Acoustical recognition of the bottom sediments in the southern Baltic Sea

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ABSTRACT

In the last decade, we made ca. 10000 km of acoustical transects using single-frequency, narrow beam 30 kHz echosounder. The main goal of our work was to determine the fundamental relationship between the parameters of backscattered signals and the type of bottom and sediments in the southern Baltic Sea. We chose several acoustical, statistical and spectral parameters of the echo envelope and compared them with morphological features of bottom sediments. The integral backscattering strength, time of backscattering, fractal dimension, moment of inertia, statistical and spectral moments of echo envelope turned out to be good descriptors of the sediments and could be used in classification procedures.

INTRODUCTION

The use of acoustic methods in the seafloor characterisation and preliminary geological analysis has been of particular interest due to their simplicity and versatility. In addition, acoustic methods are non-invasive and more cost effective than geological cores method, the disadvantage of these methods is associated with complex inverse theory of acoustical wave scattering on layered and rough seafloor. The existing theoretical models do not give satisfactory results in such inversion procedures. This is why these methods are still the subject of extensive research.

In the last decade, we have used single-frequency, 30 kHz echosounder to the acoustical recognition of the southern Baltic sediments. The main goal of acoustical measurements was investigation and description of dependencies between echo envelope parameters and types and structures of sediments. The other aim was to find a method of remote acoustical classification and recognition of southern Baltic sediments using the created set of parameters. For 30 kHz echo-soundings a model of the volume scattering of acoustic wave on the bottom was assumed. The basis for this approach was based on the fact that except the sand areas, the layer of sediments taking part in backscattering has a thickness equal to tens of spatial lengths of the sounding pulse and has to be treated as a volume scattering medium. The author also made an assumption that layers of bottom sediments have fractal structure, which is transferred onto the shape of the acoustic echo. The set of parameters describing acoustical, statistical, spectral and fractal properties of echo signals was used as the input to cluster analysis and neural network algorithms. The results of classification procedures exceed 80% of accurate sediment selections. The results were mapped and the space distribution of acoustical properties compared with geological structure was investigated.

DATA AQUISATION AND PREPROCESSING

The acoustical measurements were performed from the board of r/v Oceania using ELAC 4700, 30 kHz echosounder with the transmitter-receiver system mounted inside a V-fin body. The transducer of full beam angle 16° was towed at a depth of 2 m with the ship velocity 2-3 knots. The echosounder emitted pulses 0.3 ms long with the repetition of 90 pings per minute. The echo envelope was sampled and stored in 64 ping sequences together with ship position and parameters of echosounder adjustments. Because of pitch and roll of transmitting-receiving system, the preliminary stage of data processing was to remove the errors of swaying beam. As the result of pulse selection procedure only 15÷30% pulses with maximum values of the discriminate parameters were chosen. In the discrimination procedure, the depth of first crossing of the bottom level by signal, the position of gravity centre of backscattered echo intensity, and the acoustical energy of returned pulse, were selected from the each 64-ping data set. Subsequently, the averaging process was applied to the sets of the selected pings to achieve the best echo profiles, which were then used in the calculation of the bottom parameters.

BOTTOM ECHO PARAMETERISATION

For the acoustical description of southern Baltic sediments, a set of echo envelope parameters was chosen. The most significant parameters characterising the acoustical, statistical, spectral and fractal properties of echo signals are given as follows:

- **integral backscattering strength** S_{bs} [11]:

$$S_{bs} = 10 \log \int_{z_1}^{z_2} s_v(z)dz [\mathrm{dB}],$$

where s_v is the volume backscattering coefficient and z_1 and z_2 are limits of a depth interval,

- **attenuation coefficient** β [dB/m] [3] in the top layer of bottom sediments. In this case, the exponential law of decreasing the amplitude of an echosignal is supposed. A slope coefficient of the line fitted to values of logarithm from the echointensity of averaged profile has the meaning of attenuation coefficient.

- **time of reverberation** T_{90} (the time in which 90% of the echo energy E_{90} returns):

$$T_{90} : E_{90} \sim \int_0^{T_{90}} p^2(t)dt = 0.9 \cdot \int_0^{\infty} p^2(t)dt,$$

where p is the acoustical pressure of bottom echo signal.

- **moment of inertia** of the echo envelope, in respect to horizontal axis containing its gravity centre.

$$M\_in = \frac{\sum_{i=1}^{N} [(i - i_c) \cdot \Delta t]^2 \cdot p_i^2}{\sum_{i=1}^{N} p_i^2},$$

where Δt is the sampling rate, i_c - the sample number corresponding to position of gravity centre 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 centre.

- **spectral width parameter** n^2 denoting the concentration of the spectral power density around the mean frequency $v = m_1/m_0$ is defined as follows [1]:

$$n^2 = \frac{m_0 m_2}{m_1^2} - 1,$$

where $m_r = \int_0^{\infty} w^r S(w) dw$ are the spectral moments of the r order, $S(w)$ is the power spectral density and w denotes the echo signal envelope frequency. Another measure of the spectral width may be defined as [1]:

$$e^2 = \frac{m_0 m_4 - m_2^2}{m_0 m_4}.$$

When the spectrum is extremely narrow (the total energy of backscattered signal is concentrated around one frequency v), parameters n and e become small, i.e. $n^2 \to 0$ and $e^2 \to 0$. For the opposite case when the spectral energy is broadly distributed among frequencies, $e^2 \to 1$ and n^2 increases.

- **fractal dimension** D_{w_Mayer} of echo envelope, based on **wavelet transformation** [6].

The different mother wavelets were tested and compared. As an example of fractal dimension calculations the results obtained using Mayer wavelets are presented.

Moreover, the echo parameters such as **reflection coefficient**, **radius of autocorrelation**, **skewness**, **kurtosis**, **spectral skewness** and **spectral kurtosis** [2], and **fractal dimension** determined in the other way [8,9] were calculated.

RESULTS

The Baltic Sea is a representative example of a shallow sea with complicated layered structure of bottom sediments. A characteristic feature of the southern Baltic Sea area is the presence of offshore shallow water regions and abyssal plains separated by ridges. In a large part of the deep areas, there are sediment layers with specific properties such as the intense sedimentation of organic materials. The deeps are covered by acoustically soft semi-fluid clays and silts. Peculiar and rare acoustically soft peats are present in the Gulf of Gdañsk. A major part of shallow sea deposits consists of sands, gravel and stones.

The example of an acoustical transect lying in the North-East part of Pomeranian Bay with bottom covered by muddy sediments is shown in the Figure 1. The transect of the length of 30 km starts in the position of ϕ=54°40.263'N, λ=15°19.458'E at the depth of 61 m. In the top layer of sediment, marine clayey silt varying with depth increasing to the marine silty clay [4] is located. This layer of acoustically soft sediments takes only a small participation in a signal backscattering. Below this sediment layer is a bed of acoustically harder marine clays rising to the top of the bottom in the final part of transect. The bottom layer of sediments consists of till impenetrable for 30 kHz acoustical waves. The end of transect at the position of ϕ=54°49.601'N, λ=15°32.648'E is 73 m in depth.

Below the acoustical profile, variations in echo envelope parameters along the transect are shown. The layered structure of sediments is reflected in parameter variation. The backscattering strength S_{bs} changes values in the range of -21 dB for marine clayey silt to - 9 dB for clays. The attenuation coefficient varying from -2.5 dB/m to 0.5 dB/m for 30 kHz echo signal. The type of sediment that appeared in the top layer implicates the value of time T_{90}, in which 90% of the echo energy returns. For harder sediments in the top layer time T_{90} is 8 ms and for parts with softer sediments increasing to 25 ms. Moment of inertia describes how the echo energy is concentrated around the gravity centre. The small value of *M_in* denotes short echo and is visible for clays appearing in the top layer. The opposite situation is for acoustically soft marine clayey silt while greater value corresponds to longer echo with several parts of relatively high signal level, which may indicate sediment layers. The spectral widths and fractal dimension for short echo envelopes appearing in 10-th km of transect have small values (n^2 tends to 1, e^2 to 0.7 and D_{w_Mayer} to 1.1). The opposite tendency is observed for the silty-clay sediments in deeper regions of the investigated area where the spectral width n^2 tends to 5, e^2 to 1 and fractal dimension achieves value of 1.85. The large values of these parameters are the result of volume scattering at the layered structure of sediments.

Figure 2 shows the spatial distributions of attenuation coefficient β [dB/m] in top layer of bottom sediments, fractal dimension D_{w_Mayer} and spectral width e^2 determined at 30 kHz within the Polish economic zone. The values of attenuation varied in range from 1 dB/m in muds to 30 dB/m for sands and gravel in coastal zones. The next map demonstrates the distribution of fractal dimension D_{w_Mayer} of the echo envelop based on the wavelet transformation. The value of the fractal dimension of echo envelope carry information about the horizontally layered structure of sediments as is seen for silty-clay sediments (Fig.1) with deeper acoustic penetration. The fractal dimension has higher values exceeding 1.8. For sandy sediments with short echoes, without distinguishable layers, the fractal dimension has relatively small values, which does not exceed 1.2. The bottom map of Fig.2 shows the spatial distribution of spectral width e^2 determined at 30 kHz within the Polish Economic Zone. For sandy and shallow water areas characterised by short and smooth echo envelopes, the spectral width does not usually exceed the value of 0.6. The opposite situation is observed in the areas of Gdañsk and Bornholm Deeps where the value of spectral width reaches 1.0 and corresponds to the case when spectral energy is broadly distributed among frequencies.

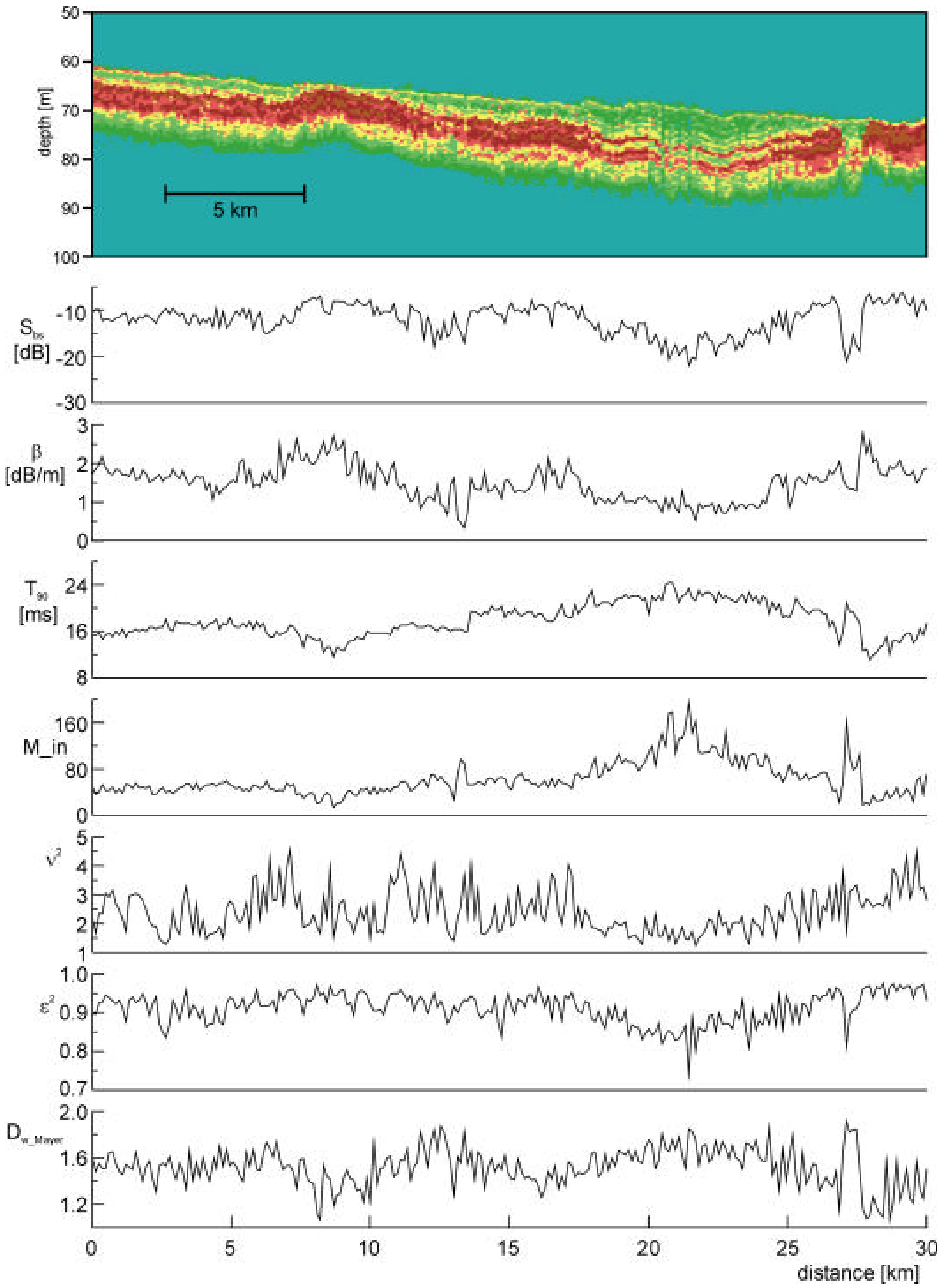

Figure 1. A selected acoustical transect in the southern Baltic and variations in echo parameters along the transect: integral backscattering strength S_{bs}, attenuation coefficient *b*, time of reverberation T_{90}, moment of inertia M_in, spectral widths n^2 and e^2, and fractal dimension D_{w_Mayer}.

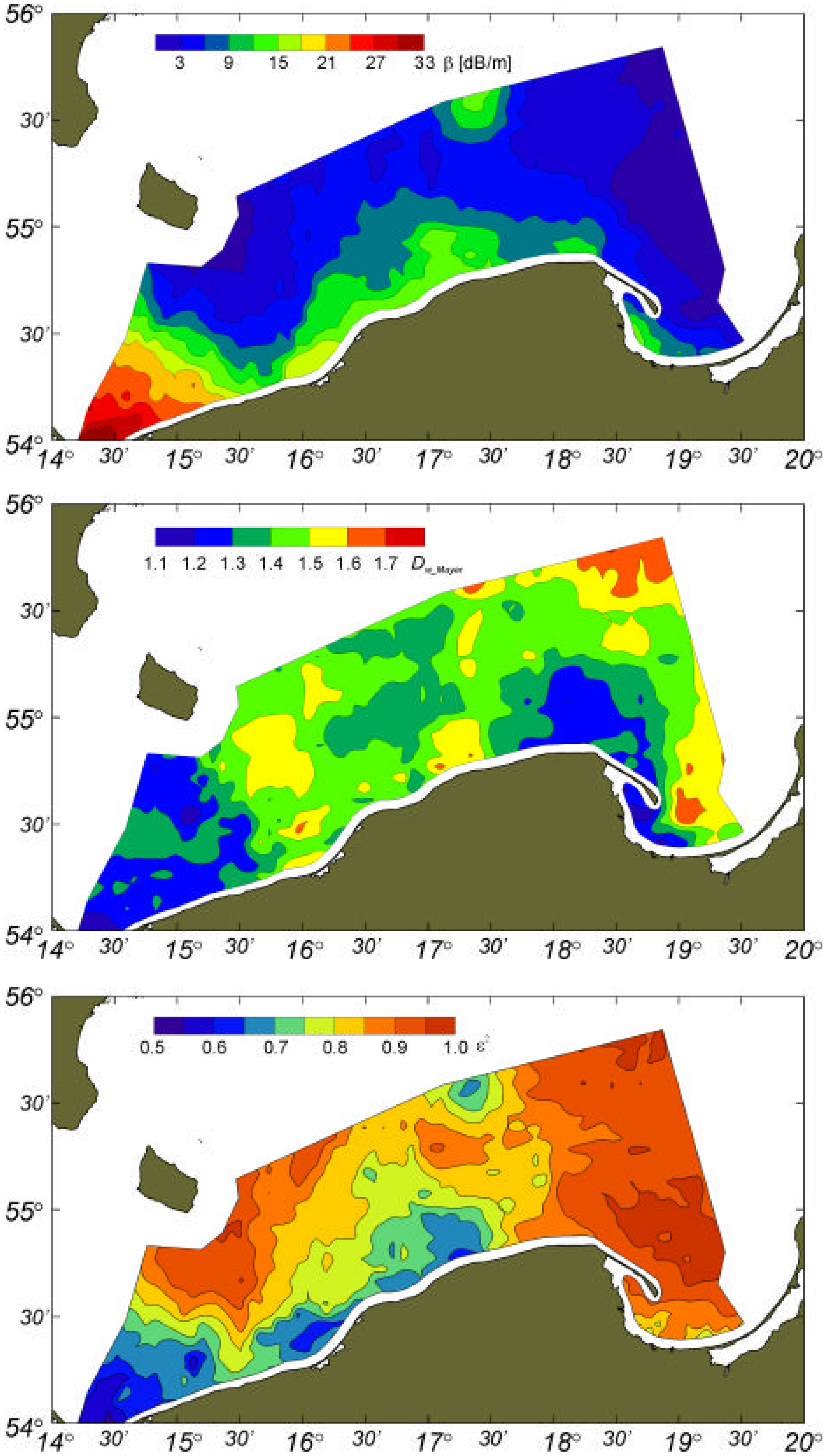

Figure 2. Maps of the estimated attenuation coefficient β in top layer of sediments, fractal dimension D_{w_Mayer} and spectral width ε^2 of bottom echo envelopes in the Polish economic zone of the Baltic Sea at the frequency 30 kHz. The spatial distributions were obtained by interpolation of values calculated for over 15.000 averaged echoes.

BOTTOM SEDIMENTS CLASSIFICATION

For purposes of sea bottom type classification, the K-MEAN algorithm of clustering [5,7,10] and error-backpropagation feed-forward neural network [8] were used. The clustering method was tested in the four areas of southern Baltic Sea. The classification process was realised for the four types of sediments most abundant in southern Baltic: coarse sand and gravel, fine grained sand, clay, silt. Results of classifications and sets of used echo parameters are collected in the Table 1.

Table 1. The results of acoustical classification conducted in different southern Baltic areas.

Region	Classification parameters	Method	% of suitable classifications			
			Coarse sand and gravel	Fine grained sand	clay	silt
A	S_{bs}, T_{90}, M_in, V, *skew*	clust. a.	82.6%	88.1%	82.3%	86.7%
B	S_{bs}, T_{90}, M_in, V, *skew*	clust. a.	89.3%	84.6%	79.4%	85.4%
C	S_{bs},, n^2, D	clust. a.	91.4%	88.1%	82.7%	89.3%
D	S_{bs}, T_{90}, D	neural n.	93.4%	89.6%	83.2%	88.1%

Regions depicted in the Tab. 1: A - Pomeranian Bay [10], B - S³upsk Furrow [5], C - Polish coast to Bornholm Island area [7], D - Gulf of Gdañsk [8].

5.CONCLUSIONS

The results obtained by the author prove that the proposed echo signal parameters describe well the structure of bottom sediments and may be successfully used in the seabed classification procedures. The averaged percentage of suitable classifications in the Pomeranian Bay achieves 84.9%, in the S³upsk Furrow 84.7%, in the area located between Polish coast and Bornholm Island 87.9% and in the Gulf of Gdañsk 88.6%. For the set of tested parameters the best results were obtained for cases where fractal dimension and neural network algorithm were used.

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Acoustical classiï¬cation of the bottom sediments in the southern Baltic Sea. Jaros"aw Tegowski). Institute of Oceanology, Polish Academy of Sciences, Powstanc! ow!Â Using a ship-mounted echosounder in several selected points in the southern Baltic Sea, studies of backscattering at 38 and 120 kHz were performed by Or"owski (1984) and Klusek (1990). The results presented here concentrate on the acoustical parameters of backscattered acoustic signals from the bottom of southern Baltic Sea. There is no detailed discussion of the geological properties of the bottom. 2. Data acquisition and signal processing. In the last decade, about 10,000 km of acoustical transects in the southern Baltic Sea area were made. Statistical evaluation showed that geological classification of the seafloor's sediments is possible by associating these attributes according to their coherence. The methodologies here developed seem to be appropriate for glacio-marine environment and coarse-to-medium silt sediment found in the study area and may be applied to other regions in the same geological conditions.Â 12. Tegowski, J.: â€˜Acoustical classification of the bottom sediments in the southern Baltic Seaâ€™, Quat. Int., 2005, 130, pp. 153â€“161 (doi: 10.1016/j.quaint.2004.04.038). 13). 13. Biffard, B.R., Preston, J.M., Chapman, N.R.: â€˜Acoustic classification with single-beam echosounders: processing methods and theory for isolating effects of the seabed on echoesâ€™. OCEANS, 2007, pp. 1â€“8. 14). Baltic Sea sediments as an important sink for organic carbon. Regional of the Baltic Sea. The main purpose of this paper is to present a large-scale. assessment of chromium contamination in sediments of southern orporation,. Taiw an.Â fides, oxidized and reduced forms of iron, reduced manganese, and iron monosulfide in pore wa- ters of the bottom sediments in the Sevastopol Bay. It is shown Hydrocarbons in the suspended matter and the bottom sediments in. station to avoid film penetration. . column of the Black and Azov Seas [11]. .. in the Feodosiya Bay, the penetration of water from the Sea of Azov occurs quite. Seismostratigraphy of bottom sea sediments in some areas of the. or Kongsfiorden areas) where the influence of a branch of the Gulf. Stream is .. area.