Acoustic properties of the Pomeranian Bay bottom sediments*

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Jarosław Tęgowski,
Zygmunt Klusek
Institute of Oceanology,
Polish Academy of Sciences,
Powstańców Warszawy 55, 81–712 Sopot, Poland; e-mail: tegowski@iopan.gda.pl

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Abstract

The properties of bottom backscattered signals in the Pomeranian Bay have been investigated using a one-frequency single beam echosounder working at a central frequency of 30 kHz. The backscattering strength, time of reverberation and attenuation coefficient in sediments were estimated and mapped for the whole area. The other purpose of the investigations was to verify the acoustic one-frequency multiparametric method in order to determine the sediment-type distribution in the Pomeranian Bay. This method was found as useful tool for sediment identification in the study area.

1. Introduction

The most reliable and robust methods of identifying bottom material are geological ones. Unfortunately, however, they are inefficient. The application of acoustic methods to characterise bottom properties from the backscattering of sound waves is now recognised as a useful and well-suited tool, especially when compared with preliminary geological core analysis. A further advantage of the acoustic method is the speed of data collection. Moreover, individual local geological formations are readily detectable and their thickness can be estimated with ease. It must be realised, however, that

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traditional acoustic or seismic mapping only partly satisfies the demand for strict interpretation and represents a trade-off between bottom-type determination and the cost of measurements. The success rate for sediment identification using remote acoustic classification is often poor. The main limitation of the acoustic method lies in the complicated inverse theory of scattering problems. In addition, existing theoretical works do not provide unambiguous results that could be used as the basis for the inversion. In this situation, the multiple approach used in this work could be a first step to achieving satisfactory results.

A large number of high-resolution continuous seismo-acoustic and echosounding profiles have been made in the whole Baltic Sea, mostly for stratigraphic purposes and to provide material for geological interpretations (*Geological map of the Baltic Sea bottom* 1989–1994). The qualitative results of those investigations together with geological core analysis provide information only about the bottom structure (Svirydov 1980). The acoustic properties of the Baltic Sea top layer sediments have been known from laboratory and field investigations since the late nineteen-sixties and early seventies (Ulonska 1968, Orlenok *et al.* 1973).

The qualitative measurements and the interpretation of the properties of echosignals reflected and scattered at the bottom of the southern Baltic Sea done so far are insufficient. The measurements covering the Polish Economic Zone of the Baltic Sea were done in 1991–1994 by Tęgowski (1994), but did not include the Pomeranian Bay. Using a ship-mounted echosounder at single points in the southern Baltic Sea, Orłowski (1984) and Klusek (1990) performed backscattering studies at 38 and 120 kHz and put forward different methods of bottom-type identification.

The present investigations focused on the parameters of acoustic signals backscattered from the bottom of the Pomeranian Bay. There is no detailed discussion of the geological properties of the bottom.

The data in this paper will be of interest to hydroacousticians, because in much acoustic work conducted in shallow-water areas a knowledge is required of the physical and statistical parameters of the signals reflected and scattered at the bottom.

2. Equipment and experimental procedures

All measurements were performed using an ELAC 4700 echosounder with a transducer full beam angle of 16° (±3 dB), working at a frequency of 30 kHz. The transmitter-receiver system mounted inside a V-fin body was towed at a depth of 2 m at 2–3 knots. The echosounder emitted pulses, typically 1–0.3 ms long, with a repetition rate of 90 pings per minute. The echo envelope was sampled at a frequency of 3 kHz and the digitised data was stored on the PC hard disk. A sequence of 64 consecutive pings with the ship's position received from the GPS system and echosounder parameters were stored as one block file and formed the basic bin of the acoustic data base. Imperfections in the echosounder hardware TVG function as well as the non-linearity of the system were corrected during post-processing. Because of the evaluation of the related acoustic and statistical parameters of the echosignals, processing of the raw data should imply a specific off-line procedure. The acoustic measurements were performed in 1995–1997 during cruises of r/v 'Oceania' along the tracks shown in Fig. 1.

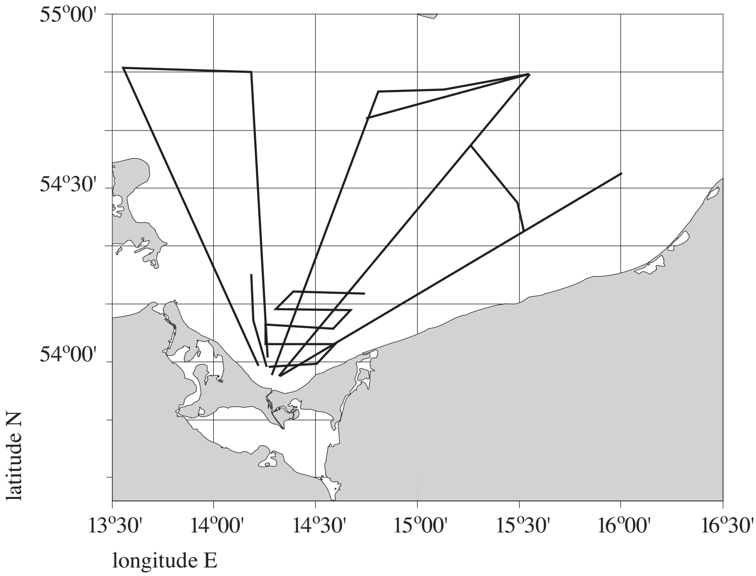

Fig. 1. Map of the survey area

3. Signal processing and calculated parameters

3.1. Parameters

The source (echosounder) emits energy, some of which is reflected at the sediment-water interface while some is transmitted into the sediments. The penetrating portion is subsequently scattered at sediment layer interfaces and by scatterers within the sediments. The received acoustic pressure is the quasi-coherent sum of signals reflected at the sediment-water interface, multi-reflected between sub-bottom layer boundaries and scattered at bottom inhomogeneities. Hence, the various aspects of the back-scattered signal should be of practical interest. To improve acoustic sediment identification, multiple parameters should be introduced to describe the backscattering in a complex way.

In the present study the echosignals reflected and scattered from the seabed were described using a set of parameters calculated from

- the integral backscattering strength S_{bs} (the logarithmic measure of the energy integrated over the total echosignal duration), which can be expressed as follows (Urick 1975):

$$S_{bs} = 10 \log \left(\sum_{i=1}^{N} s_v(z_i)\, \Delta z \right), \tag{1}$$

  where

  N – as everywhere below, is the number of samples in an echo,

  s_v – the volume backscattering coefficient;

- the normalised moment of inertia of an echo envelope, computed from the relationship

$$I = \frac{\sum\limits_{i=1}^{N} [(i - i_c)\, \Delta t]^2\, p_i^2}{\sum\limits_{i=1}^{N} p_i^2}, \tag{2}$$

  where

  Δt – the sampling period,

  i_c – the sample number nearest to the centre of gravity of the echosignal,

  p_i – the acoustic pressure sampled at time t_i;

- the reverberation time (the measure of echosignal duration), expressed as the time in which 90% of the echo energy returns

$$T_{90}: \quad E_{90} \sim \int\limits_0^{T_{90}} p^2(t)\, dt = 0.9 \int\limits_0^{\infty} p^2(t)\, dt; \tag{3}$$

- the attenuation coefficient β, estimated using the curve best fitting the ‘tails’ of an echo (there could be more than one attenuation coefficient per echo profile, depending on how many homogeneous layers could be resolved);
- the skewness of an echo envelope as a measure of envelope asymmetry, (where the values of the envelope are formally considered to be the probability density function of the depth z);
- the pressure amplitude reflectivity (the Rayleigh reflectivity in the case of a perfectly smooth seabed) of the top-most sediment layer V.

These pressures were normalised to the maximum value found in the area. For the ideal 20 lg(r) TVG function and calibrated system, we have the following estimation of the Rayleigh pressure coefficient V:

$$V = \frac{2H\,p_r}{p_0}, \tag{4}$$

where

H – distance from the transducer to the bottom,

p_r – the highest value observed in the echosignal reflected at the water-sediment boundary, measured by the receiver,

p_0 – the acoustic pressure at a distance of 1 m from the transmitter;

- the statistical properties of the bottom reverberation signals, among them the coefficient of signal fluctuation defined as

$$\delta = \frac{1}{N-k}\sum_{i=1}^{N-k}\left(\frac{p_i^2 - p_{i+k}^2}{p_i^2}\right), \tag{5}$$

- a similarity coefficient introduced by the authors.

The similarity coefficient reaches its maximum value of one for two identical profiles, as two random sets of data (uniform distribution of values) could be less than zero. This criterion determines whether the sea bottom properties are changing rapidly.

Two classes of calculated echo parameters could be distinguished:

1) parameters integrated over the whole range of pulse penetrations within the bottom material, such as the reverberation time, integral backscattering strength or skewness of profile, and
2) local parameters (for some strata only), such as the coefficient of attenuation or reflectivity.

Because of the pitch and roll of the transmitting-receiving system mounted on the exterior of the vessel, special procedures to reduce the errors due to a swaying beam were applied. The following criteria were used during post-processing – only those pings within a block were chosen for averaging for which a local maximum of returning energy or the highest locations of the centre of gravity of the envelope occur. The logical sum and logical product of these two methods were also used as an alternative. If bottom fish were present, it was up to the program operator to establish the depth of water-bottom boundary.

If other errors could influence the energetic characteristics of the echosignals, especially at high sea states, when signals were passing through a bubble screen, those pings were removed from the analysis.

3.2. Classification method

The one-parameter classification of the bottom (amplitude reflection coefficient) using a one-frequency echosounder has been found quite successful in the case of homogeneous sediments (Orłowski 1984) in the Baltic Sea. Klusek (1990) describes a three-parameter method of classifying sediment type in the southern Baltic in which the integral backscattering strength, the bottom reverberation time and the coefficient of attenuation act as descriptors. This was found to work quite well in the simplest situations. In the study area, most of the bottom is relatively flat with continuous sediment cover mainly of sand. However, in the north-east of the area, we came across fields made up of many thin (compared to the acoustic penetration depth) layers, each of which was composed of various materials of different origin. In this paper, for bottom-type identification purposes, five echosignal parameters were used, *i.e.* S_{bs}, T_{90}, V, the skewness of the echosignal shape and the moment of inertia averaged in a block of 64 consecutive echo profiles. Although some of these parameters are to a certain extent dependent on one another, (and could be neglected), calculating the clustering of the parameters in a higher dimension space helps in identifying the bottom type. An earlier application of the method was used to solve bottom identification problems on the Słupsk Bank and in the Gulf of Gdańsk (Tęgowski 1994). The results obtained in that work were encouraging as a low-cost method, where the selected echosignal parameters were easy to calculate.

For the purpose of sea bottom-type classification, the KMEAN clustering algorithm was used. Because of the different nature of the echosignal parameters and their broad range of values, each parameter was normalised to its maximum value recorded in the study area.

4. Results

Figure 2 exemplifies an acoustic survey along a transect nearly 78 km long in the western part of the study area. The starting point on a sandy bottom at a depth of 33 m was located at $\varphi = 54°50.1'$N, $\lambda = 14°08.1'$E. The area at the opposite end of the transect lay in the southern part of the Arkona sedimentary basin at $\varphi = 54°50.4'$N, $\lambda = 13°34.0'$E. The bottom depths were calculated assuming a constant sound velocity $c = 1450\,\mathrm{m\,s^{-1}}$. The same approximation was applied in the calculations of sediment thickness.

The variation in acoustic properties of the sediments along the transect is clearly visible. Acoustic analysis of the transect supports the geological analysis and reveals the main features of the sediments in the area. Here there is coarser sediment composed of sands impenetrable to acoustic waves, a transition zone where soft sediment layers thicken from 42 to 44 m depth and the typical soft sediment of the basin. On the right-hand side of the figure, there is a ten-kilometre long lens of sediments impenetrable to acoustic waves, which may contain silt with a pocket of gases.

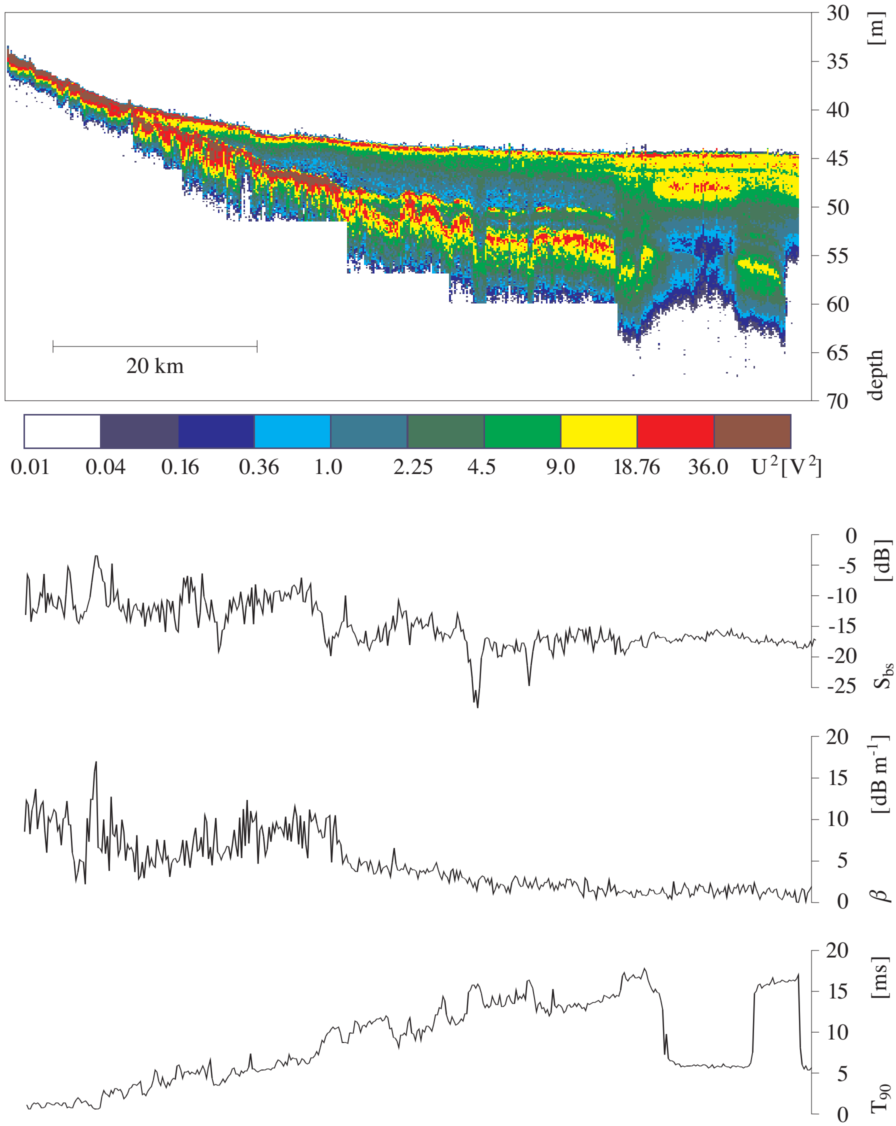

Fig. 2. Compressed echogram and selected echo parameters for an acoustic transect across the Pomeranian Bay. The transect begins at $\varphi = 54°50.1'$N, $\lambda = 14°08.1'$E and ends at $\varphi = 54°50.4'$N, $\lambda = 13°34.0'$E; profile length 78 km

The averaged values of the three main echosignal parameters computed for each block of 64 consecutive pings are given in the lower part of Fig. 2.

The next four figures (Figs. 3, 4, 5 and 6) illustrate the spatial distribution of the main echo parameters in the area.

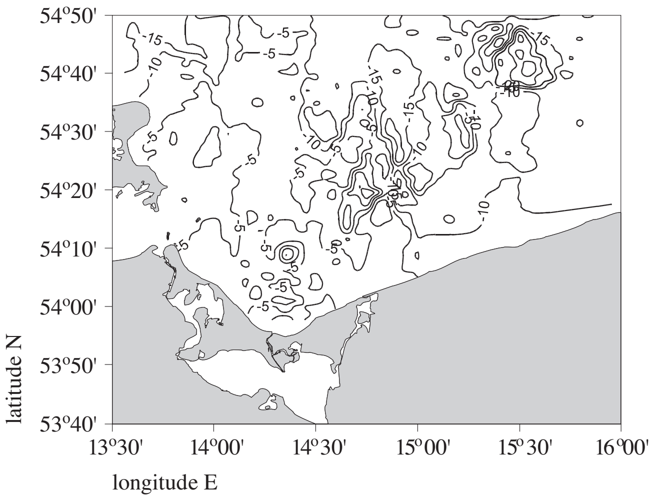

Fig. 3. Integral bottom backscattering strength S_{bs} [dB] map in the Pomeranian Bay at a frequency of 30 kHz

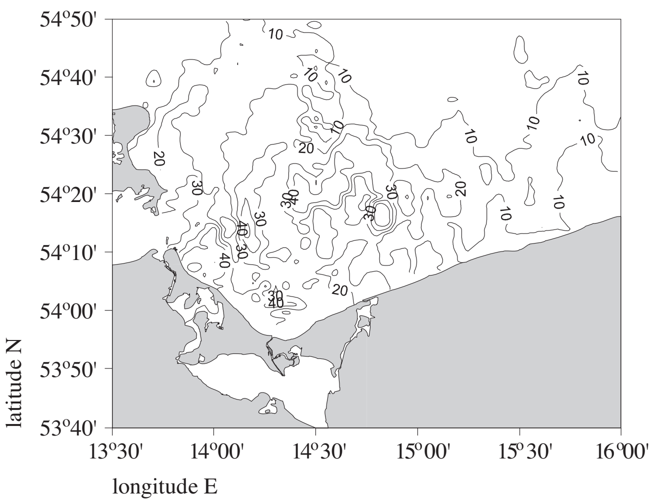

Fig. 4. Spatial distribution of attenuation coefficient β [dB m^{-1}] in the Pomeranian Bay at a frequency of 30 kHz

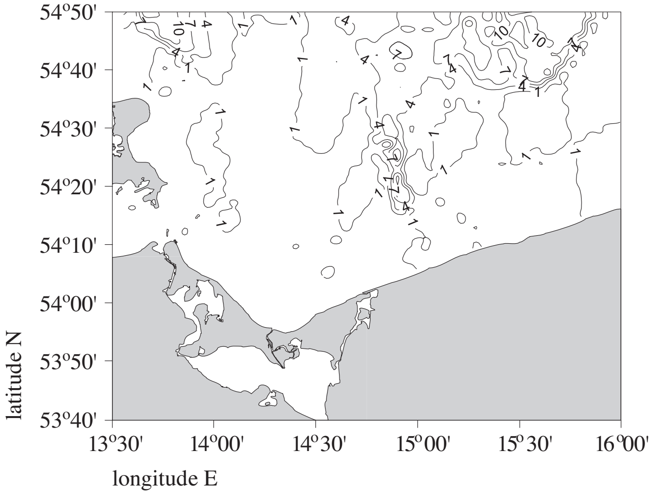

Fig. 5. Spatial distribution of reverberation time T_{90} in [ms] in the Pomeranian Bay at a frequency of 30 kHz

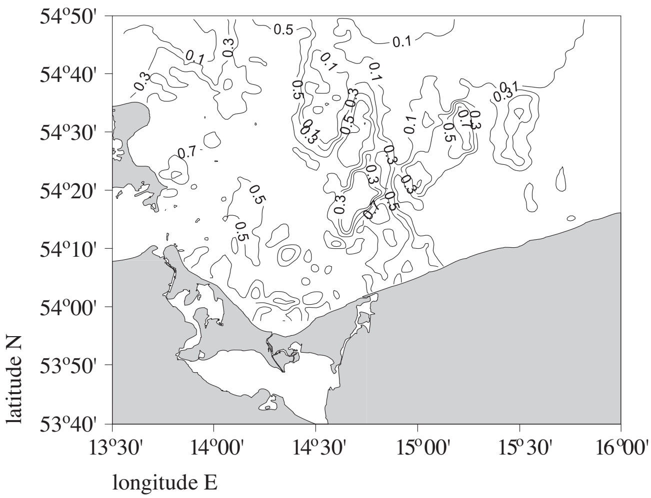

Fig. 6. Map of the normalised reflection coefficient at the water-sediment interface in the Pomeranian Bay at a frequency of 30 kHz

Figure 7 depicts the dependence between three echo parameters – the normalised reflection coefficient at the water-sediment interface, the integral bottom backscattering strength S_{bs} and the attenuation coefficient in the uppermost layer of sediments β. The points in three-dimensional space are grouped mainly into two clusters. One of these contains the highest values of the attenuation coefficient in the 20–40 dB m^{-1} range, relatively high backscattering strengths S_{bs} from –15 to –2 dB, and reflection coefficients between 0.3 and 0.9. These values characterise hard sediments – sand and sand with gravel.

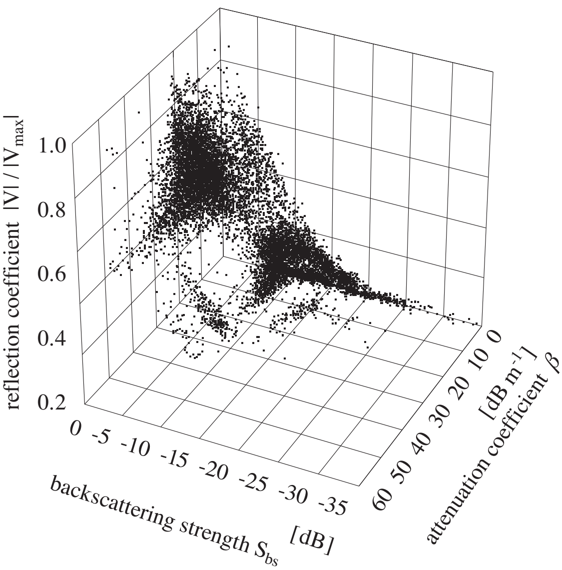

Fig. 7. Relationship between the main echosignal parameters – backscattering strength S_{bs}, attenuation coefficient in the uppermost layer of sediments β, and reflection coefficient $| V | / | V_{\max} |$ normalised to maximum amplitude at 30 kHz in the study area

The other cluster consists of points with S_{bs} values down to –35 dB and low attenuation coefficients (20 dB m^{-1}). The reflection coefficient at the boundary in this cluster is < 0.3 (relative to the maximum for a hard bottom), a figure characteristic of the silted clay sediments typical of the deepest parts of the basin. Only a few points are located outside these two clusters; this corresponds to an intensively layered bottom with a strongly contrasting acoustic impedance (clay, sand) between the layers. In the shallow-water area of the Pomeranian Bay, where the seabed is mostly sandy, the integral bottom backscattering strength S_{bs} attains maximum values. In this area S_{bs} ranges from –13 to –2 dB, the reflection coefficient from 0.3 to 0.9, T_{90} from 1 to 5 ms, the profile shape skewness lies between –1 and 1 and the gravitational moment between 0.1 and 20 ms.

In the northern and north-western parts of the Bay, where the sediments are fluid (a soft bottom), S_{bs} ranges from –13 to –35 dB, the reflection coefficient is < 0.3, the reverberation time T_{90} reaches a value of 20 ms, the skewness rises to 5, and the normalised gravitational moment to 100 m s^2.

The points where the reflection coefficients approach zero and S_{bs} values are dispersed lie in a region where a more complex stratigraphic structure with different types of strata participates in the backscattering. An example of such a case is sand covered by a layer of mud, which gives a high value of S_{bs} and a small value of $|V|$.

In general a high bottom reflectivity is characteristic of media with a more strongly contrasting acoustic impedance (the acoustic impedance of a plane wave is $Z = \rho c$, where ρ – density and c – velocity of sound in the medium).

The results of the acoustic classification shown below were calculated on the basis of 462 blocks of raw data. At the beginning of the classification procedure, the five dimensional vectors of cluster centres typical of different types of sediments were incorporated from earlier results from the Gulf of Gdańsk (Tęgowski 1994). Four bottom-type classes were chosen with echosignal characteristics as shown in Table 1.

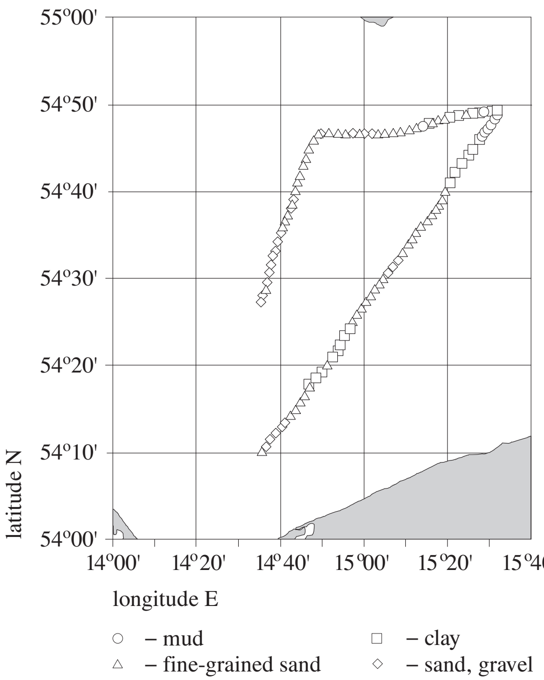

Fig. 8. An example of the automatic classification of sediments along selected transects in the Pomeranian Bay. Division into 4 types (classes) of sediments is assumed

Table 1. Computed values of echodescriptors in clusters for bottom sediment classes from the acoustic transect in Fig. 8

Cluster number	S_{bs} [dB]	T_{90} [ms]	I [ms^2]	V	Skewness
1	–19.9	9.9	107.6	0.08	5.4
2	–17.1	6.0	41.0	0.11	4.4
3	–14.5	2.9	9.2	0.18	2.5
4	–7.7	1.9	3.3	0.72	1.4

1 – muddy deposits (deeper part of the study area),
2 – clay, clayey silt,
3 – fine- and medium-grained sand,
4 – coarse sands or gravel.

5. Conclusions

The resultant parameter estimates are very reasonable for this area. If the data from Table 1 are compared with those published in Tęgowski (1994) and Klusek *et al.* (1994) from the Gdańsk area, a similarity will be seen between the Pomeranian Bay acoustic parameters and those obtained for the Gulf of Gdańsk. This leads to the conclusion that the proposed classification method satisfies the criterion of universality for similar sediments and their layering and can be implemented as a real-time method. This representation of bottom reflection in terms of a number of echosignal parameters not only allowed for more accurate identification but also gives further insight into the nature of bottom reflection itself.

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