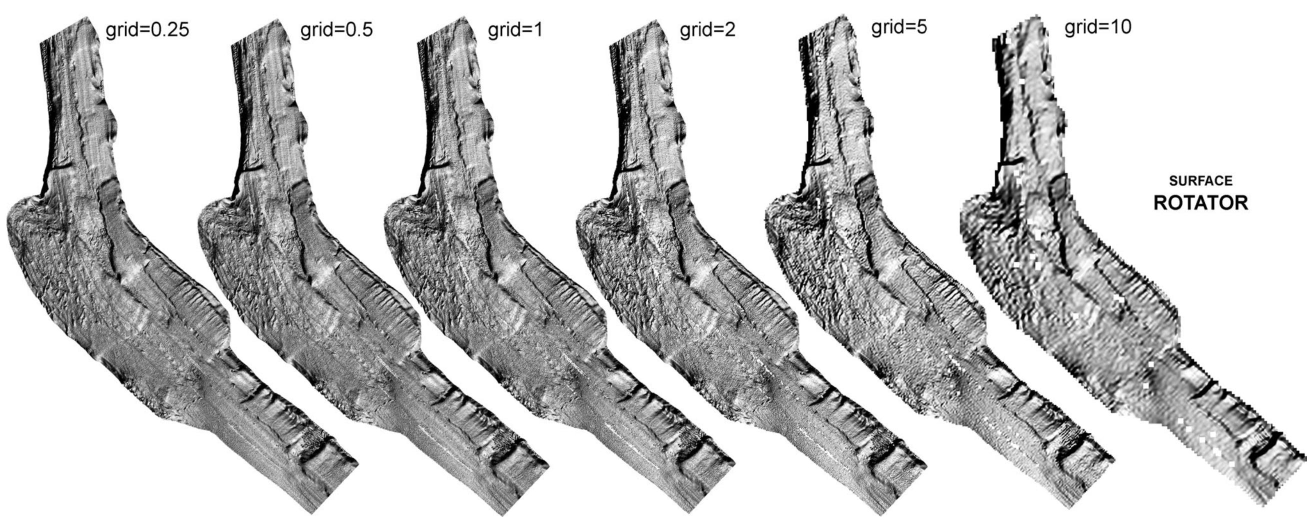

Fig. 4 'Rotator' surface described by means of grid with different resolution

It is worth noticing, that in such cases it is advisable to perform during the survey several additional profiles over the given area, in order to increase the measurement points density.

Analyzing the results for the '*wrecks*' surface we can assume that the sufficiently accurate grid size in this case is 0.25 m (mean error = 0.89 cm, 99 % error = 6.6 cm). Higher network resolution for that surface, e.g. 0.1 or 0.05 m, increases model accuracy by not more than 50 %, while the amount of data representing it grows 6 or 25 times. Resolution lower than the proposed one (e.g. grid = 0.5 or 1 m) leads to unacceptable inaccuracy of the model and for most application is just too inaccurate (and fails to satisfy S.44 Special Order).

Analyzing the error distribution for all test models we have to verify first of all whether they meet IHO standards, and to determine in which areas the errors are the largest. Figures 7, 8, and 9 present error distribution for the created models (light colors denote places where IHO standards were exceeded, white gaps in the models denote lack of data in those places—we do not determine errors in these places).

The images presenting error distributions for test surfaces confirm that for too low resolutions of grid networks the generated errors (lighter areas in the images) are too large to be accepted. It is particularly visible for the grid resolution = 5 or 10 m ('*gate*' and '*rotator*' surfaces), and grid = 0.5 m and 1 m ('*wrecks*').

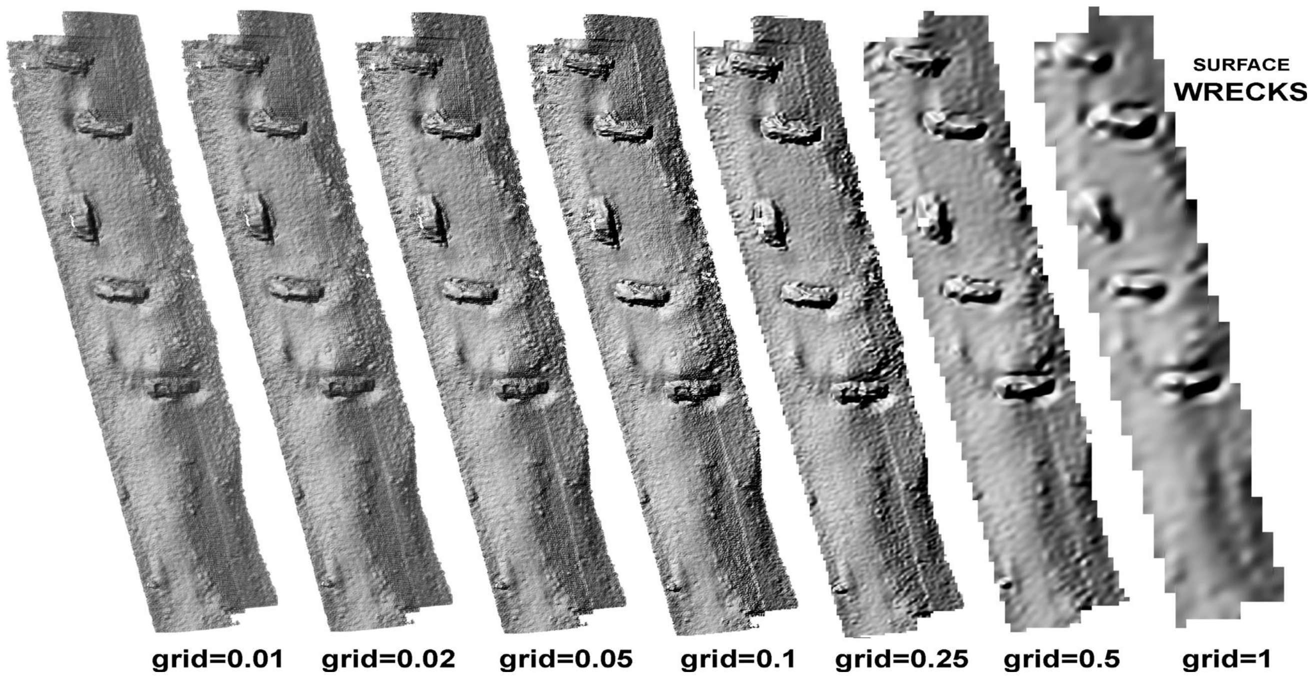

Fig. 5 'Wrecks' surface described by means of grid with different resolution

Table 3 The results obtained by comparing test surfaces with reference surfaces of various grid resolution

Resolution (m)	Mean (cm)	RMS (cm)	SD (cm)	95 % CL (cm)	99 % CL (cm)
Gate					
0.5	0.0057	0.0121	0.0105	0.0191	0.0387
1	0.0075	0.0175	0.0157	0.0239	0.0495
2	0.0142	0.0335	0.0303	0.0449	0.1014
5	0.0449	0.0922	0.0806	0.1613	0.3394
10	0.0946	0.1769	0.1496	0.3491	0.6701
Rotator					
0.5	0.0078	0.012	0.0097	0.0241	0.0434
1	0.0109	0.0173	0.0134	0.0324	0.0575
2	0.0175	0.0276	0.0213	0.0505	0.0866
5	0.0352	0.0584	0.0466	0.1014	0.1983
10	0.0654	0.1112	0.0899	0.2113	0.4323
Wrecks					
0.02	0.0024	0.0051	0.0045	0.0091	0.0199
0.05	0.0044	0.0083	0.0071	0.0153	0.0322
0.1	0.0062	0.0118	0.0101	0.0216	0.0455
0.25	0.0089	0.0169	0.0144	0.0304	0.0666
0.5	0.0168	0.0328	0.0282	0.0609	0.1361
1	0.0314	0.0643	0.0561	0.1249	0.2944

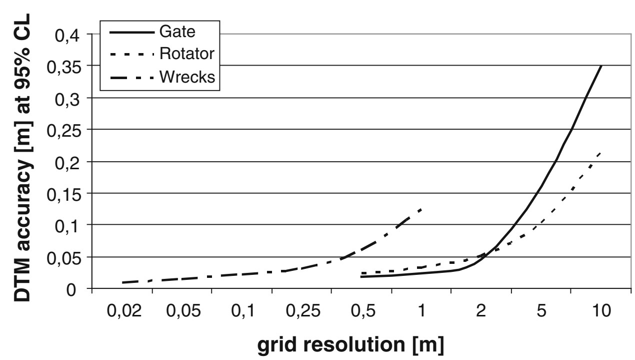

Fig. 6 Chart of results obtained by comparing test surfaces with reference surfaces of various grid resolution

Conclusions

The fundamental goal of the described research was to develop a method allowing for examining the influence of grid resolution on the accuracy of created DTMs. The author intended to obtain the answer: how much (in absolute terms) the accuracy of created model changes along with decreasing resolution. It is obvious, that the accuracy decreases, it is however difficult to assess, how much (in m).

For this purpose the method was developed, allowing to approximately evaluate the accuracy of created models depending on the assumed grid resolution. The method is based on the reference grid of very high resolution, created using measurement points (using 3 different methods of interpolation).

By means of the proposed method the experiments were performed, utilizing three different test areas obtained from the real surveys. Using those data the accuracy of models

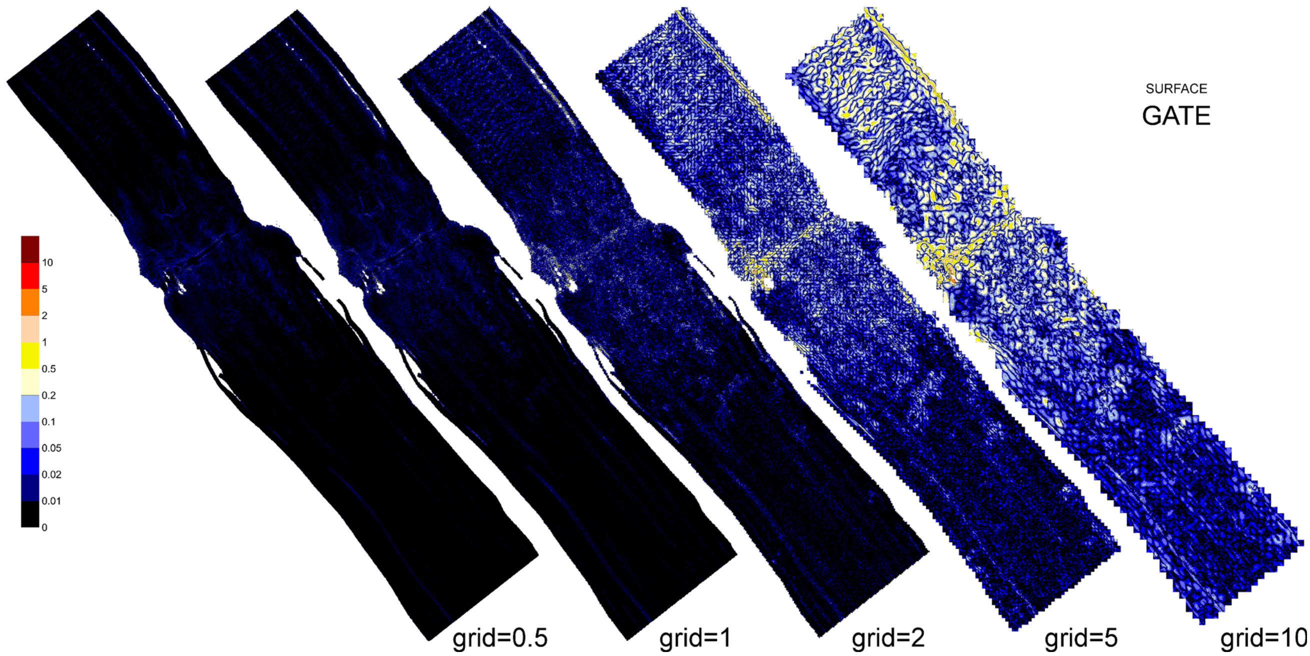

Fig. 7 Distribution of errors for 'gate' surface for different grid resolution

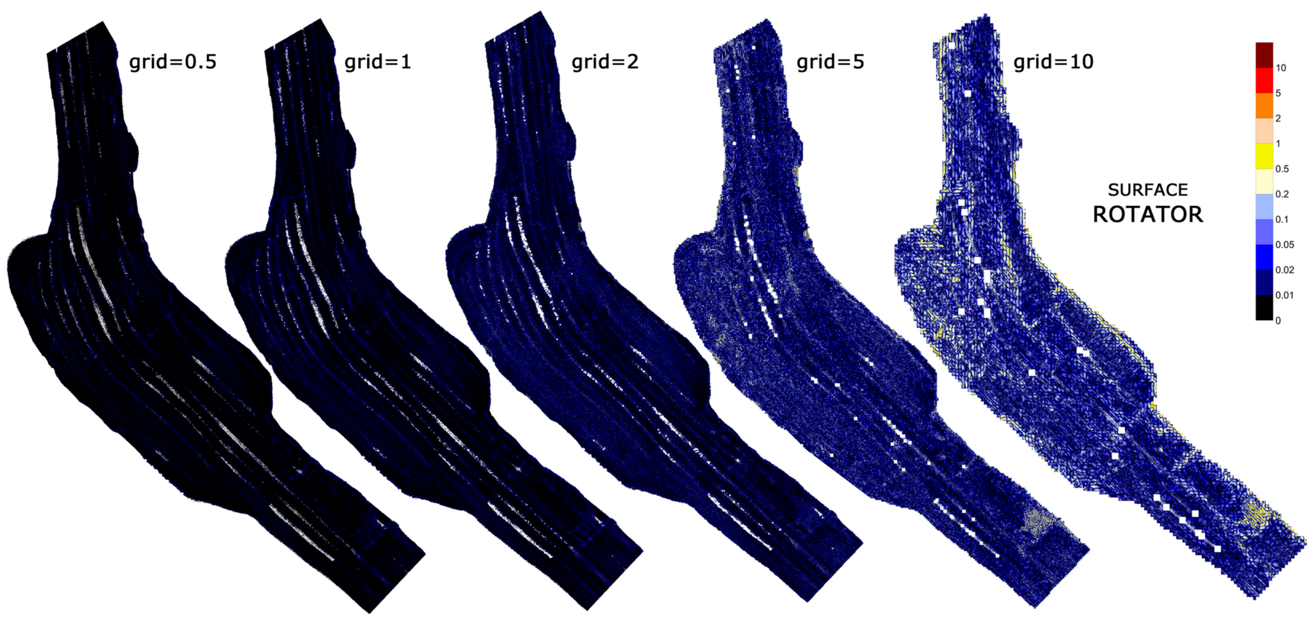

Fig. 8 Distribution of errors for 'rotator' surface for different grid resolution

created with different grid resolutions was calculated. Based on the obtained results (see Fig. 6) it can be noted, that in the range of high resolutions (0.5–2 m for 'gate' and 'rotator' and 0.02–0.1 m for 'wrecks') the accuracy of the model does not vary significantly (doubling the DTM resolution increases the model accuracy by approximately 20–40 %). In the range of low resolutions (5–10 m for 'gate' and 'rotator' and 0.5–1 m for 'wrecks') the accuracy of the model varies much more substantially (decreasing the resolution by a factor of 2 causes the drop in the accuracy of 50–60 %). As can be seen in the chart, the dependence between grid resolution and model accuracy is close to exponential.

Obviously, creating the grids several cm in size seems pointless. Taking into consideration the measurement methods (MBES), the neighbouring measurement points are 5–20 cm apart (depending on depth and beam angle). The author reckons, that the highest useful model

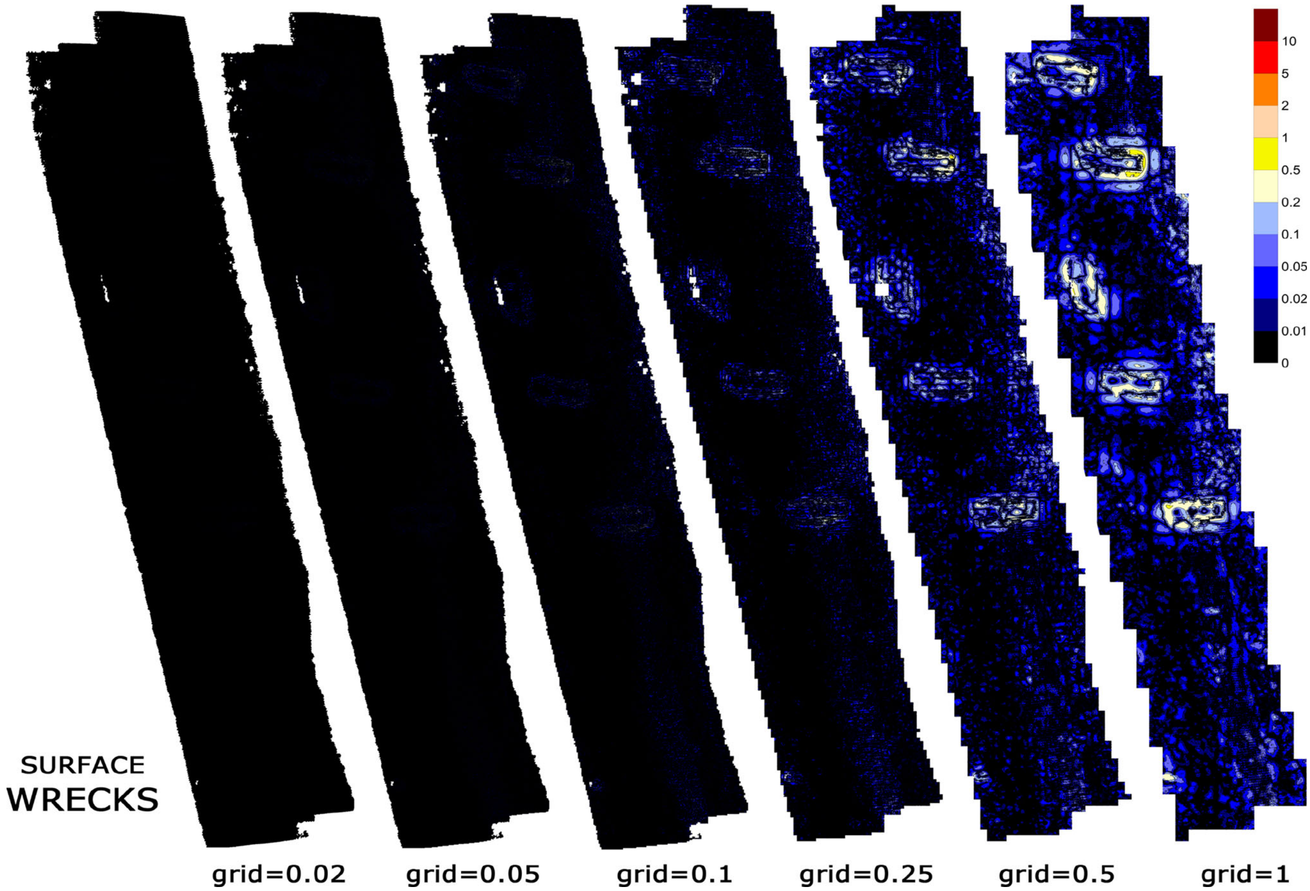

Fig. 9 Distribution of errors for 'rotator' surface for different grid resolution

resolution is approximately 10 cm—such resolution is worth using only in specific cases (e.g. over the wrecks or other untypical objects, that might be a major obstacle for sailing, or when the detailed visualization of such an object is required).

To author's best knowledge, the commonly utilized grid resolution (e.g. in Maritime Office in Poland) is 1 m. It assures a high model accuracy (approximately 3 cm), and when creating DTM no objects bigger than 1 m^3 are missed (according to IHO standards).

The described research proves, that the grid equal to 2 m also results in high accuracy models (5 cm for 95 % CL). Given that the data amount is 4 times smaller, using this resolution is worth considering, especially when creating models covering large areas. It is still up to the system's operator to select the "optimal" grid size, and the described research may be useful in assessing the resulting inaccuracies (depending on grid resolution).

Using the proposed method, each user may independently assess the influence of the grid resolution on the accuracy of DTMs, based on different, own measurement data.

In future works much more test areas should be examined, both for shallow and deep water, and for varying seabed shapes (flat, varying, big depth variations). It might be possible to obtain a method allowing for determination of grid resolution for a subarea, which would represent the seabed surface with a given accuracy. If it is possible, the next step would be developing a grid model with varying resolution in subareas, adapting to the seabed surface. Using such an adaptable grid for large areas would allow to create high accuracy models with acceptable data volumes.

The developed and herein presented method allows to estimate accuracies of created DTMs for different grid resolutions. Thanks to such approach hydrographic system users may develop their own standards for created DTMs and, consequently, for amounts of data stored in those structures, depending on the examined area and application of developed models.

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