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Sea bottom typing using fractal dimension

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SUMMARY

The article presents an attempt to apply elements of fractal analysis for the purpose of sea bottom typing. The fractal dimension was calculated as box dimension for sampled envelopes of echo signals from four types of sea bottom recorded during mobile acoustic surveys carried out in Lake Washington. The results obtained show that the simple method applied can be used for on board sea bed recognition in real time with accuracy similar to that of other methods.

INTRODUCTION

Sea bottom identification methods have a wide range of applications in hydrography, marine engineering, environmental sciences, fisheries and other domains. Acoustic methods which use the information retrieved from the acoustic bottom echo, have advantages over the other methods (e.g. geological cores or remotely operated vehicles with TV cameras), as being non-invasive, more cost effective and faster.

In general, the following approaches are used in the acoustic methods of bottom typing:

- measurement of energy ratio of the first and second bottom echo (so called "RoxAnn" method) [2],
- comparison of the actual cumulative echo envelopes with theoretical patterns [5],
- analysis of a set of values of acoustic and statistical parameters of the echo envelope using cluster analysis or neural networks [6], [7],
- division of the first echo signal [1].

It is known for a fact that the surface of sea bottom is one of examples of a fractal structure object in nature [3]. Taking this into consideration as well as the fact that fractal dimension is a measure of the complexity of a given figure which in the case of bottom is related to the roughness and hardness of the sediment, the authors made an attempt to make a simple use of the fractal dimension of the recorded echo envelopes for the purpose of sea bottom typing. The implicit assumption here was that fractal structure of the bottom is transferred onto sort of its image observed in the form of an envelope of a sonar echo.

FRACTAL ANALYSIS

In the course of examining and describing the elements of nature, it was found that the shape and structure of these elements usually shows no regularities that are characteristic of simple geometric shapes which can be easily described using the terms from Euclidean geometry. That is why this kind of geometry is not the most adequate tool to describe this type of elements. On many occasions, however, nature has proved to accommodate various types of elements with fractal structure, e.g. the structure of plants' leaves, corrugated sea surface or bottom surface [3], which suggests that fractal analysis methods are the proper methods one should use to study and describe such elements.

Fractal sets are defined as scale-invariant (self-similar) geometric objects. A geometric object is called scale-invariant, if it can be written as a union of rescaled copies of itself. Regular fractas, such as the Cantor set, Sierpiński triangle or Koch snowflake which is shown in Fig. 1, display exact self-similarity [3], [4]. Random fractals display a weaker, statistical version of self-similarity.

When we want to measure the size of fractal figures, we encounter problems. We are not able to measure the size of such figures using standard methods. The Koch Snowflake, for instance, has a surface equal to zero (we mean the side of this figure), but its length tends to infinity when the size of the measuring step tends to 0.

The Hausdorff dimension [3], [4] may be the solution of this problem, as it can be used as a measure of many very general sets, including fractals. The Hausdorff dimension of a subset X of Euclidean space is defined as a limit

$$D = \lim_{\Delta s \to 0} \frac{-\log N(r)}{\log r} \qquad (1)$$

where $N(r)$ denotes the smallest number of open balls of radius r needed to cover X.

The open ball $B(p, r) = \{x: \text{dist}(x, p) < r\}$, where dist($x$, p) is the distance between points x and p. For example, the Koch snowflake has the Hausdorff dimension equal to log 4 / log 3 ≈ 1.262.

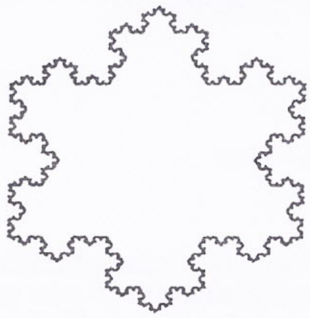


Fig. 1. The Koch snowflake, constructed as a limit of a sequence of simple iterative steps. Starting with the equilateral triangle, each consecutive stage is constructed by replacing line segments with copies of the figure _/_ . In the random version, in each stage the replacement by _/_ or ‾\/‾ may be made, with probability of 0.5 for each case.

It is visible that the dimension defined as above is the measure of the complexity of a given figure and we could apply it to measure the complexity of the shape of a digitized echo pulse from the sea bottom. It should be the indicator of the complexity and also the type of sea bottom. The shape of a digitized echo pulse, as it consists of a finite set of straight sections, is not really fractal. However, we can evaluate this dimension for such echo pulse not as a limit, but for a finite, fixed value of r.

MATERIALS AND METHODS

The bottom echoes data we used to calculate the fractal dimension were recorded in the water region of Lake Washington with the use of a digital DT4000 Biosonics echosounder with two operating frequencies: 38 and 120 kHz. Simultaneously the current position of the ship was being registered using the GPS system. Data acquisition was performed both while the ship was moving along the selected transects, and while the ship was anchored. In each case the type of sea bottom in the given water region was known. This enabled a verification of the applied method of bottom typing. The length of the pulse sent by the echosounder was 0.4 ms and the frequency of sampling the signal of echo envelope was equal to 41.66 kHz.

It is not easy to calculate the fractal dimension of a figure following the definition of the Hausdorff dimension. Therefore we decided to use the box dimension [3], that can replace the Hausdorff dimension for many sets, including shapes of our echo pulses. The box dimension for a figure on a plane is defined as follows. Let $N(\Delta s)$ denote the number of boxes in a grid of the linear scale Δs which meet the set X on a plane. Then X has a box dimension

$$D = \lim_{\Delta s \to 0} \frac{-\log N(\Delta s)}{\log \Delta s} \qquad (2)$$

The method of evaluating the box dimension of the bottom echo envelope is explained in Fig. 2.

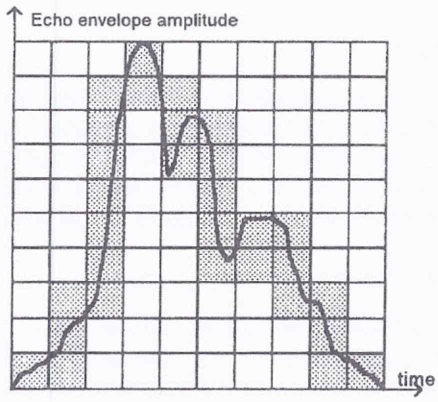


Fig. 2. Illustration of the box dimension evaluation. In the considered case, $\Delta s = 0.1$, $N(\Delta s) = 30$.

We evaluated the box dimension D for the finite value of $\Delta s = 1/36$, that is, there were 36 boxes both horizontally and vertically on the area of the echo waveform plot. Each echo pulse was normalized to the standard length and height and afterwards the number of boxes $N(\Delta s)$ was counted as shown in Fig. 2 and the box dimension was evaluated according to formula (2), but without using the limit. The amplitude threshold used for the analyzed signals was -70 dB. The box dimension was calculated for each echo pulse separately, and histograms of its values for each type of bottom were constructed and analyzed.

RESULTS

Figures 3, 4 and 5 show the histograms of box dimension values obtained for echo pulses for four types of bottom. Three sets of acquired data were analyzed: stationary data of echosounder frequency 120 kHz and 38 kHz and data from transects data of echosounder frequency 120 kHz. In each case, more than 600 pings for each bottom type were taken for the calculations. For stationary data, apart from analyzing the distribution of values of box dimension for all pulses, 10% of pings of the highest amplitude were selected in order to take into account only the echoes from pulses with the most likely normal incidence to the bottom and to drop the others, reducing the effect of a ship's pitching and rolling. However, it is easy to observe that this operation had no significant impact on the results.

The presented histograms show that in the case of the 120 kHz frequency of the echosounder (Fig. 3) there is a clear difference between the values of the box dimension for a rocky bottom and for other types of sea bottom, especially for the data collected from the anchored ship. In the case of rock the box dimension values are much higher which is in line with expectations, because the surface of a rocky bottom is more corrugated and irregular. For the other types of bottom, the obtained box dimension values at a 120 kHz echosounder frequency do not allow for a clear distinction between them, however, in the case of the data obtained from transects the general regularity is evident namely that the harder the bottom is the higher the box dimension values generally are.

What is interesting is the bimodal distribution of box dimension values for echo envelopes for rocky bottom for the data from transects (Fig. 5). This form of distribution is due to a recording made in transects of alternating series of pulses of a twofold shape. The examples of oscillograms of two classes of echo pulses from the transects are presented in Fig. 6. The existence of these two echo pulse types may be explained by alternative reception of echo signals reflected at normal incidence (specular reflection) and echo pulses received

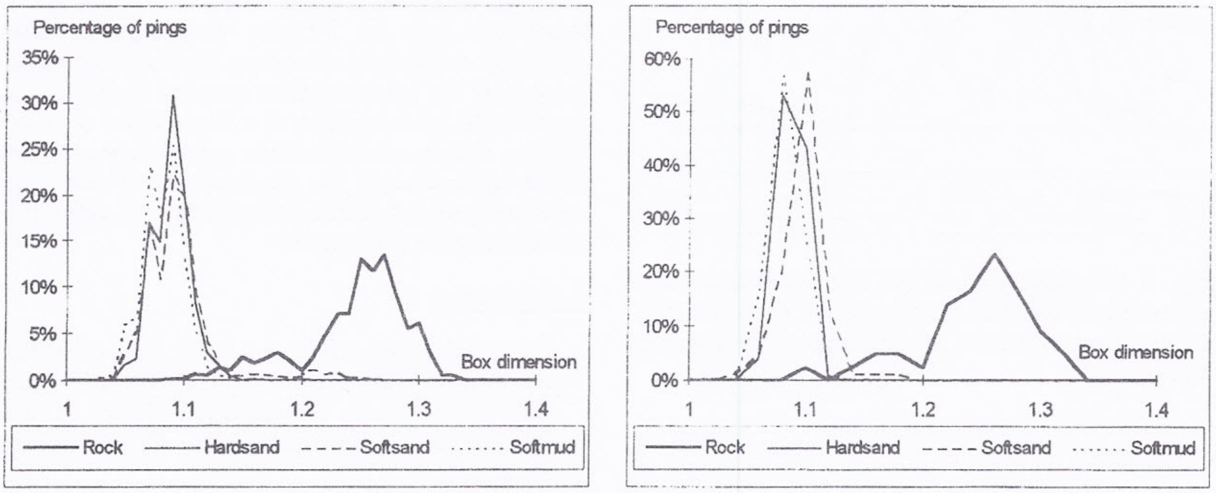


Fig. 3. The histogram of the box dimension values evaluated for echo pulses from stationary data for the echosounder frequency 120 kHz: a) for all echo pulses, b) for selected 10% of echo pulses of the highest amplitude level

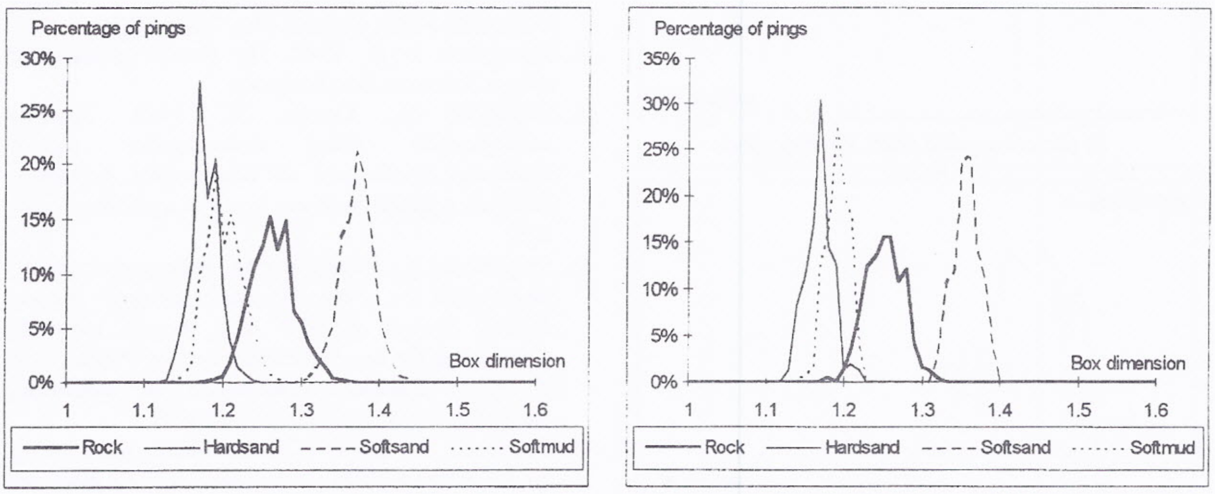


Fig. 4. The histogram of the box dimension values evaluated for echo pulses from stationary data for the echosounder frequency 38 kHz: a) for all echo pulses, b) for selected 10% of echo pulses of the highest amplitude level

at oblique incidence. The first type pulses have higher amplitude and less fluctuating envelope shape, against the higher amplitude and more fluctualing envelope shape of the second type pulses (see Fig. 6).

In the case of the 38 kHz echosounder frequency (Fig. 4), where the only data available was data from the anchored ship, there is a clear division between box dimension values obtained for various types of bottom.

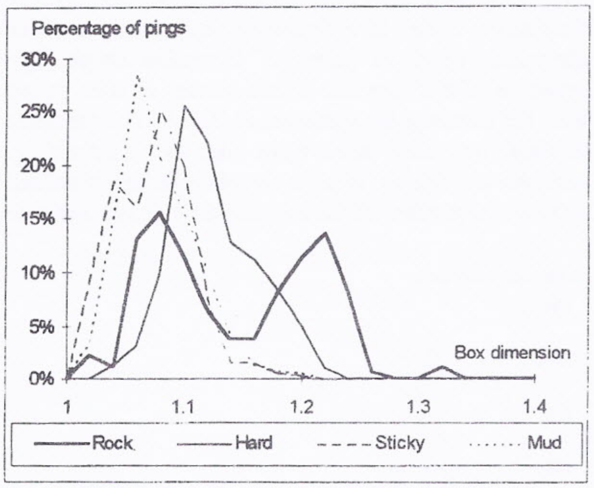
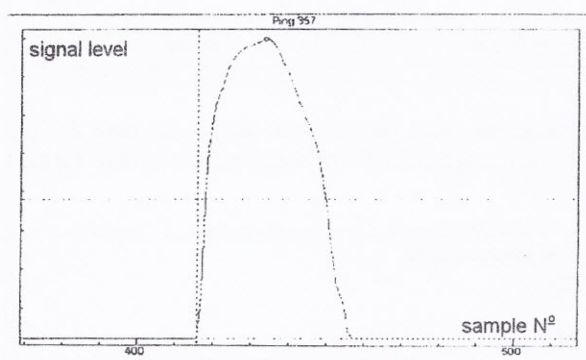
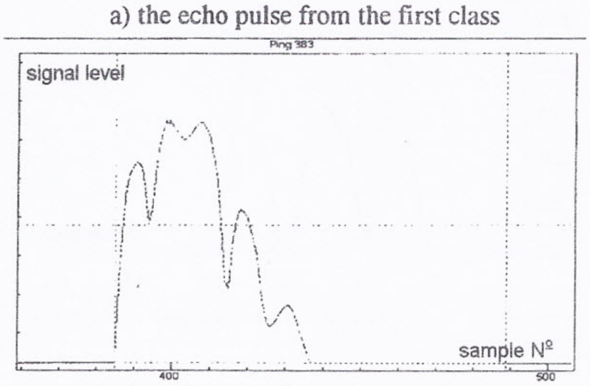


Fig. 5. The histogram of the box dimension values evaluated for all echo pulses acquired from transects, for four types of bottom, at the echosounder frequency 120 kHz



a) the echo pulse from the first class



b) the echo pulse from the second class

Fig. 6. Sample oscillograms of two classes of echo pulses, recorded for the rocky bottom from transect

However, the mutual relations between them are not in line with the expectation that echo envelopes from a bottom with higher hardness should have a higher value of the fractal dimension. This may be due to the fact that when pulses at this frequency are reflected from the bottom, for certain reasons the fractal structure of the bottom may fail to transfer itself onto its image in the echo envelope.

CONCLUSION

The results of the presented investigation are promising, as they show that evaluation of fractal dimension may be a usable method of bottom typing. The results are not worse than those obtained concurrently using other methods. However, it must be noticed that the data used were restricted only to one relatively small water region, so the method should be verified for a larger area and for different parameters of data acquisition. In this work the authors assumed, that fractal structure of the bottom surface transfers itself onto its image in the echo envelope. It is the authors' opinion, however, that an extension of the applied method could be the application of the deconvolution of scattering impulse response of seabed from bottom echo, before the fractal dimension is calculated.

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