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Statistical analysis of acoustic echoes from underwater meadows in the eutrophic Puck Bay (southern Baltic Sea)

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Abstract

In order to monitor the recovery of vegetation from pollution and the success of re-seeding efforts, acoustic echoes from the sea floor, covered and uncovered by underwater vegetation, were collected in Puck Bay (southern Baltic sea) using a 208 kHz Biosonics DT 4200 scientific echo sounder. The echo envelopes were examined and several of their parameters were recommended for further analysis. The possibility of using these parameters to distinguish between a bare sea floor and underwater meadows was tested. The parameters may be helpful in the identification of the species composition of the meadows and in accurate biomass assessment.

Keywords: Echo signals; Underwater meadows; Parametric analysis

1. Introduction

In many environmental applications, it is important to assess the spatial distribution and biomass of underwater meadows and to identify their species composition. This requires monitoring techniques that are sufficiently cheap, neither time-consuming nor labour-intensive, and which permit the synoptic coverage of a large area. It has been shown that the hydroacoustic method satisfies these requirements and is useful for detecting and characterising submersed aquatic vegetation in fresh water (Maceina and Shireman, 1980; Maceina et al., 1984; Duarte, 1987; Thomas et al., 1990) and in sea water (Spratt, 1989; Miner, 1993; Bozzano et al., 1998; Carbó and Molero, 1997; Sabol et al., 1997, 2002a; Sabol and Burczinski, 1998).

The paper scrutinises the utility of the hydroacoustic technique for monitoring the buoyant, bottom-rooted, submersed aquatic vegetation covering the acoustically hard, sandy, nearly flat bottom of Puck Bay (southern Baltic Sea). Before the 1970s, this bay was one of the biologically richest areas in southern Baltic coastal waters—multispecific underwater meadows covered most of the bottom, providing a refuge and foraging conditions for various marine organisms, including economically valuable species of fish. During the 1970s, pollution caused the state of the meadows to deteriorate drastically—the species diversity and their spatial extent shrank dramatically. At present, signs of recovery have been observed, which has encouraged efforts to restore the marine plant population. It is important to determine the extent of this recovery by monitoring the submersed vegetation. The hydroacoustic method could be useful in this respect.

The properties of the echo envelope of signals collected with a 208 kHz Biosonics DT 4200 scientific echo sounder in Puck Bay were studied. The analysis included a comparison of the echoes from the bare and plant-covered parts of the sea floor. The parameters for which a difference between echoes was noted are presented, and the significance of the difference is analysed. The effectiveness of the cluster analysis approach, based on selected parameters, in distinguishing the bare and plant-covered seabed is also discussed.

Selected features of the echo envelopes may be helpful in detecting the presence of underwater vegetation, especially where the actual bottom is undetectable. The problem of poor detection is discussed in Sabol et al. (2002b). Indeed, there was a problem with bottom detection for the hydroacoustic data we collected in some particularly dense patches of vegetation.

The analysis may also be important as a preliminary step in the identification of plant species and the accurate assessment of biomass. Identification of the brown filamentous

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algae *Pilayella* sp., which flourishes in the polluted, eutrophic waters of Puck Bay, could be significant in the accurate assessment of biomass. Clouds of these algae, saturated with air bubbles trapped in the underwater meadows, can significantly distort the echoes from rooted underwater vegetation.

Biological observations show that the vertical structure of the vegetation canopy depends on the plant species involved, as this may influence the properties of the echo envelopes. Hence, it is important to define the echo envelope parameters sensitive to this effect. The parameters investigated in the paper could be interesting from this point of view. As a further step, the possibility of using these parameters to identify plant species (including *Pilayella* sp. algae) will be investigated.

2. Materials and methods

2.1. Site conditions

The data were collected in a 500 × 500 m area in the northern part of the outer Puck Bay in May and September 2001. The sediments were homogeneous (sandy bottom) throughout the area. The bathymetry exhibited relatively little variability; the mean depth was approximately 1.7 m.

The area was colonised by submersed, vascular plants. The buoyancy of the bladders is due to the inter-cellular space, which is involved in the exchange of gases between the plant and the surrounding water. The maximum height of the vegetation canopy was around 40 cm.

The spatial distribution of the vegetation was patchy. The species composition of most patches was complex, the dominant species being *Zostera marina*, *Zanichellia* sp. and *Potamogeton* sp. However, almost monospecific patches were also found. The brown filamentous algae *Pilayella* sp., typical of eutrophic waters, was present in many patches (up to 8% of total biomass).

2.2. System description and data collection

The study was conducted from a small survey boat with precise navigational instrumentation. The acoustic measurements were performed using a downward-looking Biosonics dual-beam echo-sounder with a working frequency of 208 kHz. The narrow, 6° width beams were used for emitting and receiving. The transducer pulsed at the rate of 8 pulses s^{-1} and the signal duration was 0.1 ms. The envelope of the received echoes was sampled at 41.7 kHz. Simultaneously with the acoustic measurements, positional data were recorded using a D-Global Positioning System (DGPS) TRIMBLE SE4000 sampled at 1 Hz. The positioning precision of this system is approximately 0.3–1 m. Both acoustic and position data were stored on a laptop PC.

Fifty transects parallel to the local shoreline with a fixed distance between them were sampled using the echosounder and DGPS.

Additional observations involved stationary ground truth sampling and detailed visual inspection of the underwater meadows, enabled by the optically transparent shallow water conditions of Puck Bay.

The stationary ground truth samples were collected at random locations (one in May and seven in September) within the study area. The applied methodology closely resembled that described in Sabol et al. (2002a). The data collected were used mainly to verify the algorithm for detecting the bottom and measuring the height of the vegetation canopy (the algorithm is discussed in detail in another paper currently in preparation). Nevertheless, the information on the spatial distribution of the vegetation and the species composition of the underwater meadows also contributed to the present analysis.

Detailed visual inspection of the spatial distribution of the meadows, together with DGPS localisations of the boundaries between vegetated and bare areas, was carried out over some of the hydroacoustic transects. The visual observations were helpful in evaluating the differences between the relevant parameters for the vegetated and bare sea floor.

2.3. Data processing

The position-referenced hydroacoustic data were processed in order: (1) to develop an algorithm for detecting the bottom and measuring the height of the vegetation canopy; and (2) to analyse the echo envelopes.

A signal-processing algorithm for bottom detection and tracking, and vegetation detection was developed. A separate paper, which discusses this algorithm and its precision in detail is in preparation. Here we will only describe it briefly. Analysis of the echo signal envelope has shown that, unlike the algorithm of Sabol et al. (2002a), the depth of the sharpest rise of the echo envelope cannot be used to localise a vegetation-covered sea floor. The algorithm we have developed is based on the observed difference of echo levels for the bottom and the plants. In the majority of echoes from a vegetated bottom the highest echo level corresponds to backscattering from the water-bottom boundary. The algorithm uses the locations of the maxima in the series of echo envelopes to determine the bottom position. For detecting the presence of vegetation, an acceptable level of accuracy of this algorithm was demonstrated for a flat bottom and a relatively sparse vegetation.

The present paper focuses on the analysis of the envelopes of the collected echoes. The signals reflected from a bare sea floor and underwater meadows were compared. Examples of echo envelopes for plant-covered and bare sea floors are presented in Fig. 1a, b, respectively. These show that the echo duration from a non-vegetated sandy bottom is approximately defined by the pulse width, whereas the echoes from vegetated areas are significantly longer. The figure also highlights the difference in shape of the echo envelopes. The envelopes are smoother for the echoes from the non-vegetated bottom. These distinctions should be reflected in

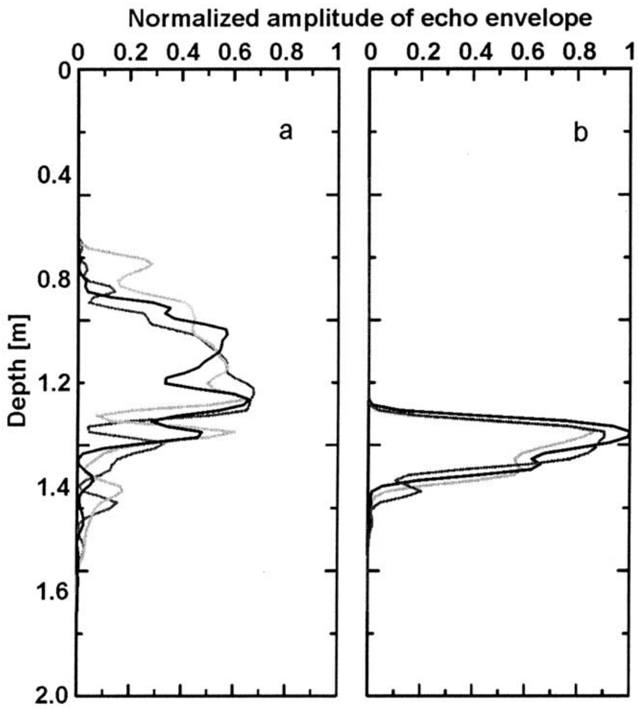

Fig. 1. (a, b) Normalised echo envelopes for the vegetated (a) and uncovered sea floor (b).

the values of the parameters controlled by the echo signal width and "smoothness".

A series of echo envelope parameters was studied. The analysis involved calculating the moments of different orders (up to the fourth order) for the echo envelopes in time- and frequency-domains and combinations of moments. The fractal dimension of an echo envelope, dependent on the variability of the echo envelope, was also computed. Two approaches were tested in parallel. One was based on the calculation of this parameter as the log–log slope of the power density spectrum (Hastings and Sugihara, 1994). It should be noted that a large set of echo envelope samples is required for this approach. However, this condition is not satisfied for short echoes from a sandy bottom, so this technique cannot be used for them. Therefore, an alternative approach, free from this limitation, was employed: this uses the wavelet transform (Simonsen and Hansen, 1998). The calculations were done for several classes of wavelets.

The analysis yielded three parameters whose values with respect to a bare sea floor and underwater meadows display the most conspicuous differences. These parameters are described in the next section.

3. Results and discussion

The echoes from covered and uncovered bottoms were compared with respect to the following parameters.

3.1. Description of the selected parameters

1. The normalised moment of inertia of the echo intensity, with respect to its centre of gravity, is defined as

$$M_i = \frac{\sum_{i=1}^{N} (i - i_c)^2 \cdot p_i^2}{\sum_{i=1}^{N} p_i^2} \quad (1)$$

where i is the number of the echo sample, p_i denotes the acoustic pressure for the ith sample, and N is the total number of echo samples. Here, i_c describes the sample number corresponding to the position of the centre of gravity for the echo signal intensity, which can be expressed as

$$i_c = \mathrm{int}\left[\frac{\sum_{i=1}^{N} i \cdot p_i^2}{\sum_{i=1}^{N} p_i^2}\right] \quad (2)$$

where int stands for the integer inside the brackets.
The normalised moment of inertia indicates how the echo energy is concentrated around the centre of gravity. The smaller the value of M_i, the shorter the echo pulse duration; conversely, a larger value of M_i reflects a longer echo pulse duration, which may indicate the presence of vegetation.

2. The spectral width parameter v^2 is expressed as (Clough and Penzin, 1975)

$$v^2 = \frac{m_0 \quad m_2}{m_1^2} - 1 \quad (3)$$

where m_r (r = 0, 1, 2) are spectral moments of the 0th, 1st and 2nd orders, respectively. The rth order moment is defined as

$$m_r = \int_0^{\infty} \omega^r S(\omega)\, \mathrm{d}\omega \quad (4)$$

where $S(\omega)$ is the power spectral density of the echo signal envelope and ω denotes the frequency. The mean frequency can be given by w $= m_1 / m_0$.
The spectral width parameter is defined by the mean frequency ϖ and by the concentration of the spectral power density around it. The larger the mean frequency, the smaller the parameter. The spectral width parameter is larger in a spectrum where the spectral energy is more broadly distributed among the frequencies; it is smaller in the opposite case.

3. The fractal dimension was calculated using the wavelet transform approach (Simonsen and Hansen, 1998), as discussed in section 2.
The wavelet transform of a signal $y(x)$ in a domain x for a shifted and scaled version of a mother wavelet $\psi(x; a, b)$ can be expressed by

$$c(a,b) = \int_{-\infty}^{\infty} y(x) \frac{1}{\sqrt{a}} \psi\left(\frac{x-b}{a}\right) dx \quad (5)$$

where a and b are scale and translation parameters. The wavelets can be created by choosing $a = 2^j$ and $b = 2^j k$, where j and k are both integers. Wavelets are non-zero over only small intervals of x. They are formed by dilation and translation of the function $\psi(x)$ and the scaling function $\phi(x)$, using the relationships

$$\psi_k^j(x) = 2^{-j/2}\,\psi(2^{-j}x - k) \text{ and } \phi_k^j(x) = 2^{-j/2}\,\phi(2^{-j}x - k).$$

To estimate the fractal dimension, the use of several wavelets was checked. The best results were obtained for Daubechie's orthonormal wavelets of order M. Their first M moments are zero, and functions $\psi(x)$ and $\phi(x)$ are related to those on the finer length scales by

$$\phi(x) = \sqrt{2}\sum_{k=0}^{L-1} h_k\,\phi(2x - k),$$

$$\psi(x) = \sqrt{2}\sum_{k=0}^{L-1} g_k\,\psi(2x - k),$$

where $L = 2M$. The coefficients h_k and g_k are linked by the relationship: $g_k = (-1)^k\, h_{L-k-1}$, with $k = 0, 1, ..., L - 1$.

The wavelet transform of the self-affine function $y(x)$, defined as $y(x) \cong \lambda^{-H}\, y(\lambda x)$, where H is the Hurst exponent $(0 \le H \le 1)$ and λ is a constant, is expressed using the result of Simonsen and Hansen's (1998) derivations

$$\begin{aligned} Wyxa,b \; &= \; W\lambda - H\, y\lambda xa,b \\ &= \lambda^{-(1/2)-H}\, W[y(x)](\lambda a, \lambda b) \end{aligned} \qquad (6)$$

as

$$W[y](\lambda a, \lambda b) \cong \lambda^{(1/2)+H}\, W[y](a, b). \qquad (7)$$

Here $W[y(x)](a, b)$ is a wavelet transform of the self-affine function $y(x)$. On averaging both parts of this expression over the translation parameter b, the following expression can be derived:

$$W[y](\lambda a) \cong \lambda^{(1/2)+H}\, W[y](a)$$

where

$$W[y](a) = \langle |W[y](a, b)| \rangle_b. \qquad (9)$$

Here, the brackets $\langle ... \rangle_b$ describe the averaging over the b translation parameter. The Hurst exponent H and the respective Hausdorff dimension (or fractal dimension) $D = 2 - H$ can be calculated from the slope of a log-log plot of $W[y](a)$ versus a using a linear regression algorithm.

The fractal dimension is defined by the variability of the echo envelope and is smaller for smoother envelopes.

3.2. The results of calculations

The parameters described in section 3.1. were calculated for the echo signals collected over the study area (Figs. 2a, e).

The echogram for the part of the acoustic transect crossing the central part of the study area is shown in Fig. 2a. The solid black line above the echogram indicates the presence of vegetation as confirmed by visual inspection. Two underwater meadows almost uniformly covered by plants were visually examined. Their boundaries were localised using the DGPS.

Fig. 2b presents the variation in plant height along the transect. The algorithm briefly described in section 2.3 was used to determine the height of the vegetation. The presence of visually confirmed vegetation is indicated in the same way as in Fig. 2a. There was good correlation between the underwater meadow boundaries as indicated by the echogram and the field observations.

The normalised moment of inertia M_i, the spectral width parameter v^2, and the fractal dimension D_{Db7} for the signals scattered from underwater meadows and the bare sea floor are shown (Fig. 2c–e). The figures demonstrate the growth of all the parameters in the vegetated areas.

Further interesting result (Fig. 3a–c) show the spatial distributions of the spectral width parameter v^2 (a), the normalised moment of inertia M_i (b) and the fractal dimension D_{Db7} (c) calculated for the study area. The logarithmic scale is used on the map for the normalised moment of inertia. The scale bars are given on the plots. It is important to note the apparent identity of the patchiness structure of the different parameters, which the maps show up (Fig. 3a–c). For example, the patch corresponding to the largest values of the parameters is clearly visible in the central part of the investigated area on all three maps. To understand the reasons for the correlation in the spatial distribution of the parameters, it should be remembered that they are defined by the various properties of the collected echoes: the moment of inertia is influenced by the echo thickness, the fractal dimension depends on the echo envelope variability, while the frequency width parameter can be defined by both the echo thickness and the echo envelope "smoothness". The parameters are not functionally dependent, and the correlation in their spatial distribution is explained by the fact that their values differ for a sandy bottom and underwater meadows. Indeed, the parameters can probably be regarded as indicators of underwater meadows.

Accuracy analysis was carried out in order to assess the significance of the differences between the parameters for a plant-covered and a bare sea floor, and the possibility of using them as indicators of underwater meadows. In an attempt to classify the collected echoes reflected from a bare and a plant-covered sea floor ("bare sea floor" and "plant" pings, respectively), suitable thresholds were considered for each of the parameters. The thresholds divide the parameter variability range into two parts corresponding to covered and uncovered bottom conditions. Then, for each of the parameters, the pings for which the parameter is larger than the threshold are classified as a "plant" ping. In the opposite case, they are defined as "bare sea floor" pings. The results of the classification are illustrated in Figs. 2c–e using the vegetation occurrence indicator—thick solid black (c) or grey and black (d, e) lines. The black and grey lines correspond to the various threshold values stated in the legends.

The accuracy of classification was assessed for the each parameter. This was done by comparing the results of the classification with the result obtained using our detection algorithm (Fig. 2b, see section 2.3). The results of the detection algorithm were selected for the comparison because it

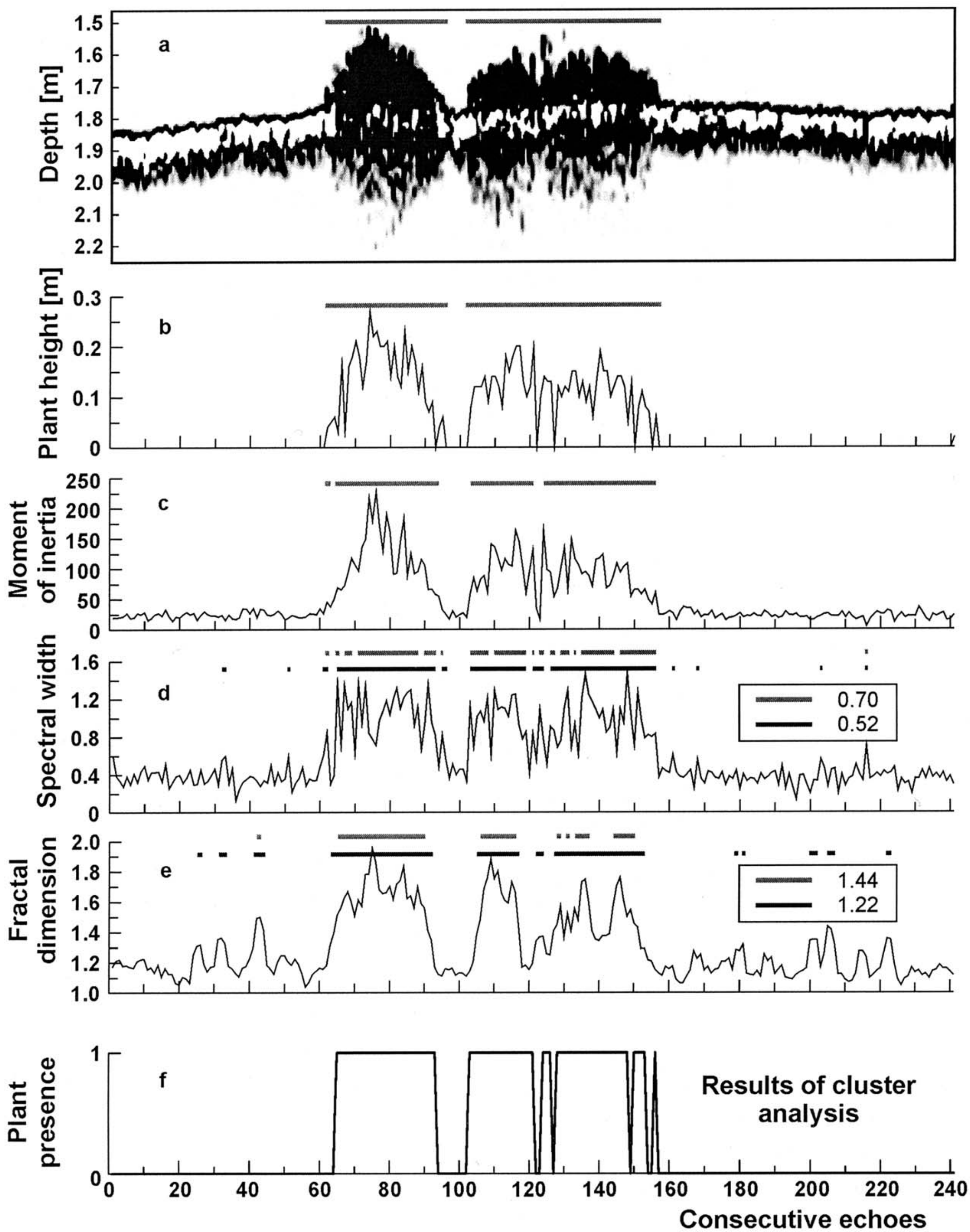

Fig. 2. (a-f) Echogram (a) and variability in echo parameters along a selected acoustic transect—variations in height of the vegetation canopy (b); variability of the normalised moment of inertia M_i (c), spectral width parameter v^2 (d) and fractal dimension D_{Db7} (e). The results of the cluster analysis classification procedure are presented in plot *f*. The thick, unbroken black lines in plots *a* and *b* indicate the presence of plants, verified bya non-acoustic method. The thick unbroken lines in plots c–e, indicating the occurrence of vegetation, were obtained from a comparison of the calculated parameters with the respective selected thresholds, given in the legends.

was sufficiently accurate to detect the presence of the vegetation on a flat bottom. This algorithm was verified using a combination of visual inspection (September 2001 measurements, results of which are presented in this paper) or video

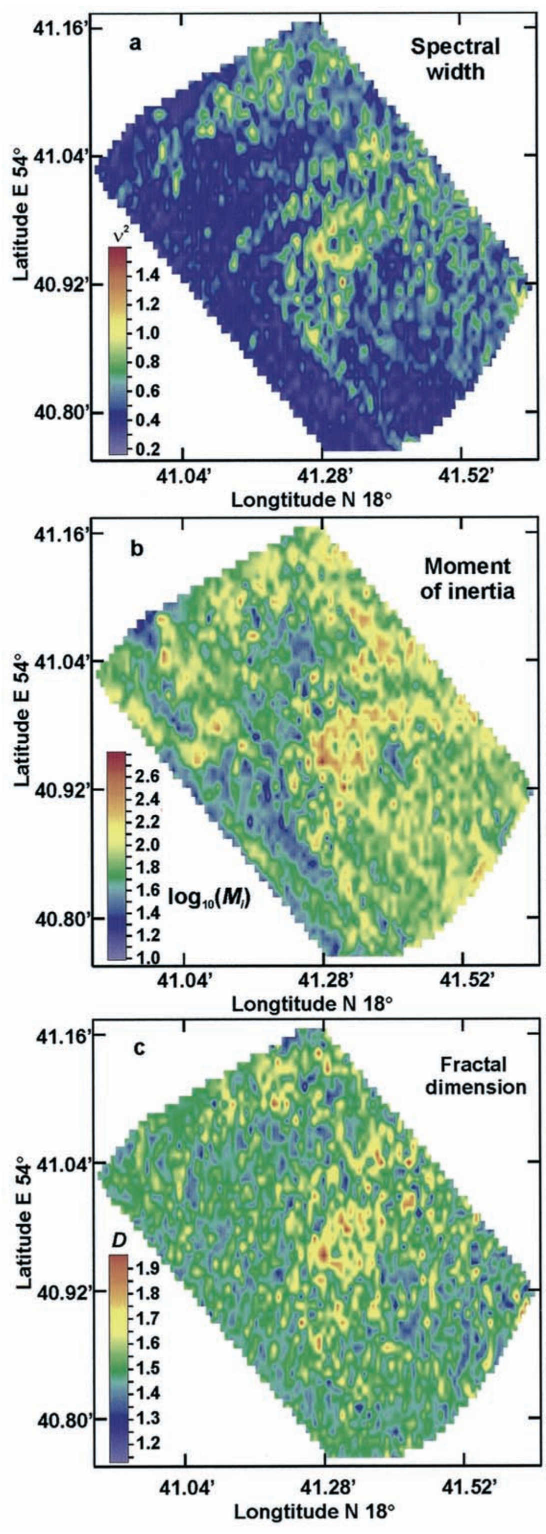

Fig. 3. The spatial distribution of the selected parameters in the study area.

filming data (later measurements made in 2002) and DGPS to localise the boundaries of the underwater meadows. The correlation with respect to the detection of the boundaries positions of underwater meadows was high.

Comparing the vegetation indicators (Fig. 2c–e) with the indicator (Fig. 2a, b), it can be concluded that using the moment of inertia gives the best agreement with the results of the detection algorithm. Agreement is poorest for the fractal dimension parameter. A more accurate comparison demonstrated that:

1. for the moment of inertia M_i (Fig. 2c), the false alarm and miss detection errors are, respectively, equal to 2.5 and 2.4% for the chosen threshold of 38.61.
2. for the spectral width parameter v^2 (Fig. 2d), the false alarm error decreases from 8.3 to 1.9% and the miss detection error increases from 4.8 to 14.3% for thresholds from 0.52 to 0.70.
3. for the fractal dimension D_{Db7} (Fig. 2e), the false alarm error decreases from 14 to 1.3% and the miss detection error grows from 16.7 to 38.1% for thresholds from 1.28 to 1.44.

For the data presented in the echogram (Fig. 2a), the selected parameters can be regarded as indicators of underwater vegetation. However, these data were collected under "ideal" conditions—a flat bottom of constant depth and vegetation patterns of comparable height. Sea floor conditions of greater complexity were also examined, including variability of bottom depth and meadows where the plant height is very variable. Our study demonstrated that the use of just one parameter is not sufficient to detect vegetation under such conditions. Therefore, the possibility of cluster analysis for detecting underwater meadows was also studied. A number of clustering algorithms were tested for the data presented in the echogram (Fig. 2a). They differed in the number of parameters used, the number of groups classified, and the classifying procedure. The K-MEAN algorithm of clustering (Späth, 1982), applied in the three-dimensional space of the selected parameters for three classes—"high plants", "low plants" and "bare sea floor" pings, displayed better accuracy. The classification results are comparable with those based on the one-parameter approach using the moment of inertia. The results of applying the clustering procedure are shown in (Fig. 2f) where the vegetated and non-vegetated bottom conditions are indicated by the unit-and zero-values, respectively.

Using this classifying procedure, a map of the vegetation distribution along the acoustic transects (Fig. 4) was constructed. The vegetation specified by cluster analysis (both groups—"high" and "low" plants) is indicated by dots, which correspond to the geographical co-ordinates of the respective echo signal measurements. The results of the clustering analysis were verified by detailed visual inspection of a given transect (4000 echoes were collected over this transect). The calculated false alarm and miss detection errors were found to be 3.2 and 37.7%, respectively. It was demonstrated that cluster analysis gives better results than just one of the selected parameters in distinguishing shorter vegetation in cases where the height of the vegetation varies.

4. Conclusion

The paper analyses the properties of the envelope of the echoes collected using a 208 kHz Biosonics DT 4200 scien-

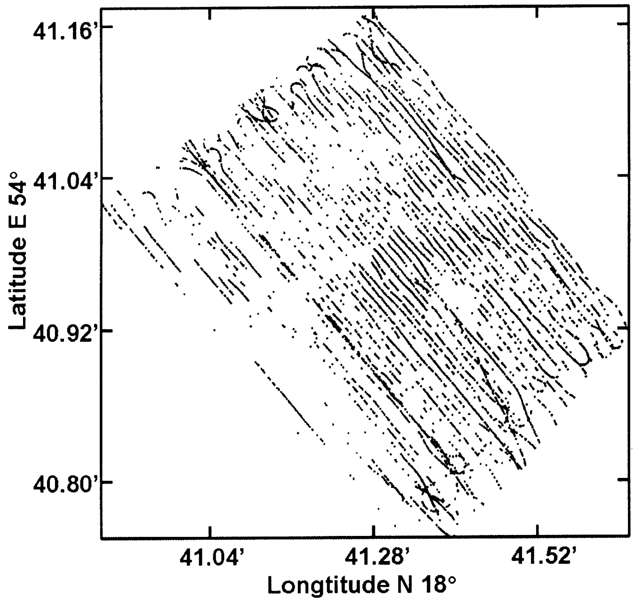

Fig. 4. Map showing the occurrence of vegetation in the study area; the map was constructed on the basis of cluster analysis classification.

tific echo sounder in Puck Bay. Comparison of the echoes from bare and vegetated sea floors shows that for the echo envelope parameters—the moment of inertia, the spectral width parameter and the fractal dimension—the difference is significant. This difference is evaluated. It is the most significant for the moment of inertia, and this parameter can be used to distinguish a bare sea floor from underwater meadows wherever the bottom is flat and the vegetation patches are of comparable height.

The effectiveness of cluster analysis (K-MEAN clustering algorithm, applied in the three-dimensional space of the selected parameters for three classes—"high plants", "low plants" and "bare sea floor" pings) in distinguishing a vegetated from a non-vegetated sea bed is demonstrated. This procedure is more effective for detecting shorter vegetation where there is significant variability in the height of the meadows than if onlyone of the selected parameters is used.

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