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Application of high-density bathymetric data for visualization of MSIS sonar data

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Abstract

Mechanically scanned imaging sonars (MSIS) are mainly used for detection of small objects or aiding in underwater navigation in limited area. Obtained images are detailed and, especially for not experienced user, they may give an impression of a photography. However, the acoustic method of acquisition of sonar data must be taken into account, as understanding observed scene is essential to properly interpret the data. To aid the process of image interpretation the reference data may be used. In this paper the application of bathymetric data to MSIS sonar images is proposed.

To match high resolution of MSIS images the density of bathymetric data must exceed the requirements of S-44 IHO norm. For this research a swath bathymetric system based on phase interferometry of acoustic signal was used to obtain such data in shallow waters. The article covers the motivation of usage of such data in comparison to other existing bathymetric systems.

The proposed method uses acquired data to create additional channel in sonar image emphasizing sea-bed gradient in relation to sonar head position and distinguish invisible / shadowed areas. Proposed method is based on directional derivative of a sea-bed. Method presented in this article is a part of bigger research on enhancing interpretative potential of stationary sonar images [1].

Introduction

High resolution MSIS sonar imaging allows for a detailed visualization of the bottom of the analyzed underwater area. Already in the process of image registration, sonar operator receives an initial image of the scanned area. This type of sonar is used primarily in shallow waters, lakes, rivers and coastal sea areas [1, 2]. Due to the user-friendly nature of the device, usually its operator is also the target image recipient – a member of emergency services, water police, underwater construction supervisor, etc. It is a person, who expects to acquire the post-interpretative information, based on sonar imaging, on any underwater obstacles and its height, the position of a searched object, or a general overview of the analyzed area – the bottom surface layout or the technical condition of an underwater structure.

Unfortunately, in order to achieve the maximum amount of information from the registered acoustic data, it's necessary not only to apply appropriate image processing techniques, but to possess proper knowledge and experience in the interpretation of such imaging as well [3]. The sonar imaging technology makes it possible to exchange acoustic signal into lines of pixels informing of the intensity of the wave reflected off an object. However, in case of MSIS sonar imaging, the polar layout of the registered sonar lines constitutes a problem in terms of proper visualization [4]. Another hindrance is the lack of specific underwater geo-reference of the image (lack of knowledge of the head's exact position) or the utter lack of image positioning data for a person who was not present during its registration. The interpretation of the image alone can prove inconclusive. Photointerpretation focuses mainly on determining the basic features of the imaged object, such as its shape, size, color, etc, as well as intermediary features such as shadow and topographical placement [5]. Still, the crucial issue is that the interpretative potential of a digital image is linked to its resolution, bit depth, object distinguishability [6] and the so called context [7] which is constructed based on the existing knowledge of the person interpreting the imaged environment. The drive to make the sonar imaging analysis process more and more automated requires the study of how the interpreter's knowledge affects the reception of the imaged content. In order for this interpretation to be as correct as possible, the interpreter must be provided additional information. Depth data collected at the registration spot immensely affect the perception of the images received from a scanning sonar. Knowing the topographical layout, one can determine if the positioning of the objects and their imaged acoustic shadows reflect their actual positions and height.

The method presented in the article is part of a wider study carried out on enhancing the interpretative potential of the imagery collected from a sonar performing scans under the research project titled "Development of geodata processing methods in hydrographic surveys on sea and inland waters". High density bathymetric data used for the method is also useful in precise positioning of the sonar image, making it a natural fit for the purposes of the presented method. Segmenting the image based on the drops in terrain gradient determined on the basis of bathymetric data enrich the visual context, granting the user a better chance of understanding the underwater situation within the imaged area.

High-density bathymetric data

Due to the fact that sonar examinations are often conducted together with bathymetric survey, there is a good chance that obtained data can be easily used to enhance sonar imaging. However there are only few practical ways to acquire bathymetric information of examined area equivalent for sonar imaging of high resolution. It is mostly caused by cost efficiency of surveying, which is strongly related with the time needed to obtain data. For shallow water areas most systems needs close profiling of survey lines to obtain intended data coverage and density. Therefore, bathymetric systems with sonar transducers using phase interferometry are most suitable for acquisition of such data.

Interferometric data of bathymetric system

A bathymetric systems that are able to obtain high density data are multi-transducers echosounder, multibeam echosounders and interferometric system. The first hydrographic system consists of several of the single-beam echosounders mounted in line, which allows to get 100% depth coverage with good resolution and the viewing angle up to 150°. The second one generates large count / big amount of pings, called swath and obtaining eight times the measured depth coverage during one acquisition profile. Big viewing angle – over 200° and the coverage parameter allows for 100% data coverage with depth resolution of 1 cm. Interferometric system is a specific modification of the multi-beam system, based on the phenomenon of signal interferometry. The bathymetric data is acquired simultaneously in the vertical plane of the beam – like with traditional sonars – and in the horizontal plane, like with the lateral sonar. The depth points are acquired basing on the measurement of time it takes the hydro-acoustic wave reflected off the object to return to the transducer in echo form, and also on the measuring the phase difference in the hydro-acoustic waves reaching the piezoelectric sensors installed in the transducer [8]. The interferometric system allows for a 100% data coverage of the analyzed body of water much faster than multi-beam, due to large operating viewing angle – 240°, which permits to obtain big coverages of the seabed areas and at the same time meeting the minimal requirements as to the precision and density of the scan, in concordance with the International Hydrographic Standards [9]. The developers in technical specifications of interferometric systems list the measurement range width of up to twelve times the measured depth with a viewing angle of 240°, while maintaining high resolution of the data. The maximum coverage parameter – 12× in case of the GeoSwath Plus – significantly reduces the time necessary for the process of data acquisition. The acquisition parameters of bathymetric data acquisition by the EA MCU32 multi-transducer system, RESON SEABAT 7101 multi-beam echo sounder [10] and the GS+ interferometric sonar [11] has been presented in table 1.

Table 1. Comparison of operational parameters of bathymetric measuring systems (developed on the basis of technical specifications)

Parameter	EA MCU32 16 transducers	RESON SEBAT 7101	GeoSwath Plus
Operational frequency	200 kHz	240 kHz	250 kHz
Viewing angle	112°	210°	240°
Maximum coverage (footprint) for depth =10 m calculated for depth 10 m	 50 m	7.5 × depth 75 m	12 × depth 120 m
Depth resolution	1 cm	1.2 cm	0.3 cm

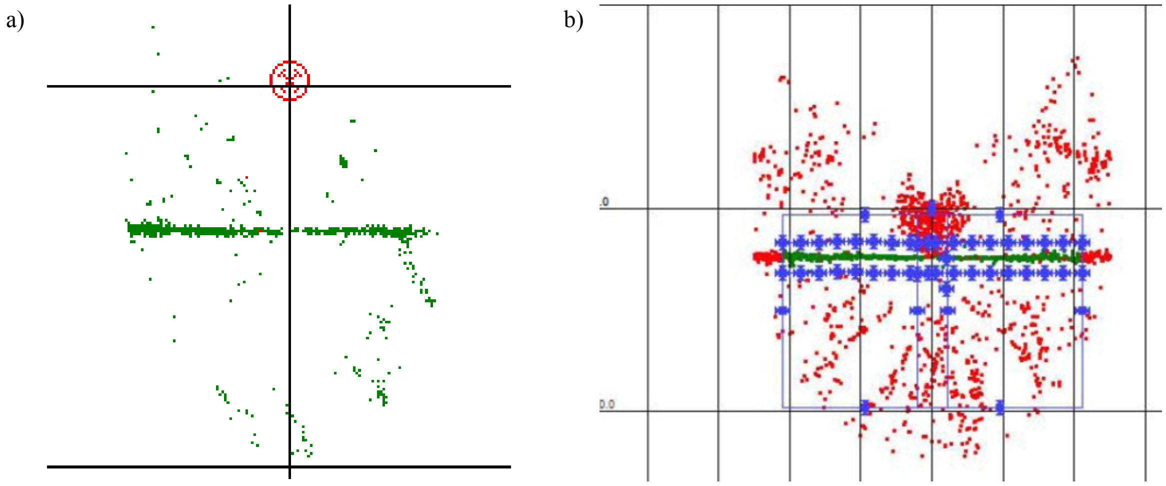

Fig. 1. Data acquisition without (a) and with applied filtration (b)

The maximum coverage causes very large amount of data. High density bathymetric data collected through the interferometric system in both vertically and horizontally ways, become too dense, marked with errors and “polluted” with numerous interferences. All of this makes statistical processing: reduction and generalization, a necessity. Therefore, it is easy to observe that the time saved during acquisition is inversely proportional to the time needed for the processing of the acquired bathymetry. Figure 1 presents the data acquisition window in GeoSwath Plus software.

Every point in the image – green or red means one measured point. Because of sizeable amount of measured depth points, as well as an abundance of registered interference, developers of interfrometric systems had to provide users of this hydrographic system with filtrating, and then the processing and gridding algorithms. It allows users to reduce the amount of the data and to choose way of its generalization.

The grid used for generating a digital terrain model DTM should constitute a local generalization in order to provide the most accurate gradient changes. The size of the generated grid must be adequate to the resolution of the sonar image being segmented. Indeed, the data collected using a scanning sonar are characterized by a resolution of several centimeters [1] due to which, the characteristics of the bathymetric data serving as basis for generating the gradient map must be of high density and of high resolution. The bin size should therefore be as close to the registered sonar image resolution in terms of size as possible.

Data representation

Unequivocally detailed information on the depth of the body of water in the scanned location

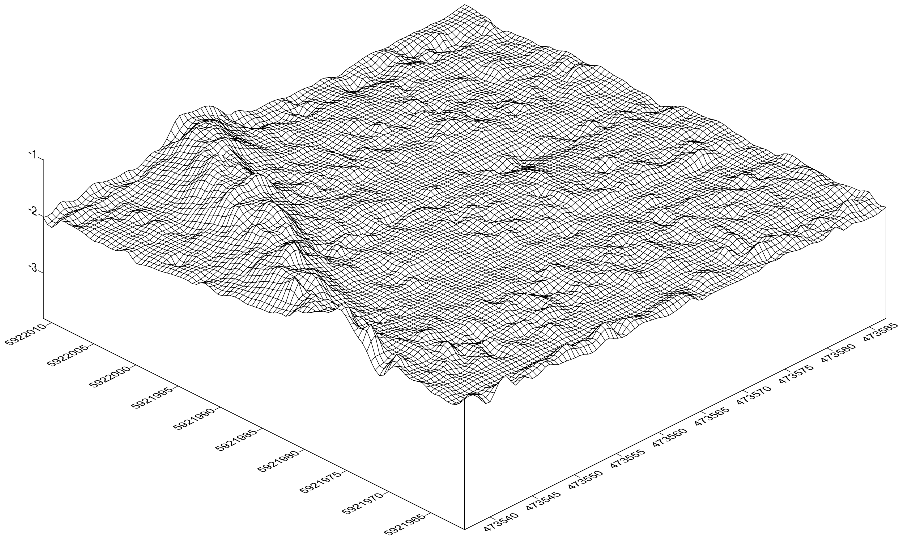

Fig. 2. Example of DTM, which is narrowed to the sonar image spatial domain

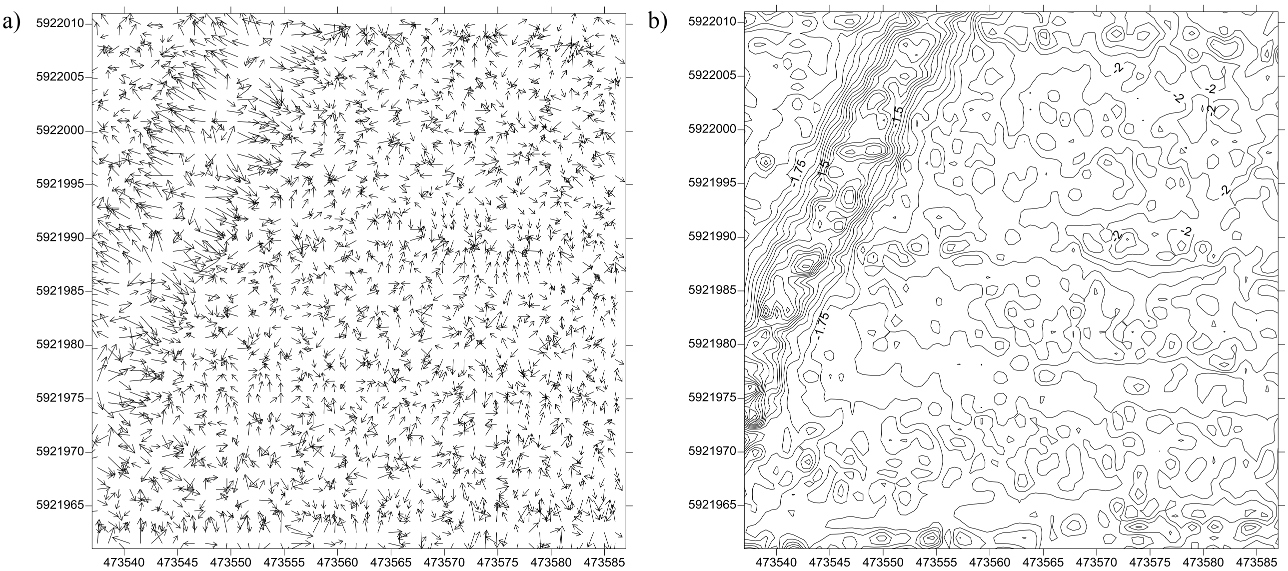

Fig. 3. Gradient map (a) and contour map (b) of bathymetric data from exemplary sonar image spatial domain

increase the user's ability to properly interpret the received image. However, the proper preparation of information is a key. They can be presented separately, as a three-dimensional DTM model, but they are still unfeasible for the automation of the process, due to their size and indirectness in relation to the sonar image.

If the sonar image has known spatial reference then the set of bathymetric data needs to be narrowed to the same area that is covered by the sonar data. High density bathymetric data of the analyzed surface can be treated as a scalar field and transformed into a gradient map in the form of a vector map, showing the direction and size of the changes in the scalar field. In such a way, the turning of each of the gradient vectors shows the direction in which the scalar field increases the most. The density of the vectors depends on the density of the acquired bathymetric data (Fig. 3a).

Another way of representing 3D bathymetric data in 2D domain is a contour map (Fig. 3b). Both forms can be theoretically added as an additional layer to sonar data. Although it gives a sort of additional information to the interpreter that is not direct. The data itself isn't in any way coherent with the image, despite the same spatial area it represents. It shows changes of the bottom shape, which is of significant importance, but it doesn't relate with sonar data, which strongly depends on where the position of transducer was while registering the image. Another problem with such data is its visualization. Detailed data needs detailed representation to fully reflect the shape of underwater area. Being only an addition to sonar data as extra layer, this detail needs to be restrained and generalized, which is exactly the opposite. To fully relate bathymetric data to sonar data and adjust its visualization at the same time, different approach is proposed.

Sonar data enchantment by depth information

The method consists of 2 stages. The role of the first one is to determine the invisible areas in sonar image based on the examined bottom depth in center of sonar image matrix (position of the sonar transducer) and analysis of gradient values along each ray of sonar beam. Assuming the ideal conditions: there are no suspended objects in the water body, there are no false reflections visible in the image and echoes of recorded sonar signal originate only from the direction of the recipient area of the acoustic wave – the only invisible areas in the image are locations of the acoustic shadow (Fig. 4).

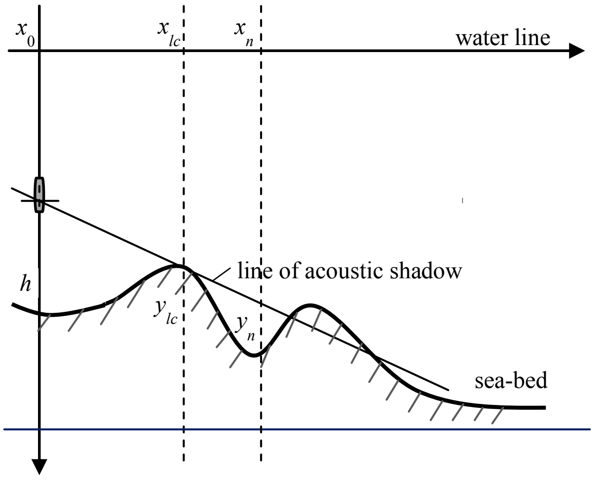

Fig. 4. Defining line of acoustic shadow, as a tangent to local maximum of the bottom section fuction

In the reality such situation never occurs, therefore, it is helpful to identify which sonar information is actually false information, meaning it is located in the area out of sight in sonar image.

Assuming given sonar image is a BAT matrix and the transducer position is sonar image center, it corresponds to the bathymetric data matrix position BAT ($N+1$, $N+1$). Taking into account it was the source of the acoustic beam of length N, then for each of the beams corresponding to one line of pixels generated during the rotation of transducer, one can treat bottom section as a function $y(x)$. Pair of values (x, y) for each point corresponds to the position along the line (x), and its depth value (y). The value of y_0 for the transmitter can be determined by adding height of the tripod on which it was suspended to the depth of the bottom. For each local maximum y, so called line of shadow, needs to be calculated from simple equation for line that intersects two points:

$$(x_{lc}-x_0)(y-h)=(y_{lc}-h)(x-x_0) \tag{1}$$

where:

x_0, h – sonar transducer position;

x_{lc}, y_{lc} – consecutive position in line and value of depth for local maximum of y.

While moving along the beam line (N), one needs to check if for the latest local maximum the value of determined line of shadow is above the depth value (y). In practice, to be able to determine if an area lies in shaded area, one needs to check if this value is not starting to drop. The area will remain shaded as long as for the last local maximum the line of shadow will stay above the value y.

For each point of each beam information about the invisibility or visibility of the area is stored in the VIS matrix of corresponding resolution to resolution of BAT matrix and thus corresponding to its sonar image (Fig. 5).

The second step of the method is to use information about a change in the gradient to determine the subareas characterized by a particular change in the configuration of the bottom relative to the sonar position. The gradient is a vector field indicating the directions of the fastest growth of the scalar field at each point. It is a differential operator. The module is a derivative of the gradient vector for the greatest growth. For the three-dimensional gradient operator input data can be shown as:

$$\nabla f = \left[\frac{\partial f}{\partial x},\frac{\partial f}{\partial y},\frac{\partial f}{\partial z}\right] \tag{2}$$

For the purpose of the method, however, it is necessary to determine gradient change not in all of three directions, but relative to the position of the sonar (image center) – in the direction indicated by each ray beam. This implies the determination of directional derivatives at each point of the consecutive beam. Obtained values speak of the gradients speed decrease or increase, while moving away from the position of the transmitter along sonar line. The values of derivatives, easily obtained using the same (1) equation, as directional factor of function is in the matter of fact a directional derivative, are stored in the VIS matrix corresponding to the following pixels. Information about potential shaded areas is not overwritten.

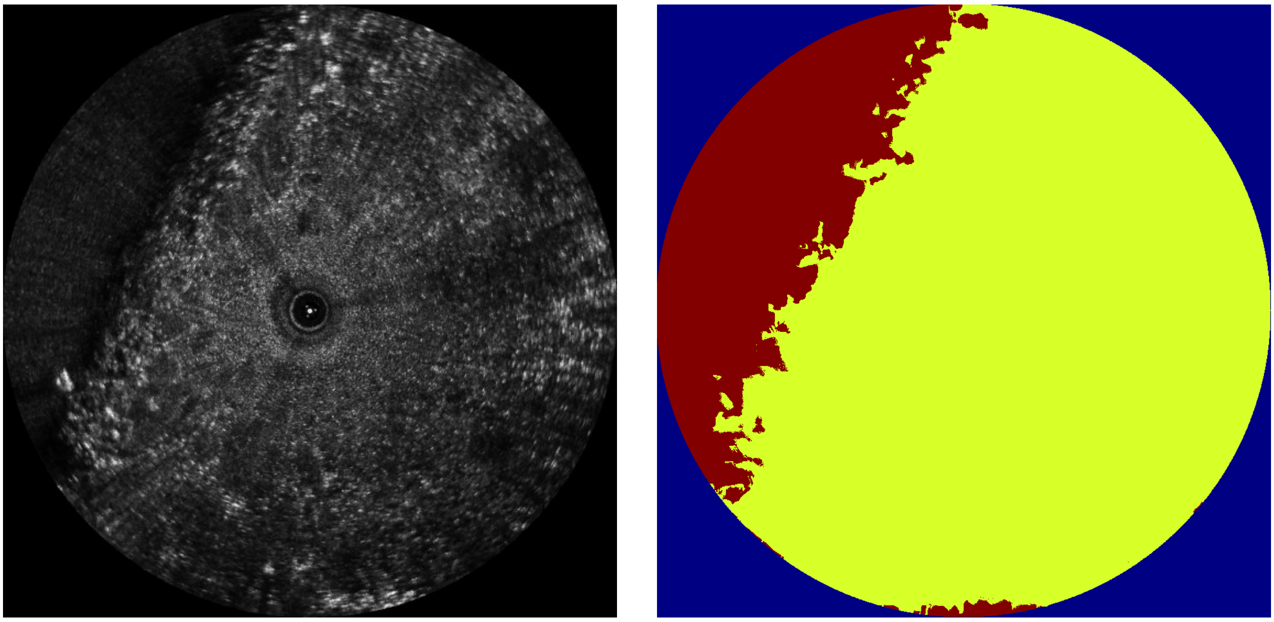

Fig. 5. Example sonar image with corresponding VIS matrix visualizing invisible areas

The last phase of the algorithm sets out limits for the classes, taking into consideration the gradient value range for the entire image. There is a possibility to introduce a fixed, user-determined division. Finally, a result matrix is generated, adopting five values for individual pixel classes:

1. The invisible (obscured) area;
2. Dismissible gradient – steep of the slope is small, can be ommited;
3. High gradient in the direction of $TH(x, y)$ – rising slope;
4. High gradient in the direction opposite to $TH(x, y)$ – falling slope;
5. No data.

This matrix reflects the influence of terrain topography on the image. It aids in the sonar image interpretation process, especially for people who are less experienced. It can be added to the image as a separate channel, while the original image remains unaltered (see Fig. 6). The number of classes can be altered, but during authors research it was narrowed taking into consideration human perception limits [12].

Method was tested on images scanned on shallow waters in port areas and lakes. It allowed to indirectly add information to images. It can be easily visualized by dividing the image using colormap or drawn-on lines during post-processing. In this research the first solution was adapted. Figure 7

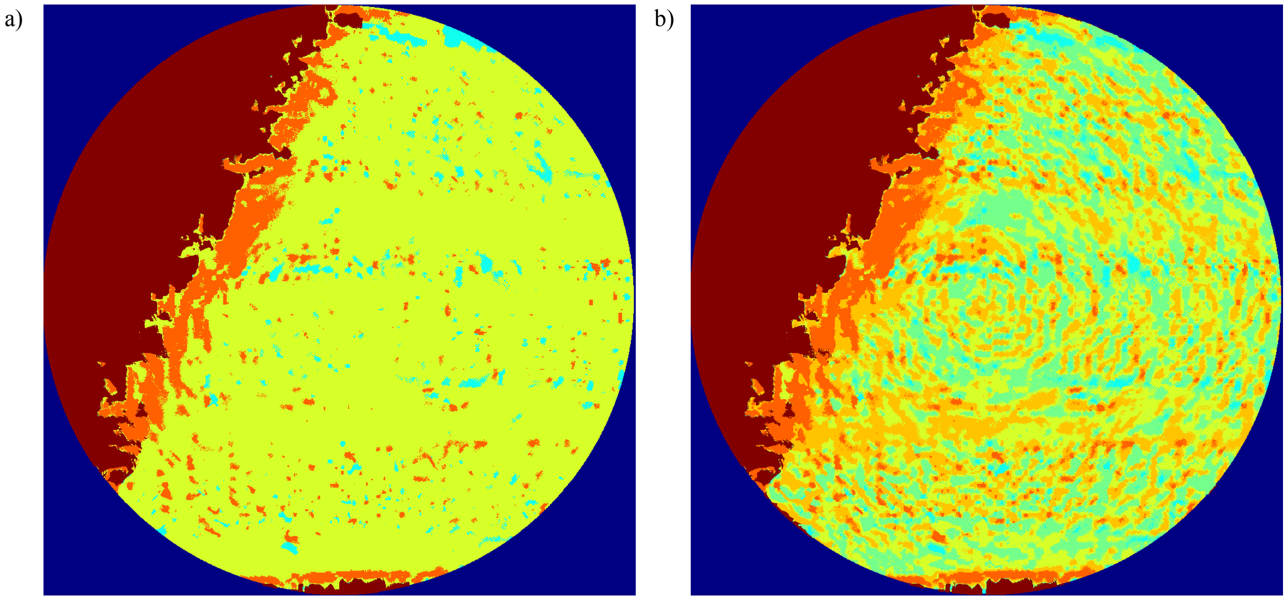

Fig. 6. Examples of 5(a) and 7-class (b) division into areas depending on gradient values

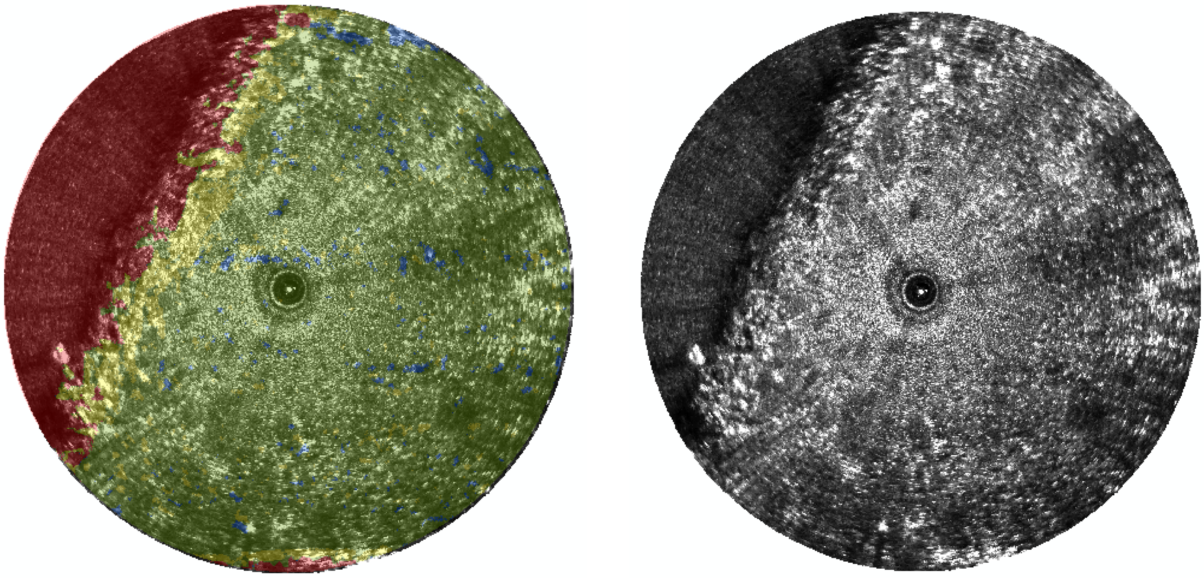

Fig. 7. Exemplary sonar image with (on the left) and without (on the right) additional channel based on created classes

presents comparison between one-channel sonar image and the same image with added information about bottom gradient.

In the image green color (class 2) represents generally flat area or an area of bottoms gradient that has no influence on the sonar information in this region. Yellow color represents steep rising slope of the bottom in relation to sonars head position, while blue spots represent sudden drops (classes 3 and 4). Red color indicates area that is unobtainable by sonar signal, thus any found echo in this zone doesn't represent bottoms surface (class 1). No data class in image matrix was replaced with white pixels.

Conclusions

The method primarily allows to determine the areas invisible to the sonar beam, which due to the hydro-acoustic wave being reflected off the water surface etc. is far from obvious. False echoes of objects can manifest in the image's obscured areas. For a person lacking experience in sonar data interpretation, this can be extremely misleading. Furthermore, the algorithm effortlessly browses through bathymetric data and classifies significant topographic variations (slopes, crevices, etc.), denoting areas that may prove problematic for proper assessment in terms of the height of found navigational obstacles. The method is significant for the automation and improvement of the interpretative potential of sonar images. The generated segmentation matrix divides the image into fixed subsections, thus possibly acting as the basis for using local image processing methods in order to improve the user's reception. Method presented in this article is a part of bigger research on enhancing interpretative potential of stationary sonar images.

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