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Multibeam Sonar Data Processing for Seafloor Classification

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Introduction

Despite many years of the development of methodology for sensing the seafloor by means of underwater acoustics, the currently used techniques are still not mature enough and not ready to be utilised in numerous different (i.e. with respect to a water region character, used equipment type etc.) tasks. Therefore the hydroacoustic methods, both utilising vertical observations (e.g. by singlebeam echosounders), as well as those relying on wide-angle sensing (by sidescan sonars and multibeam sonars), are still the subject of extensive research.

In this paper, after a short review on underwater acoustic equipment and methodology used nowadays in seafloor characterisation, the concept and the results of a combined method of multibeam sonar data processing for seabed classification are presented.

Acoustic Sensors and Techniques Used for Seafloor Characterisation

Several types of acoustic devices are used in seafloor characterisation, depending on the more precisely defined aim of the investigation, viz.: seafloor mapping, subbottom profiling, physical sediment parameters estimation, desired accuracy, resolution etc. The utilised equipment may include singlebeam echosounders, multibeam sonars, sidescan sonars, various types of subbottom profiles (seismic sources, chirp sonars, parametric sources), and other equipment.

One of the first developed approaches to singlebeam seabed classification was based on calculation of the first and the second bottom echo energy and the use of these quantities directly as seabed type descriptors. The method was proposed by Orłowski [1] and further developed by Chivers et al. [2] The authors showed that the first echo may be treated as the so-called seabed roughness index while the second echo may be used as the seabed hardness index.

The usefulness of several singlebeam echo parameters in seabed classification, including statistical and geometrical descriptors of an envelope, was shown in 1994 by Klusek et al. [3]. In 1998 Stepnowski and Łubniewski [4] introduced the fractal dimension of an echo envelope as a significant descriptor of seafloor properties.

In 2005, Valree et al. [5] confirmed the usefulness of a set of six energetic, statistical, spectral and fractal parameters of 66 kHz and 150 kHz singlebeam echosounder signals in seabed classification by the detailed ground truthing procedure performed in a North Sea survey area.

In 1997-1999 Pouliquen et al. [6, 7] developed a model of acoustic signal scattering on the seabed – the so-called BORIS (BOttom Response from Inhomogeneities and Surface) model. This model operates in the acoustic pressure domain and allows for prediction of the full, narrow or wide band echo signal for single sounding, assuming the detailed, high resolution geometric model of seabed and full description of the transmitted signal.

In 2011, Siemes et al. [8] presented the comparison of using two schemes of model-based inversion of sediment properties from singlebeam data. In the first scheme, the complete echo envelope, modelled in the acoustic intensity domain, is used to invert the sediment mean grain size, the seabed surface roughness spectral strength and the volume scattering parameter. In the second scheme, the echo energy value is used to invert the bottom reflection coefficient and subsequently the mean grain size.

Multibeam sonars are widely used in applications like high resolution bathymetry measurements, underwater object detection and imaging, etc. For multibeam seafloor characterisation and classification, several approaches have been investigated and utilised. Many of published works, e.g. [9], are based in principle on investigation of characteristic, local features of sonar image which is composed of pixels, the grey level of which corresponds to backscattering strength for particular beam echoes and transmissions.

Another approach utilises the dependence of echo properties on incident angle in multibeam sounding, mainly the backscattering strength for a given echo. The detailed discussion on the appropriate pre-processing of multibeam echoes, including the need of calibration and artefacts removing, as well as on statistical properties of the seafloor echo backscattering strength, is given in [10]. In [11, 12] the statistical Bayesian approach to seabed classification using backscattering strength calculated for multibeam echoes is presented.

Finally, besides the approaches mentioned above based mainly on utilisation of measured data features in the phenomenological manner, the multibeam seafloor characterisation methods relying on the inversion of seabed physical parameters have been also investigated. For instance, in [13] the authors presented the model-based geo-acoustic seabed properties inversion scheme to be applied on the dependence of multibeam seafloor reverberation on the beam incident angle. The model used in this study was the extension of the BORIS model mentioned in the previous section, the so-called BORIS Small Slope Approximation (BORIS-SSA) model.

The Methodology Concept

The proposed approach to seafloor classification relies on the combined use of three different techniques. In each of them, a set of descriptors foreseen to be applied in the seabed classification procedure, is calculated using a given type of data obtained from multibeam sonar system. The schematic concept of the applied approach is shown in Figure 1.

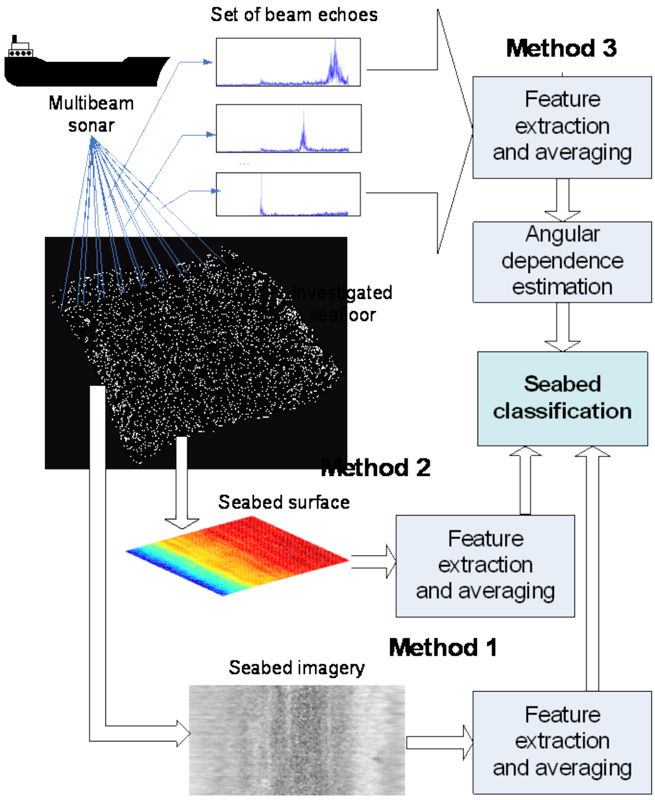

Figure 1: The scheme of the integration of three different techniques in one combined method of seafloor classification using multibeam sonar

In the first technique used, i.e. *Method 1* in the figure, the grey-level sonar echograms of seabed surface are utilised [14]. In the course of data processing, a set of parameters describing the local region of sonar image is calculated for each bottom type. The parameter set includes but is not limited to: 1) basic statistical parameters describing the grey level distribution, i.e. local mean (*MEAN*) and standard deviation (*STD*), 2) the slope of the autocorrelation function of a grey level (in along track direction) approximated for a local region of the image (*SL_AUTC*).

In the second technique of multibeam sonar data processing (*Method 2* in Figure 1), the 3D "bathymetric" model of seabed surface is utilised [15]. It is constructed as a set of (x, y, z) points obtained from the detected bottom range for each beam, within the multibeam sonar seafloor imaging procedure. Next, for the local region of the constructed seabed surface, the set of descriptors is calculated, e.g.: rms height (*SURF_RMS*) and skewness of height (*SURF_SKEW*).

In the third technique of multibeam sonar data processing (*Method 3* in Figure 1), the set of echo signal envelopes received in the particular beams is analysed [16]. The data processing procedure in this method is more complex than in the two previous ones. Firstly, after detection of a bottom echo in the received signal, the set of echo parameters is calculated for an appropriate part of each beam echo. The parameters include: 1) the normalised moment of inertia I of the echo envelope, with respect to the axis containing its gravity centre [14], 2) fractal dimension D of an echo envelope, interpreted as a measure of its shape irregularity [14]. In the next stage, for each seabed type, the dependence of I and D parameter values of the particular beam incident angle is estimated. Using the estimated I and D angular dependence, the following parameters are calculated for each sounding (swath) for the application in the seafloor classification procedure: 1) the approximated slope of the angular dependence of the beam echo moment of inertia $I(\varphi)$, for the angle range of [2°, 17°] (*I_SLOPE*), and 2) the same approximated slope for the beam echo fractal dimension $D(\varphi)$, for the angle range of [4°, 19°] (*D_SLOPE*).

Finally, using the results obtained by the techniques described above, the 2D or 3D plots of calculated values for selected pairs of echo parameters were constructed. Also, using the calculated parameters, the supervised classification tests have been performed, with using 20% of the dataset as a training set with respect to each case of seabed type. Sample results are presented in one of the next sections.

The Experiment

The field data acquisition for verification of the proposed approach is summarized as follows. The measurements were conducted using Kongsberg EM 3002 sonar in the Gulf of Gdansk region of the Southern Baltic from 2007 to 2009. Several sites of different seafloor types were investigated, but the results of the current investigation refer to 4 selected sites, characterised by the following true seabed types: mud, anthropogenic sand and mud, fine grained sand, and coarse grained sand. The information about seafloor type was taken from the geological map of the Gdansk Bay. Figure 2 presents the simplified geological chart of the investigated water region, taken from [17], along with locations of multibeam data acquisition sites.

The sonar operating settings were as follows: frequency: 300 kHz, beamwidth: 1.5° x 1.5°, transmitted pulse length: 0.15 ms, echo sampling rate: 14.3 kHz. The bottom depth was in a range between 10 m and 100 m. Approximately, 1000 swaths from each of four seafloor types were processed. For each swath, 160 beams covered the angle sector from -65° to 65°.

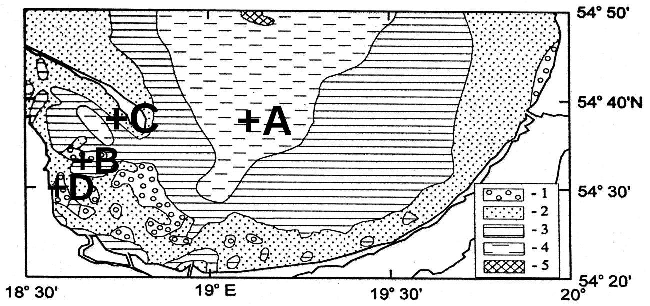

Figure 2: The geological map of the Gdansk Bay, taken from [17]: 1 – gravels, stones, 2 – sands, 3 – marine silty clay, 4 – mud, silt, 5 – glacial marine clay, with added locations of measurements indicated by letters A, B, C and D corresponding to seabed types listed in the Fig. 3 caption

Results

Sample results, with respect to the selected triplet of parameters: *I_SLOPE*, *STD*, *SL_AUTC* as a seabed type descriptors, are presented in a form the 3D plot in Fig. 3 and in a form of classification procedure confusion matrix in Table 1. The simple minimum distance classifier with Euclidean metrics was used.

It is visible that the choose of this set of 3 descriptors allows for quite good separation of the particular seabed classes as well as for very good classification performance – expressed in total of 97.19% correct classifications. As it may be seen in Figure 3, only the fine grained sand overlaps to some extent with the coarse grained sand (but it should be taken into account that these two bottom types do not differ too much from each other, especially regarding their acoustical response).

Of course, the proposed methodology should be more widely verified, in specific, by using larger amount of field data and with respect to several water regions.

Table 1: Confusion matrix for minimum distance classification of 4 seabed types using *I_SLOPE*, *STD*, *SL_AUTC* triplets as the descriptors

Assigned class / True class	Mud	Anthr. sand and mud	Fine grained sand	Coarse grained sand
Mud	**100%**	0%	0%	0%
Anthr. sand and mud	0%	**100%**	0%	0%
Fine grained sand	1.25%	0%	**90%**	8.75%
Coarse grained sand	0%	0%	1.25%	**98.75%**
Correct classifications - total: 97.19%				

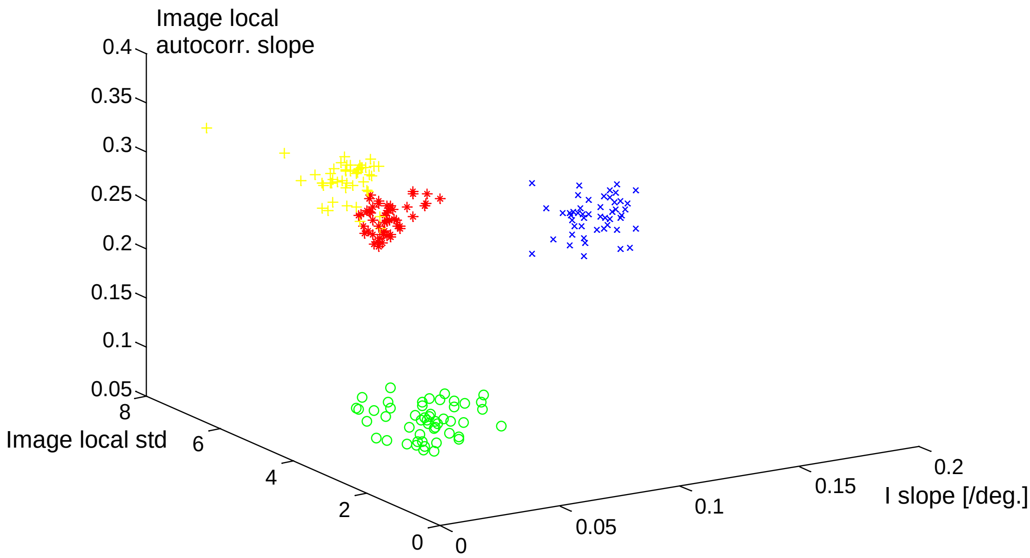

Fig. 3: Plot of triplets of calculated parameter values: (*I_SLOPE*, *STD*, *SL_AUTC*) for 4 seabed types: mud (blue, x letters), anthropogenic sand and mud (green, circles), fine grained sand (yellow, crosses) and coarse grained sand (red, stars)

In the course of the presented investigation, the additional study regarding the details on the manner used in particular parameters calculation, have been performed. In particular, the algorithms for *STD* and *SL_AUTC* calculation have been more deeply tested, namely, the influence of the particular (somehow arbitrary) choose of the algorithm settings like:

- the used sector of beams (i.e. the range of beam angles) in defining the sonar image subset for processing (*BEAMS*);
- the used sonar image subset size in along-track direction (number of lines/soundings) (*SOUNDINGS*); *BEAMS* and *SOUNDINGS* values define the size

(*BEAMS* defines also the across-track location) of the image subset used for single parameter value calculation;

- the used maximum offset in the autocorrelation function slope estimation (*MAX_LAG*)

on the results have been investigated.

The obtained results may be summarised as follows:

- The obtained class separation as well the classification results are quite sensitive to the choice of *BEAMS*. In particular, the results significantly better than in other cases have been obtained for the beams range from a beam no. 86 to a beam no. 95 (with total number of 160 beams) what corresponds to beam angles near normal incidence but not including the 0° beam.
- The obtained results are better for *SOUNDINGS* of about 40 or 60 and worse for *SOUNDINGS* above 80.
- The MAX_LAG (being equal 3, 4, 5 or 6 pixels during calculations) does not influence significantly the results.

Conclusions

After a short review of underwater acoustic technology and methodology developed recently and used nowadays in seafloor characterisation, the approach to seafloor classification, which relies on the combined, concurrent use of three different methods of multibeam sonar data processing, was presented. It has been primarily justified that all techniques are useful in seafloor characterisation, and the fusion of them improves the classification performance. Using the examples of particular parameters, the influence on the specific manner and details regarding their calculation, i.e. the size of the applied current local window to a sonar image, on the obtained classification performance was also investigated.

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