Application of angular dependence of sonar echo features in seafloor characterisation and imaging

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ABSTRACT
Two applications of angular dependence of sonar echo features in seafloor characterisation and imaging are presented, namely, the use of side scan sonar data for 3D reconstruction of bottom relief and submerged object shape, and application of multibeam data for seabed type classification. With regards to the first application, the proposed algorithms using an adopted shape from shading (SFS) approach, are presented. The algorithms use the assumed and evaluated model of backscattering strength dependence on incident angle, and utilise also the information from shadow areas. The obtained results of 3D shape reconstruction are depicted and the performance of the algorithms is discussed. Regarding the second application, the proposed approach is based on calculation of a set of parameters of an echo envelope, similarly as in seafloor classification using single beam echosounder. These parameters are extracted for each consecutive beam allowing the estimation of their dependence on the seafloor incident angle. The relation between seabed type and calculated echo parameters and its angular dependence, is investigated. The preliminary results obtained using multibeam data records from different seabed types are presented and discussed.

INTRODUCTION
Application of multibeam sonars for high resolution bathymetry measurements and seafloor and underwater objects imaging is quite well verified in many cases and widely used in practice. On the contrary, some other important applications, closely related to this subject, are less verified with respect to methodology and techniques utilised in sonar data processing. Some of them are presented and discussed in this paper, namely, the use of side scan sonar data for 3D reconstruction and imaging of bottom relief and submerged object shape, and the application of multibeam data for seabed type classification. Both applications are based on the dependence of information extracted from a sonar echo on a seafloor incident angle.

3D RECONSTRUCTION OF BOTTOM RELIEF AND SUBMERGED OBJECT SHAPE FROM SIDE SCAN SONAR DATA
The proposed algorithm is based on the problem inverse to image formation, namely Shape From Shading (SFS), which is one of classical problems in computer vision [1]. The geometry used in derivation of the reconstruction algorithm is presented in Fig. 1. The beam of a side scan sonar covers an angular sector from \( \varphi_{\text{min}} \) to \( \varphi_{\text{max}} \). At the time instant \( t_i \), the seafloor surface \( S_i \) is insonified. The backscattering model was assumed as Lambert-like form [2]. The \( \theta \) angle between ray to point \( P_i \) on seafloor surface and normal \( \vec{N}_i \) to a plane tangent to surface at \( P_i \) does not need to be defined in vertical plane \( XOZ \).

The 3D bottom relief was reconstructed by estimation of an altitude \( z(x, y) \) sequentially for consecutive discrete points \( (x, y) \) on a plane, using the scheme depicted in Fig. 2. For the \((i, j)\) iteration (where \( i \) – number of processed line in the sonar image corresponding to one sonar ping, \( j \) – number of pixel belonging to this line), i.e. the point \( P_i = (x_i, y_i, z(x_i, y_i)) \) altitude estimation, the local triangle facet was being taken into account, with vertices at two previously estimated points \( P_{i-1, j} = (x_{i-1}, y_{i-1}, z(x_{i-1}, y_{i-1})) \) and \( P_{i, j-1} = (x_{i+1}, y_{i+1}, z(x_{i+1}, y_{i+1})) \), and currently estimated
point \( P_i \). Using the applied model, the value chosen for \( z_{ij} \) allows for calculation of normal \( \vec{N}_i \) to the surface facet, the angle \( \theta_i \) and the local intensity \( I_i \) value, which then may be compared with that from the original sonar image. The analytical form of the expression for optimal \( z_{ij} \), i.e. that giving \( I_i \) equal to a measured value, is impossible to obtain in a general case. On the other hand, it may be shown that in the applied model, \( I(z) \) is a monotonic function of \( z \) variable within the range \([z_{ij_{\min}}, z_{ij_{\max}}]\), where \( z_{ij_{\min}} \) corresponds to \( \theta_{ij_{\min}} = 0^\circ \) and \( z_{ij_{\max}} \) to \( \theta_{ij_{\max}} = 90^\circ \). Therefore, the simple binary algorithm, starting from initial \([z_{ij_{\min}}, z_{ij_{\max}}]\) searched interval, was used for \( z_{ij} \) estimation. It was the iterated algorithm which in \( k \)-th iteration proposed the new \( z_{ij_{\text{mid}}} \) as the midpoint of the current \([z_{ij_{\min}}, z_{ij_{\max}}]\) interval, and then appropriately reduced the interval to its left or right half. Namely, if an echo intensity \( I \) calculated for \( z_{ij_{\text{mid}}} \) was less than intensity taken from the currently processed pixel of sonar image, the left half was chosen for the consecutive iteration, otherwise the right half was chosen.

Figure 1.- Geometry used in derivation of the seafloor relief reconstruction algorithm

Figure 2.- Illustration of the bottom altitude \( z(x_i, y_i) \) estimation in \((i, j)\) iteration of the algorithm
For 3D seafloor relief reconstruction, the algorithm described above was applied, and it is further referred to as "2\textsubscript{Dn}" algorithm. For submerged object shape reconstruction purpose, two modifications of the proposed algorithm have been made, namely:

1) the simplified geometry was used, i.e., the normal to an insonified surface was assumed to be perpendicular to y axis, e.g., to the track direction, and for the z(x, y) altitude estimation, the altitude z(x, y, i) from previous was no longer used,

2) the estimation of the elevation change using the dimension of acoustic shadow areas was utilised in the following manner: in a case of a shadow zone detection, the length of shadow area along x axis was calculated as \[ \Delta x_{sh} = x_{i+j} - x_i, \] where \( j \) – the number of pixels belonging to a currently detected shadow area. Then the altitude values from \( z_{i+1} \) to \( z_{i+j} \) were set to unknown, and the \( z_{i+j} \) value was calculated as

\[ z_{i+j+1} = \frac{\Delta x_{sh}}{\tan \phi}, \quad (\text{Eq. 1}) \]

This modified version of the "2\textsubscript{Dn}" algorithm with applied only first of the above modifications is further referred to as "1\textsuperscript{Dn}" algorithm, while the algorithm version with applied both 1) and 2) modifications is further referred to as "1\textsuperscript{D}+shadow" algorithm.

What is more, one additional modification has also been made for the seafloor relief reconstruction "2\textsubscript{Dn}" algorithm. It is described in details in [2] and its purpose is to remove the effect of the strong divergence of consecutive, adjacent vertical sections of the reconstructed seafloor relief z(x, y) parallel to x axis (corresponding to consecutive processed sonar pings). The main idea of this modification was as follows. For currently processed pixel \((i, j)\), to ignore the estimated z(x, y, i) value and set it to the corresponding z(x, y, i+1) value for previous ping, if the leaving a "perturbation zone" (the location of a local shape similar to a "hole" or a "hill" for instance) in seabed relief, and entering back a "flat zone" (surrounding area of a relatively flat seabed) was detected. The criterion used to determine whether we are in "perturbation zone" or "flat zone" was based on comparing the currently estimated slope of the reconstructed relief with that obtained for previously processed adjacent pixels in sonar image [2]. The reconstruction algorithm with this modification is further referred to as "2\textsuperscript{D} enhanced" algorithm.

The seafloor reconstruction results are presented in Fig. 3. The bottom side scan sonar image is presented in Fig. 3a, while the reconstruction results obtained using "1\textsuperscript{Dn}, "2\textsuperscript{Dn} and "2\textsuperscript{D} enhanced" algorithm are presented in Fig. 4b, 4d and 4f respectively. In addition, the enlargement of the selected parts of the reconstructed surfaces by these 3 algorithms is shown in Fig. 3c, 3e and 3g. Fig. 4, concerns the wreck shape reconstruction results. Namely, Fig. 4a presents the original side scan sonar image of wreck, while Fig. 4b presents the 3D reconstruction results for a fragment of the wreck shape using "1\textsuperscript{D}+shadow" algorithm. Sonar images have been downloaded from the Web page of the Marine Sonic Technology, Ltd.

Several details of bottom topography (Fig. 3a) and the wreck shape (4a) might be recognised in the reconstructed shape (seafloor relief - Fig. 3b, 3d and 3f, and after magnification, Fig. 3c, 3e and 3g, and wreck - Fig. 4b), but the large divergence of consecutive, adjacent vertical sections of z(x, y) parallel to x axis, resulting in large undulations along y axis of the recovered shape, is visible unfortunately. However, this effect is less visible for some parts of bottom surface enlarged in Fig. 3e – "2\textsubscript{Dn}" algorithm in comparison with contents of Fig. 3c – "1\textsuperscript{Dn}" algorithm, what partially justifies the advantage of the "2\textsubscript{Dn}" reconstruction algorithm. What is more, when comparing the "2\textsuperscript{D} enhanced" algorithm results (Fig. 3f and 3g) with those of "1\textsubscript{Dn} and "2\textsubscript{Dn}" algorithms, the further improvement is seen. The inconsistency of adjacent across track vertical sections of z(x, y) and the resulting large surface undulations along y axis was removed to some extent. It is especially visible when comparing the cases of magnified reconstructed surface.

**SEAFLOOR CHARACTERISATION USING ANGULAR DEPENDENCE OF MULTIBEAM ECHO FEATURES**

The seafloor characterisation methods using parameters extracted from single beam echo are well known and verified (see [3] and [4] for example). The proposed approach relies on calculation of a set of echo parameters for each consecutive beam of multibeam sonar, and the estimation of the parameter dependence on the seafloor incident angle.

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Figure 3.- Seafloor reconstruction results: a) processed bottom side scan sonar image; the reconstruction results: b) “1D” algorithm, c) “1D” magnified, d) “2D” algorithm, e) “2D” magnified, f) “2D enhanced” algorithm, g) “2D enhanced” magnified.

Figure 4.- Wreck shape reconstruction results: a) original side scan sonar image, b) 3D shape reconstruction results for a fragment of the wreck using “1D+shadow” algorithm.
In the investigation, the following echo parameters were calculated:
1. The echo energy calculated as the sum of squared acoustic pressure values of all echo samples.
2) The normalised moment of inertia \( I \) of the echo envelope, with respect to the horizontal axis containing its gravity center:
\[
I = \frac{\sum_{i=1}^{N} [(i - i_c) \Delta t] p_i^2}{\sum_{i=1}^{N} p_i^2}, \quad \text{(Eq. 2)}
\]
where \( \Delta t \) is the sampling rate, \( i_c \) - the sample number corresponding to position of gravity center of the echo signal, \( p_i \) - the acoustic pressure value sampled at the time \( t_i \). It describes how the echo energy is concentrated around the gravity center.
3) The envelope skewness \( S \) – the third statistical moment of an echo envelope (with assumption that the echo envelope itself acts as the probability density function. It measures the asymmetry of an echo shape along the time axis.
4) Fractal dimension of an echo envelope, interpreted as a measure of its shape composedness, calculated as a box dimension approximation of a Haussdorff dimension, as described in \([3]\).

The data used in the preliminary testing of the proposed approach to multibeam seafloor characterisation were acquired by the RESON SeaBat 7125 sonar with operating frequency 400 kHz. Approximately 100 swaths from each of two seafloor types (hard sand and soft sand) were processed. The data were acquired in a shallow water region of Pacific Ocean, near Santa Barbara, CA, USA. For each swath, 256 beams covered the angle sector from -75° to 75°, but only the echoes for beams corresponding to angular sector from -25° to 25° were selected for further processing and parameter calculation.

After detection of bottom echo in the received signal, the above set of echo parameters was calculated for the appropriate part of each beam echo, with averaging of obtained values for the whole set of echoes of the same transmission angle (for all swaths). The seafloor was assumed to be approximately flat, therefore the transmission angle was assumed to be equal to the incidence angle. The obtained results are presented in Fig. 5 in a form of plots of a dependence of parameter value on a beam transmission angle for two bottom types.

As it could be expected, the echo energy (Fig. 5a) has greater value for hard sand than for soft sand, and for both cases its value decrease with the increase of the incident angle. It is generally in line with the results obtained previously by other authors (\([5]\) for instance).

The same as above may be also said with regards to moment of inertia (Fig. 5b), but additionally, the sets of obtained values of this parameter are entirely disjoint, i.e. any value obtained for hard sand is greater than any value obtained for soft sand, regardless the beam angle. If a such behaviour was confirmed by more wide experimental verification for several parameter values, it might constitute the foundation of the fast method of bottom typing by multibeam sonar. In such a method, a large sector of seafloor would be covered by a single sounding (swath), and within this sector, the bottom type could be locally determined using the information from only one beam, regardless its transmission angle.

In a case of envelope skewness (Fig. 5c), the quite similar features as in moment of inertia may be visible, but with the limitation to the narrower sector of the incident angle.

Although two bottom types cannot be easy separable using fractal dimension of echo envelope (Fig. 5d), the results obtained in this case show the interesting features of angular dependence of this parameter. For normal incidence, echo from harder seabed has smaller fractal dimension value than the one from softer seabed, but its increases more fast with increase of the incidence angle for hard sand than for soft sand. It may indicate that for hard sand, the contribution of the mirror reflection at normal incidence is greater than for soft sand, what results in a quite strong and smooth echo from harder seabed near the 0° incident angle, and quite fast decrease of
echo level, and at the same time increase of its shape composedness (measured by fractal
dimension for instance) with increase of the incident angle. For soft sand, this effect is weaker.

![Graphs](image)

Figure 5.- Dependence of calculated echo parameter value on a beam transmission angle
for two bottom types: hard sand (red) and soft sand (green): a) echo energy,
b) moment of inertia, c) echo shape skewness, d) fractal dimension

CONCLUSIONS
Two applications of the approach based on angular dependence of sonar echo features in
seafloor characterisation and imaging has been presented: 3D reconstruction of bottom relief
and submerged object shape from side scan sonar data, and the application of multibeam data
for seabed type classification. In both cases the obtained results are promising. In the first case,
the future work should concentrate on implementation of more advanced both SFS and shadow
processing algorithms. In particular, the authors predict that the algorithm performance
improvement could be achieved by taking into account the information obtained not only from a
current ping and one previous ping, but from a number of previously processed pings. In the
second case, it has been primarily justified that the information extracted from multibeam
seafloor sensing data in a form of an angular dependence of several echo parameter value,
may be useful in seafloor characterisation. First of all, however, the verification of the proposed
approach using larger amount of experimental data is needed.

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