ACOUSTICAL TECHNIQUES OF UNDERWATER MEADOW MONITORING IN THE PUCK BAY (SOUTHERN BALTIC SEA)

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The main motivation of this paper was to develop acoustical techniques to monitor underwater meadows. The data, collected with down-looking echo sounder, were used to develop method of bottom detection and tracking and measurement of vegetation canopy height in the Puck Bay. This method and its accuracy are discussed in details. The other possibilities of recognition between covered and uncovered bottom were also reviewed. The effectiveness of using side scan sonar in study vegetation spatial distribution is demonstrated.

INTRODUCTION

Acoustical techniques have been successfully employed in monitoring of underwater meadows, which is important in many environmental applications [1-9]. Their effectiveness has been demonstrated in vegetation detection, measurement of vegetation canopy height and biomass estimation.

It is very important to develop the acoustical methods in the eutrophicated Puck Bay in order to monitor the recovery of vegetation from pollution and the success of re-seeding efforts in this area. For their implementation it should be accounted for that:

1. distinguishing between bare and vegetated sea floor and bottom detection (determination of bottom depth) are important initial steps, enabling accurate biomass estimation, measurements of plant height and acoustical identification of vegetation species;

2. previous study [4 - 6] has demonstrated that proposed detection algorithms are sensitive to the acoustical properties of bottom and plants. This includes the dependence on type of sea floor, its bathymetry and plant species. The state of basin eutrophication also can impact on the recognition procedure. Eutrophication can result in the presence of filamentous brown algae (*Pilayella sp.* algae in the Puck Bay, for example), which can change character of acoustical echoes from underwater meadows. Therefore, it is not possible to employ directly the algorithms developed previously [4-6] to detect the buoyant bottom-rooted submersed aquatic vegetation covering the acoustically hard, sandy, nearly flat bottom of the Puck Bay. The properties of acoustical echoes from bare sea floor and vegetated floor should be studied in detail in this area.

In our previous paper [8] the analysis of the echo envelopes, collected in Puck Bay using a down-looking echo sounder, is presented. The possibility of the distinguishing between a bare sea floor and underwater meadows was discussed.

The present paper also addresses acoustical detection of underwater meadows in the Puck Bay (southern Baltic Sea). Acoustical data, collected using down-looking echo sounder and side scan sonar, were processed. The data collection and analysis are discussed in Section 1. The algorithm of bottom detection and tracking and plant height measurement was developed, processing the data collected by the echo sounder (Section 2.1). The other possibilities of vegetation detection are discussed in Section 2.2. Map of vegetation spatial distribution was produced using the side scan sonar data (Section 2.3).

1. APPROACH

1.1. SITE CONDITIONS

The data were collected in a 500 m x 500 m area in the northern part of the outer Puck Bay in 2001 (May and September) and 2002 (July and September). The area is shown in the map, presented in Fig. 1. The bottom was sandy throughout the entire area. The bathymetry was slightly variable with the mean depth approximately 1.7 m.

The area was colonised by submersed, vascular plants. Plant bladders were buoyant due to the inter-cellular space, filled by gas. This space is involved in the exchange of gases between the plant and the surrounding water. The maximum height of the vegetation canopy varied depending on the season and hydrological conditions from 10 to 40 cm.

The spatial distribution of the vegetation was patchy. Generally, the species composition of most patches was complex. In the area *Zostera marina*, *Zanichellia sp.* and *Potamogeton sp.* were dominant. The brown filamentous algae *Pilayella sp.* flourished in the polluted, eutrophic waters of the Puck Bay. It was observed that the clouds of these algae were trapped by the underwater meadows or freely swam in water column when strong wind conditions prevailed. Biological sampling demonstrated that these algae were present in numerous patches (up to 8% of total biomass).

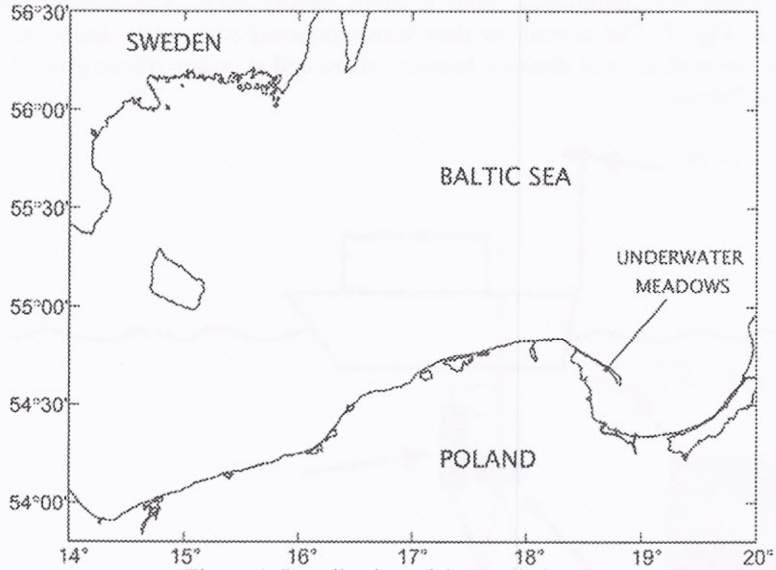

Figure 1. Localisation of the studied area

1.2. DATA COLLECTION AND PROCESSING

During the experiments the acoustical, biological and positional data were collected. Two kinds of acoustical measurements were performed. The data were collected by a down-looking 208 kHz Biosonics DT 4200 dual-beam echo sounder and a side scan sonar DF-1000 EdgeTech. Their working parameters are presented in the Table 1.

parameters	**down-looking echo sounder**	**side scan sonar**
working frequency	208 kHz	100 and 400 kHz
beam width	6^0 (the narrow beams were used for emitting and receiving)	horizontal: 1.2^0 and 0.5° at 100 kHz and 400 kHz respectively vertical: 50^0 at both frequencies
pulse rate	8 pulses s^{-1}	14 pulses s^{-1}
pulse duration	0.1 ms	0. 1 ms (100 kHz) 0.01 ms (400 kHz)
sampling frequency of echo envelope	41.7 kHz	24.0 kHz

Table 1. Parameters of down-looking echo sounder and side scan sonar, used in measurements.

Simultaneously with the acoustical measurements, positional data were recorded using a DGPS TRIMBLE SE4000 with the sampling frequency 1 Hz. The positioning precision of this system is approximately 0.3 – 1 m. Both, acoustical and positional data were stored on a laptop PC.

The study was conducted from a small survey boat. The measurement scheme is presented in Fig. 2. The acoustical data were collected along fifty transects parallel to the local shoreline with a fixed distance between them and at points where ground truth sampling was also performed.

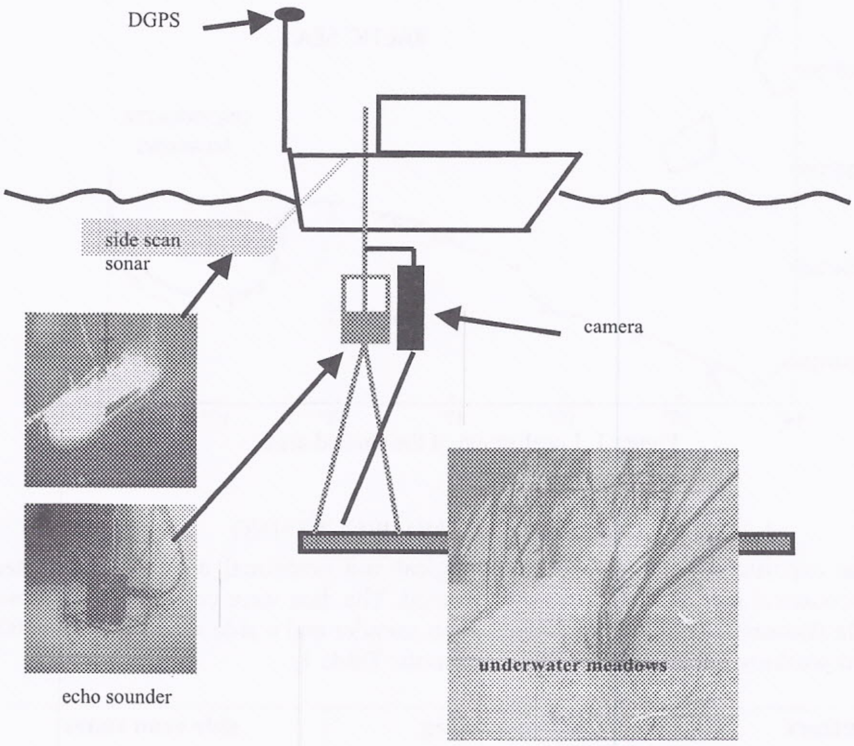

Figure 2. Measurement scheme

Additional observations involved:

- stationary ground truth sampling;
- detailed visual inspection of the underwater meadows, which was possible due to the optically-transparent water conditions of Puck Bay (measurements in 2001);
- observations by underwater video camera, co-aligned with echo sounder transducer (measurements in 2002).

The stationary ground truth samples were collected at a few random locations within the study area. The applied methodology was close to that described in Sabol *et al.* [5]. The water depth and plant height were measured by diver. These data were used in order to verify the algorithm for detecting the bottom and measuring the height of vegetation canopy. The additional information on the spatial distribution of the vegetation, the species composition of the underwater meadows, the tilt angle of the plants and plant biomass, was also collected (biological sampling and underwater filming by diver).

Detailed visual inspection of the spatial distribution of the meadows (May, September 2001) and the observations made by underwater video camera, co-aligned with acoustical transducer (July, September 2002) were carried out along some of the acoustical transects.

They were very helpful in the development of acoustical algorithms of underwater meadows detection. The collected information was used in order to check the correctness of the boundaries between vegetated and bare areas, indicated acoustically.

The position-referenced acoustical data were processed in order to:

(1) develop an algorithm for detecting the bottom and measuring the height of the vegetation canopy (data, collected by down-looking echo sounder);

(2) develop algorithms for recognising the bottom, covered by vegetation, and uncovered floor (data, collected by down-looking echo sounder);

(3) draw the maps of vegetation spatial distribution within studied area in different seasons (data collected by side scan sonar).

2. RESULTS

2.1. ALGORITHM FOR BOTTOM DETECTION AND TRACKING (DOWN-LOOKING ECHO SOUNDER)

A signal-processing algorithm for
- bottom detection and tracking,
- vegetation detection and
- estimating the vegetation canopy height

was developed, analysing the data, collected by down-looking echo sounder. The algorithm is based on the observed difference of echo levels for the bottom and the plants. In the majority of echoes from a floor, covered by vegetation, the highest echo level corresponds to backscattering from the water-floor boundary. The developed algorithm differs from the algorithm of Sabol *et al.* [5], in which the depth of the sharpest rise of the echo envelope is used to localise a vegetation-covered sea floor.

The algorithm includes:

1. preliminary examination of echograms and removing pings with the data quality problems (pings with excessive noise, for example);
2. study of echograms in order to establish the depth range, which is not "contaminated" by subsurface reverberation and "ghost-bottom" effect. The data are analysed only within the selected window;
3. detection of the maximum value of the envelope in each ping. The sample of this maximum (number is denoted as n_{max}) refers to the boundary between water column and sea floor. Bottom depth z_b is estimated as $z_{ech} + n_{max}\,\Delta z$, where z_{ech} describes depth of echo sounder transducer face in respect to water surface and Δz is depth increment, defined by the sampling rate of echo envelope;
4. detection of the first (from top to bottom) sharpest rise of the echo envelope in each ping. The respective sample (number is described as n_{veg}) corresponds to the upper boundary of vegetation canopy. The depth of the boundary z_{veg} is evaluated as $z_{ech} + n_{veg}\,\Delta z$.
5. pings, for which $z_b \approx z_{veg}$, are classified as echoes form bare floor. Pings, for which $z_b < z_{veg}$, are recognised as echoes form vegetated bottom. The height of vegetation canopy is estimated as the difference $z_{veg} - z_b$.

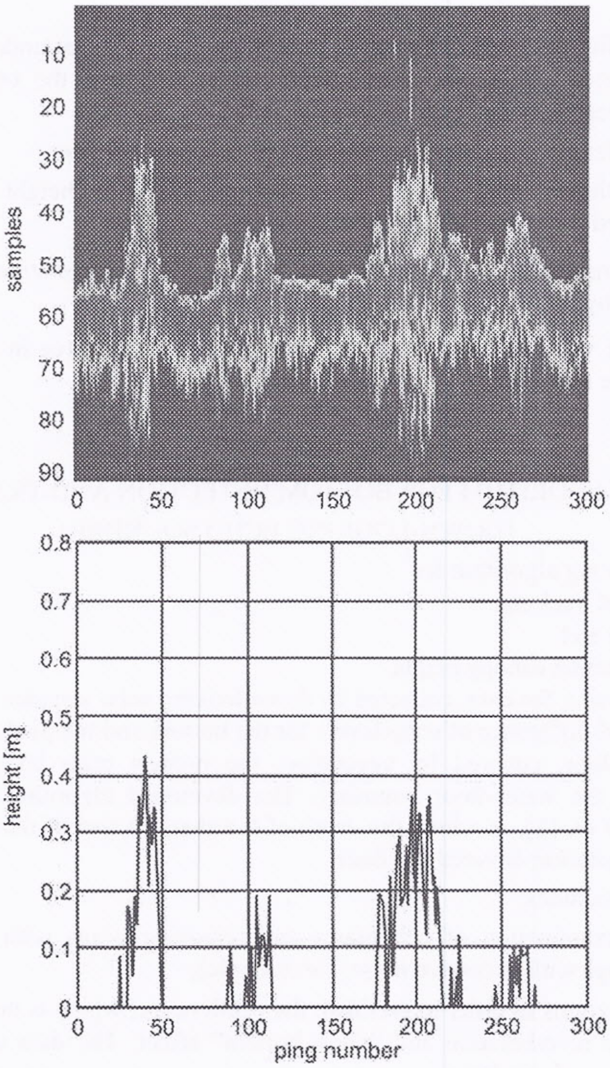

Figure 3. Echogram (*a*) and variability in height of vegetation canopy (*b*)

Our study demonstrated that the developed algorithm cannot be applicable in case of:

- high-dense vegetation;

- the occurrence of the dense filamentous brown algae within the vegetation canopy. These algae are saturated by bubbles and give echo, comparable with the echo from the sandy bottom;

- sharp variability of the distance between the transducer face and the bottom. This could be caused, for example, by boat pitch and roll or bottom roughness.

In two first cases the maximum of the echo envelope can be located not in the water-sediments boundary, but within the vegetation canopy.

Fig. 3 demonstrates the application of the described algorithm to the data, presented in the echogram (Fig. 3a). The echogram data were collected during the transect in the middle part of the studied area. The presence of underwater meadow is visible in the echogram. Fig. 3b presents the variation in plant height along the transect.

The positions of boundaries of underwater meadows, determined using the developed algorithm, were compared with the positions found on the basis of visual inspection and observations by video camera. There was good (near-100%) correlation between the positions as indicated by the acoustical algorithm and the field observations.

Accuracy of canopy height measurements was evaluated by comparing the acoustical algorithm estimates with physically measured values at stationary ground truth points. The result is presented in Fig. 4. Acoustical estimates of plant height exhibited good agreement with ground truth vegetation canopy height measurements. This is only preliminary result because of the insufficient amount of the collected data. The comparison for three ground truth points is only demonstrated. The acoustical data, collected in the other five points were not suitable for the accuracy analysis. The developed acoustical algorithm can not be applied to these data because of swaying of the survey boat, caused by wind.

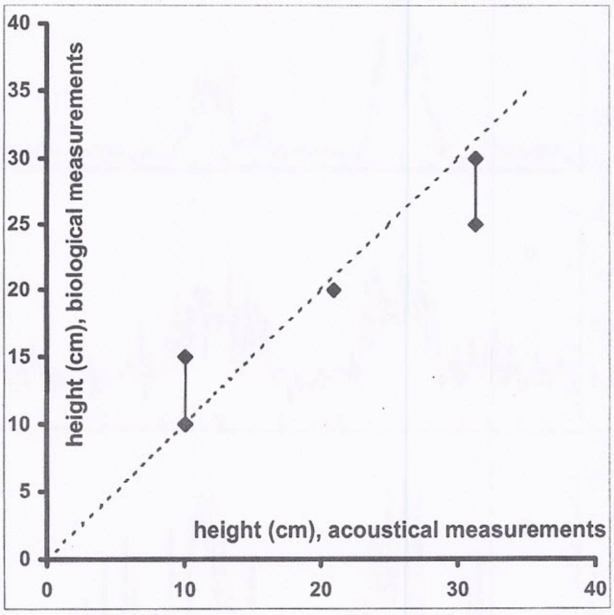

Figure 4. Comparison between vegetation canopy heights, measured acoustically and physically at stationary ground truth points

2.2. ALGORITHMS OF DETECTION OF UNDERWATER MEADOW PRESENCE (DOWN-LOOKING ECHO SOUNDER DATA)

In the previous section the conditions of poor detection for the collected acoustical data were discussed. Sabol *et al.* [6] met also this difficulty during their measurements. This problem encouraged our work on the development of other algorithms of underwater meadows detection.

2.2.1. "PARAMETRICAL" ALGORITHM

The first of these algorithms was discussed in details in [8]. This algorithm is based on the discrepancy of properties of the echo envelope of signals collected with a down-looking echo sounder from the bare and plant-covered sea floor.

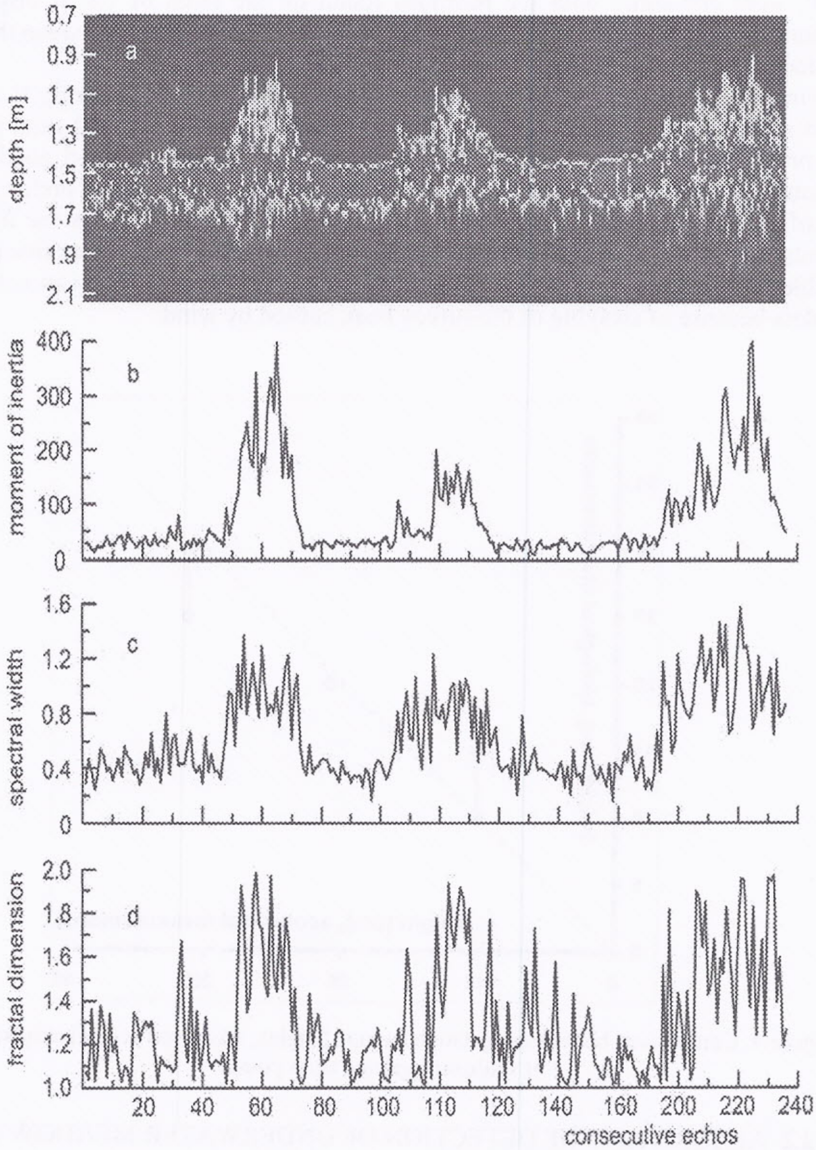

Figure 5. Echogram (*a*) and variability in echo parameters along a selected acoustical transect – variability of the normalised moment of inertia (*b*), spectral width parameter (*c*) and fractal dimension *(d)*

It was demonstrated (see Fig.1 of the cited paper) that the duration of echoes from a non-vegetated sandy bottom is significantly shorter than from vegetated areas. Moreover, the envelopes are smoother for the echoes from the non-vegetated bottom. It was demonstrated that the differences are reflected in the values of the parameters controlled by the echo signal width and "smoothness". The analysis yielded three parameters whose values with respect to a bare sea floor and underwater meadows display the significant differences. These parameters are

- the normalised moment of inertia of the echo intensity, with respect to its centre of gravity;
- the spectral width parameter;
- the fractal dimension of echo envelope.

The difference in these parameters for vegetated and bare sea floor is demonstrated in Fig. 5b – d for the collected data, echogram for which is shown in Fig. 5a. It is shown that the parameters are higher for bottom covered by plants.

The significance of the differences was evaluated statistically [8]. It was demonstrated that

1. for a flat bottom of constant depth and vegetation patterns of comparable height the selected parameters can be regarded as indicators of underwater vegetation;
2. for sea floor conditions of greater complexity the use of just one parameter is not sufficient to detect vegetation. The cluster analysis classification procedure (K-MEAN algorithm), applied in the three-dimensional space of the selected parameters displayed good accuracy.

2.2.2. NEURAL NET RECOGNITION

Neural net recognition directly based on the raw signal itself was tried as a preliminary step. In this approach the relevant signal parameters were simply the time samples. The advantage of this approach is that the scheme is quickly implemented and bears little operator-induced bias. The only bias introduced here is the choice of the training population and the portion of time samples selected to be fed into the neural net.

The neural net was based on Round Base Functions. The motivation was to perform a blind recognition with a minimum amount of *a priori* knowledge. The algorithm was run on a software simulation of a ZISC neural net chip.

Fig. 6 shows the classification results. The test was run on both linear and log-scale echoes. For the data, presented in the echogram (Fig. 6a) the results based on dB levels are much more encouraging. For each ping, 64 time samples were fed to the neural net. The selected range is shown in Fig. 6a between two horizontal white lines. The white and cyan stars in the top graph show the data used for training the net. The white star samples correspond to sandy bottom echoes (pings: 121-130 and 200-209) and cyan star echoes - plant echoes (pings: 600-619). The bottom graph shows the neural net's output. There are quite a few unrecognised echoes. It can be seen that the approach has a problem with recognising shorter vegetation patches. Indeed, those in the vicinity of 300^{th} ping and those between 500^{th} and 600^{th} pings have not been recognised. This result is to be correlated with the fact that these patches were not used in the training process.

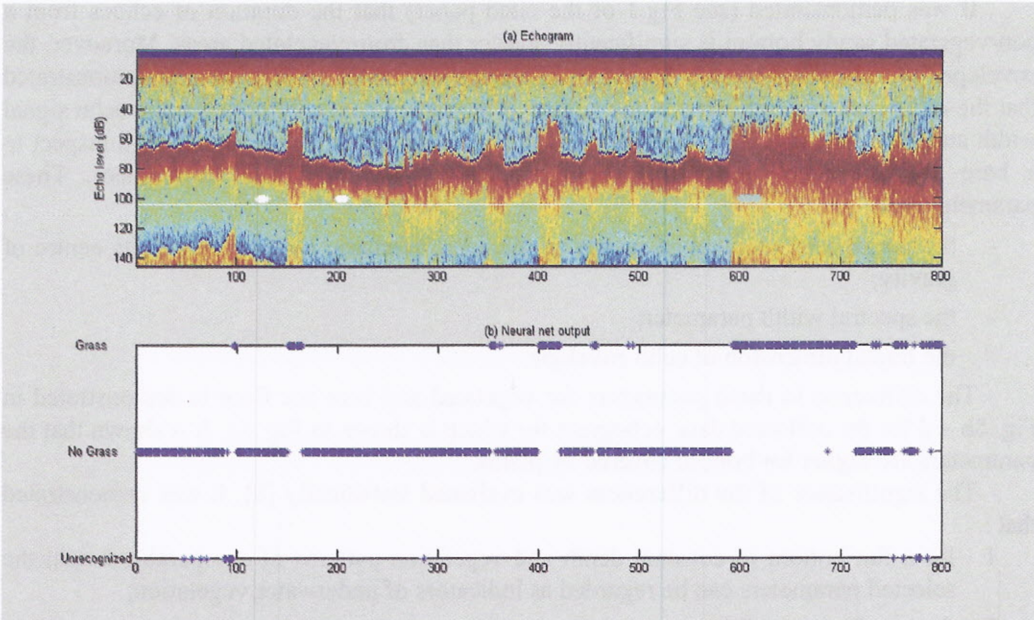

Figure 6. Neural net recognition; echogram (a) and the neural net's output (b)

2.3. MAPS OF PLANT SPATIAL DISTRIBUTION (SIDE SCAN SONAR DATA)

The side scan sonar data were collected using DAT tapes and employing the system of data acquisition CODA UniSense. This system enabled correction of navigation data and the removing the non-linear effects. After the processing the data were used to obtain maps of vegetation spatial distribution employing ArcView system. The maps are presented in Fig. 7.

Longitude and latitude in two co-ordinate systems: geographical and WGS – 84 (projection UTM – 34) are presented in the axes (by red and black colour respectively). Green fuzzy cloud-like features correspond to vegetated bottom. Verification of this map was made using visual inspection along a few acoustical transects, as it was described in Section 1.2. Good correlation was demonstrated in the determination of boundaries between uncovered and covered bottom.

CONCLUSIONS

The signal-processing algorithm of bottom detection and tracking, recognition of vegetation and estimating the vegetation height has been developed by analysing data, collected by a 208 kHz Biosonics DT 4200 down-looking echo sounder in the Puck Bay. The accuracy of this algorithm has been discussed. The algorithm is applicable in the case of flat bottom conditions for relatively sparse vegetation with relatively small content of *Pilayella sp.* algae. Good agreement between acoustical estimates of plant height and ground truth vegetation canopy height measurements has been demonstrated. The good correlation between the positions of boundaries of underwater meadows, determined using the developed algorithm and the field observations (visual inspection and observations by video camera) has been found.

Two developed methods of recognition between bare and vegetated sea floor have been reviewed. The effectiveness of parametrical methods, based on one-parameter- and cluster analysis-classification procedures, have been noted in case of a flat bottom of constant depth. Comparable height of plants is also important for applicability of the first procedure.

The possibility of the neural net recognition has been preliminary studied. The obtained result encourages the further work on the application of this method.

The usefulness of side scan sonar in monitoring of the spatial distribution of underwater meadows has been demonstrated. Accounting for that, this technique is significantly quicker comparing to classical biological methods and does not depend on the water transparency, as air-borne photograph method, we strongly recommend using side scan sonar for the monitoring.

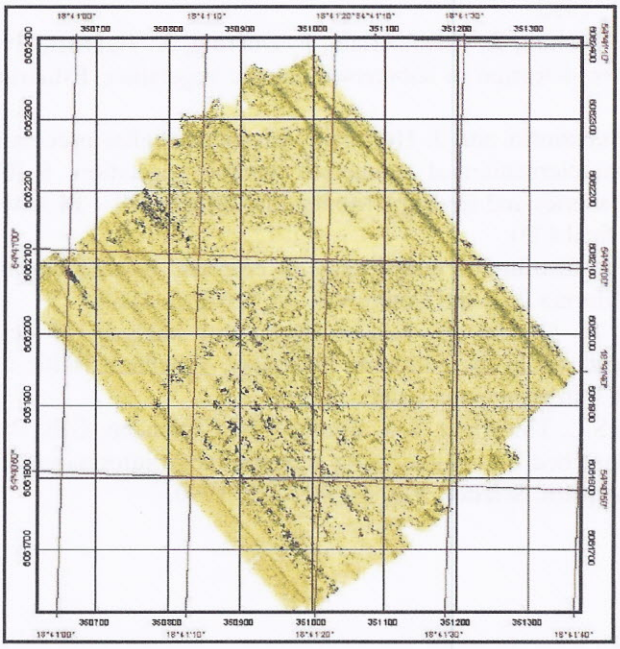

Figure 7. Map of underwater meadows in studied area, the Puck Bay, May 2001.

The conducted study demonstrated the effectiveness of the acoustical detection of underwater meadows. The obtained results could be very helpful in further development of acoustical methods of underwater vegetation assessment (biomass estimation and plant species identification).

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