ABSTRACT

Oceanographic studies often involve identification of the seabed – its shape, sediment type, coverage by phyto- or zoobenthic colonies, and thus the presence of benthic habitats. Various bathymetry features and backscattered acoustic signal intensity information recorded by multibeam echosounders have been successfully used to separate areas of distinct habitats (Diesing and Thorsnes 2018; Lecours et al. 2015; Held and Schneider von Deimling 2019). The use of a gyrocompass and measurement of position during surveys enable the production of accurately located maps with spatial resolution of several centimeters (Montereale Gavazzi et al. 2016). Recordings made with multibeam echosounders have been used with great success in recent years for seafloor mapping. They allow simultaneous recording of bathymetric data at several hundred points and, during the movement of the survey vessel, produce an accurate model of the seabed and a map of the intensity of the backscattered acoustic signal. The results of these works are very useful for navigation authorities and for investors planning structures located on the seabed. Seabed surveys are also extremely important in times of rapid climatic and environmental change, allowing the monitoring of the seabed environment and the benthic habitats present. Mapping and classification of benthic habitats provides the information necessary to establish Marine Protected Areas. Such activities are included in Marine Strategy Framework Directive 2008/56/EC, Water Framework Directive 2000/60/EC and Habitats Directive 92/43/EEC. These include the need to develop methods for mapping and monitoring the seabed.

In addition to bathymetric information, the most commonly recorded information about the seabed with a multibeam echosounder is the relative intensity of the backscattered acoustic signal. It depends on factors related to the measuring device, such as signal frequency, receiver sensitivity, directional characteristics of the transducer; factors related to the environment through which the acoustic wave and the returning signal are transmitted, such as temperature and salinity; factors related to geophysical features of the seabed, such as seafloor surface roughness or sediment density. In addition, the relative intensity of the acoustic signal backscattered from the seabed, recorded by a multibeam echosounder, shows a strong dependence on the angle of incidence on the seabed. Figure 1 shows an example of this relationship recorded during my research.

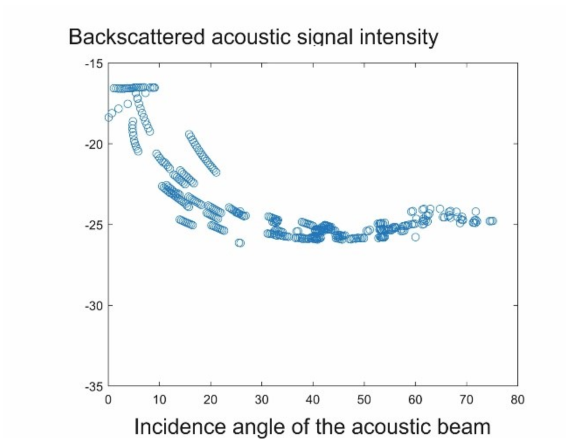

Fig. 1. Example of the angular dependence of the intensity of an acoustic signal backscattered from the seafloor.

The information contained in backscattered signals is used in non-invasive seafloor classification algorithms; however, the angular dependence of the intensity of such a signal makes correct classification very difficult. The problem to be solved is to unify the intensity map of backscattered acoustic signals by bringing the intensity of the signals throughout the study area to values corresponding to a single angle of incidence of the acoustic beam on the bottom. An example of such a correction was implemented in the commercial FMGT QPS software with a tool called Geocoder (Fonseca and Calder 2005). I prepared maps of the relative intensity of backscattered signals over the study area using the Geocoder tool, but I observed large errors in such maps for incidence angles close to 0°. Therefore, I decided to develop my own angle varying gain method (publication 3), which was a challenging task.

Acoustic seafloor classification and mapping using repeatable, automated methods still needs improvement, despite the progress made in recent years. Seabed parameters calculated for bathymetry and intensity of backscattered acoustic signals are directly related to the spatial extent of habitats and often used in seabed classification. Some recent publications highlight the need for new parameters describing the seafloor for benthic habitat mapping (Diesing et al. 2016), so I used spectral parameters calculated from a digital terrain model that are completely new to supervised benthic habitat classification.

The results of backscattered acoustic signal intensity measurements presented by researchers, made using different frequencies of the emitted signal or during separate measurement cruises, usually differ significantly in the ranges of values. This makes it difficult to conduct an automatic or semi-automatic classification of benthic habitats. The observed differences are influenced by a number of factors such as the frequency of the emitted acoustic signal, changing absorption of acoustic waves in the water during different measurements, or the direction of the vessel during the measurements as well as changing physical parameters describing the bottom surface and the sediment present on it.

Although relative intensities of bottom backscattered signals are often used in research work, they do not inform about the actual scattering properties, because their value depends not only on the type of sediment on the bottom, but also on the measuring device and factors related to the parameters of the pulse sent. It is the real values of bottom backscattering strength (BBS) that are an immanent feature of benthic habitats. To record them, it is necessary to use an acoustically calibrated echosounder, correct the result for sound absorption in the water and for losses associated with geometric sound propagation, and to take into account the size of the surface from which the recorded signal was scattered. Acoustic calibration of a multibeam echosounder is not a simple task. Recently, acoustically calibrated multibeam echosounders from Kongsberg and NORBIT have been available on the market. There is still very little information in the literature on the real values of backscattering strength of different benthic habitats for signal frequencies above 100 kHz. Theoretical models of the scattering of acoustic signals on the seabed work for the frequency range from 10 kHz to 100 kHz (APL-UW model 1994). Many singlebeam echosounders use signals with frequencies within this range, while multibeam echosounders and sidescan sonars use much higher frequencies. Researchers still lack detailed information on the backscattering of sound from the seafloor for sonar signal frequencies greater than 100 kHz. Angular characteristics of the actual backscattering strength are a physical feature of benthic habitats and are an important acoustic property thereof. Knowledge of these characteristics of benthic habitats will enable the creation of a catalog of backscattered acoustic signal intensities dependent on signal frequency, angle of incidence, and environmental parameters. This will enable a better understanding of environmental processes occurring on or affecting the seafloor than has been possible to date.

Measuring the absolute values of the angular dependence of backscattering strength is also necessary to assess spatial and temporal variability in benthic habitat characteristics. The relative strength of backscattered signals has been the most effective parameter for benthic habitat classification in many works (publication 1; Gaida et al. 2020; Buscombe et al. 2014; Preston 2009). This emphasizes the importance of this parameter and draws attention to the need to measure it as accurately as possible so that it can be used for research in the most efficient way (Lurton and Lamarche 2015).

Thesis Objectives

The main objective of the dissertation is to build a reliable system for acoustic characterization of seabed habitats, which consists of:

- building a digital model of the seabed of the studied regions together with its parameterization,
- building a map of the intensity of the backscattered acoustic signal brought to a single angle of incidence,
- determining the angular characteristics of the absolute strength of the acoustic signal backscattered from the seabed for signals of selected frequency.
- non-invasive classification of benthic habitats.

Furthermore, the objective of this dissertation is to find parameters describing the seabed surface that increase the prediction power in supervised classification and are not dependent on the frequency of the signal used when recording the seabed with a multibeam echosounder and are also not dependent on other changes in relative acoustic signal intensity values during different measurement campaigns. An additional objective is to develop an in-house empirical algorithm for correcting the angular dependence of the backscattered signal intensity, which enables further use of this parameter in the classification process.

Study area

To test the new research methods, an area of the seabed was selected, which comprises different types of benthic habitats within a small area. Bathymetric data and backscattered signal intensities were recorded with a multibeam echosounder in a survey area of ~1.4 km^2 located about 1.5 km north of the port of Rowy in the southern Baltic Sea (publication 1; publication 2; publication 3). A digital bathymetry model and a map of relative intensities of acoustic signal backscattered from the bottom were prepared from the recorded data. In the study area, there are areas covered with very fine sand (VFS), sand or sand with gravel locally forming ripple marks (S), sandy gravel or gravelly sand (SG-GS), boulders and pebbles covered with mussels *Mytilus trossulus* (B), boulders and pebbles covered with mussels *Mytilus trossulus*, overgrown with red algae (R), and an artificial structure, i.e. a shipwreck (A). Sediment samples were collected with a Van Veen grab sampler and video recordings were made with a camera on a remotely operated vehicle (ROV). A total of 57 seabed locations were surveyed and inventoried. The collected sediment samples were analyzed in a laboratory to determine their granulometric composition, while locations of large boulders where sediment samples could not be obtained were visually assessed from recorded video. Inventory points were then assigned to the six groups listed previously (Folk and Ward 1957; Wentworth 1922).

Description of the work carried out as part of the dissertation

Classification of benthic habitats

In recent years, hydroacoustic studies have intensively searched for the best possible methods of geomorphological analysis of the seafloor (Goff and Jordan 1988; Wilson et al. 2007; Micallef et al. 2012; Diesing and Thorsnes 2018; Gafeira et al. 2018; Lucieer et al. 2018). Different methods are used to classify benthic habitats (Diesing et al. 2020), which can generally be divided into supervised and unsupervised classification, where the number and characteristics of the resulting classes are not distinguished at the beginning of the process. Often, bottom sediment samples are used to determine the classes and where they occur in situ. During clustering based on parameter map analysis, classes may be assigned to individual pixels or pixels grouped into objects with similar features. Finally, the way of assigning data to different groups can be done by different methods such as support vector machine, random forest, k-means clustering algorithm, k-nearest neighbors, classification and regression trees, neural networks (Diesing et al. 2020; publication 1; publication 2). The points inventoried on the seafloor can be divided into two groups – a training group that participates in "teaching" the algorithm for correct class assignment and a validation group for checking the correctness of the prediction. The classification method based on supervised object-based analysis implemented in eCognition software using multi-scale segmentation, the Boruta feature selection algorithm and comparison of the results of several classification algorithms produces very good results described, among others, by an overall accuracy of more than 80% (publication 1; Janowski et al. 2020) was therefore selected for habitat classification in my study.

In the case of supervised object-based analysis (publication 1; publication 2), the input factors for classification are bottom sediment samples, bathymetric maps, maps of relative intensity of the acoustic signal backscattered from the seafloor, and maps of parameters calculated from these. Statistical parameters calculated in many works for bathymetry include slope, aspect, curvature and standard deviation. Examples of parameters calculated for relative intensity of backscattered signal maps are standard deviation and textural parameters (gray level co-occurrence matrices – GLCM) (Haralick et al. 1973; Montereale Gavazzi et al. 2017; Prampolini et al. 2018; Samsudin and Hasan 2017), including homogeneity and contrast. In the study of benthic habitat classification methods, analyses at multiple spatial scales deserve special attention (Lecours et al. 2015; Misiuk et al. 2018). There are many possible parameters to prepare maps, so it is important to determine which of them significantly describe the study area. This is accomplished through the Boruta feature selection algorithm (Kursa and Rudnicki 2010), determining the importance score, or by principal component analysis (Jolliffe 2002), which determines the degree of cross-correlation of individual variables. For habitat clustering, parameter maps that significantly describe the variability of the study area and are not highly correlated with each other should be selected (publication 2).

One of the recent trends in benthic habitat mapping is the use of multifrequency data recorded by multibeam echosounders. The frequency dependence of backscattered acoustic signal intensity has been observed in laboratory and field studies, testing the value of this parameter for different sediment types (publication 1; Jackson et al. 1986; Urick 1983; Feldens et al. 2018; Gaida et al. 2018). Acoustic recordings of seafloor sediments conducted at several frequencies often provide more information on physical and biological properties of seafloor habitats compared to studies using a single frequency. It has been observed that fine sediments such as sands and silts scatter acoustic signals at a given frequency differently than coarser sediments such as gravel, shells, or boulders (Jackson et al. 1986; Gaida et al. 2018).

Lyons et al. (2002) described one of the first applications of the Two-Dimensional Fourier Transform (2D FFT) to high-resolution seafloor characterization. The use of 2D FFT made it possible to obtain a spatial distribution of the power spectral density of the digital terrain model. The same technique has been used in several other studies (e.g., Briggs et al. 2005). The method has been improved and applied to analyze high-resolution bathymetry obtained from modern hydroacoustic measurements, including multibeam echosounders (Cazenave et al. 2008; Lefebvre et al. 2009). Schönke et al. (2017) applied the Fourier transform to describe seafloor micro irregularities using underwater laser scanning in the southeastern North Sea.

For the classification of benthic habitats, I proposed to use parameters describing the study area, calculated from the digital seabed model. I introduced a new group of spectral parameters calculated from the digital seabed model into the object analysis (publication 2). These are: spectral moment m0, spectral moment m2, mean frequency, spectral width, spectral skewness, Q-factor, spectral skewness defined for central moments, and fractal dimension. I divided the digital bottom model into small squares, each successive square overlapping 90% of the position of the previous one and in each square I calculated the power spectral density using the 2D FFT algorithm (Fig. 2).

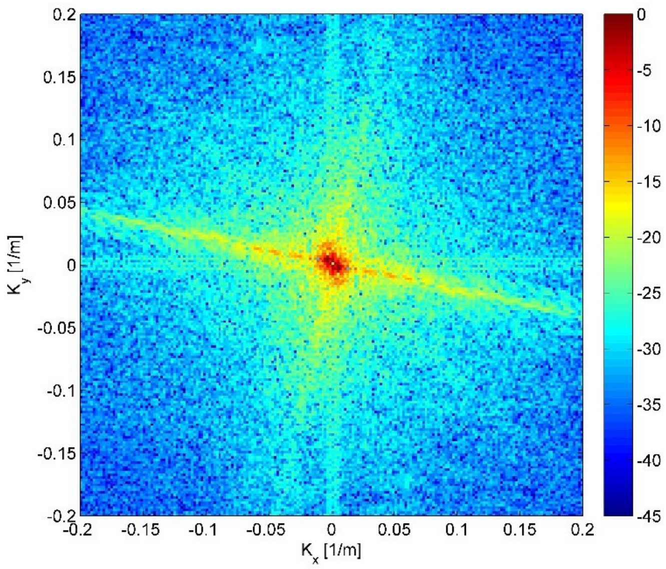

Fig. 2. Example of power spectral density computed in a window covering a section of a digital elevation model.

In each of the windows (Fig. 2), I made cross-sections of the power spectral density every 5 degrees and calculated the spectral parameters from the thus obtained two-dimensional cross-sections. The averaged results of a parameter from each window were combined into a map of the spatial distribution of that parameter in the studied area. In Fig. 3, I have presented an example of the parameter – spectral moment 2, which was calculated in a 20x20 m window.

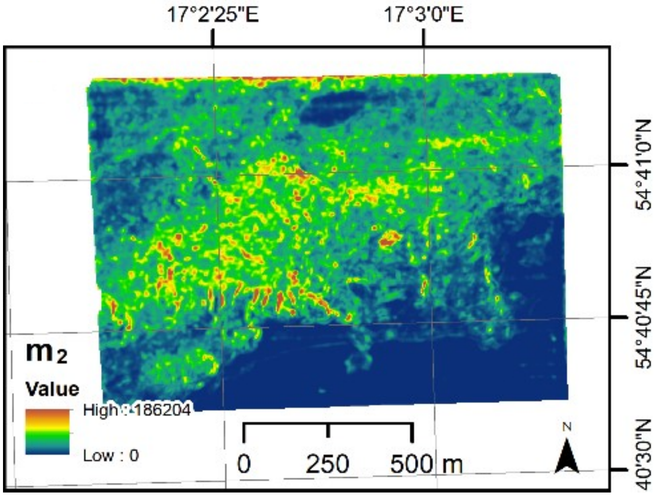

Fig. 3. Distribution map of the spectral moment (m2) values, calculated in a 20x20 m moving window.

In publication 2, a set of sample parameter maps that may be involved in the seafloor classification process was prepared, including statistical parameters, spectral parameters, and gray level co-occurrence matrices. It was then verified which of the 62 parameter maps were most relevant for supervised classification using the Boruta feature selection algorithm (Kursa and Rudnicki 2010). This feature selection algorithm uses random forest (RF) machine learning (Breiman 2001). OBIA object-based classification was implemented using eCognition software (publication 1; publication 2; Blaschke 2010; Janowski et al. 2020). In the multi-resolution segmentation algorithm (MS), pixels with similar features were combined into groups with specific shapes and sizes (Benz et al. 2004). The best classification result was achieved with the method – Support Vector Machine (SVM). An overall prediction accuracy of 86% was obtained when comparing the classification result with a set of validation sediment samples.

The absolute value of the bottom backscattering strength

The IHO Hydrographic Standards (2008) describe in detail the quality of multibeam echosounder bathymetric measurements, but the standards associated with multibeam backscatter echosounder measurements are extremely rare in the literature. The compendium "Backscatter measurements by seafloor-mapping sonars: Guidelines and Recommendations", developed by the BSWG GeoHab group, is the first document of its kind to focus on the quality of backscattered acoustic signal intensity data recorded by a multibeam echosounder (Lurton and Lamarche 2015). The intensity of backscattered acoustic signals should be recorded with acoustically calibrated devices, giving access to the real strength of backscattering (Lurton and Lamarche 2015; Eleftherakis et al. 2018).

Providing real values of seafloor backscattering strength requires the use of a sonar whose characteristics and sensitivity during signal transmission and reception are well determined at a given frequency and angle of incidence on the seafloor. Furthermore, it requires the use of accurate transmission loss compensations and reverberation surfaces (Lurton and Lamarche 2015; Eleftherakis et al. 2018). In recent years, results of only a few studies of benthic habitats using an acoustically calibrated multibeam echosounder have been published (Wendelboe 1018; Eleftherakis et al. 2014; Weber et al. 2018; Roche et al. 2018). These papers present selected characterizations of the real backscattering strength for several habitat types using signals of different frequencies under known environmental parameters. When such measurements become frequent, it will be possible to create a comprehensive catalog showing the angular characteristics of the real backscattering strength for different benthic habitats.

For the measurements presented in publication 3, I used an iWBMSh multibeam echosounder (model STX) acoustically calibrated by its manufacturer, NORBIT. Additionally, the recorded backscattering intensity values were corrected by me for the size of the reverberation area and assigned to the angles of incidence of the acoustic beam on the bottom. In the publication, I presented curves showing the angular dependence of the real backscattering strength for benthic habitats present in the study area for an acoustic signal at 150 kHz. This is an extremely important result in the context of understanding the acoustic characteristics of benthic habitats.

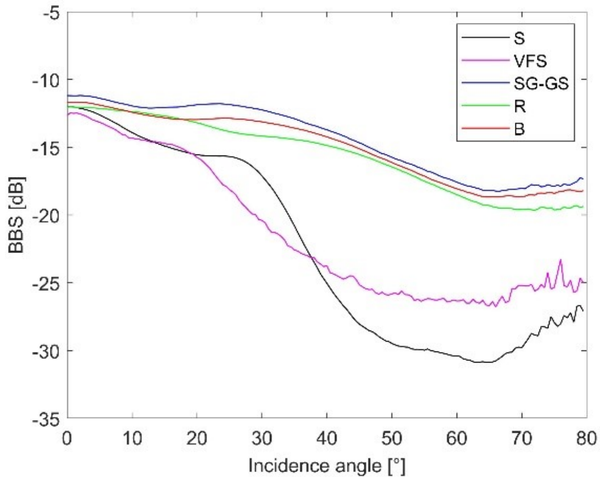

Fig. 4. Results of the real value of the backscattering strength as a function of incidence angle for areas covered with very fine sand (VFS), sand or sand with gravel locally forming ripple marks (S), sandy gravel or gravelly sand (SG-GS), boulders and pebbles covered with mussels *Mytilus trossulus* (B), boulders and pebbles covered with mussels *Mytilus trossulus*, overgrown with red algae (R) for acoustic signals of 150 kHz.

The real values of backscattering strength obtained in the study were as follows: –12 to –31 dB for areas covered with sand or sand with gravel locally forming ripple marks (S); –12.5 to –27 dB for areas covered with very fine sand (VFS); –10.5 to –18 dB for sandy gravel or gravelly sand (SG–GS); –12 to –20 dB for boulders and pebbles covered with *Mytilus trossulus* and overgrown with red algae (R); and –11.5 to –18 dB for boulders and pebbles covered with *Mytilus trossulus* (B).

For macroscale flat seabed types (areas covered with very fine sand, areas covered with sand or sand with gravel locally forming ripple marks), I observed a large reduction in the real backscattering strength with increasing deviation of the wave direction from vertical, and for more irregularly shaped seabed types (sandy gravel or gravelly sand, boulders and pebbles covered with the bivalve *Mytilus trossulus*, boulders and pebbles covered with the bivalve *Mytilus trossulus* and overgrown with red algae), the decrease in the value of the real backscattering strength for more tilted beams was smaller. The real backscattering strength values obtained for sandy gravel or gravelly sand, boulders and pebbles covered with clams *Mytilus trossulus* and overgrown with red algae, and boulders and pebbles covered with *Mytilus trossulus* were higher than for areas covered with sand or sand with gravel locally forming ripple marks and areas covered with very fine sand. The absolute backscattering strength curves for areas covered with sand or sand with gravel locally forming ripple marks and areas covered with very fine sand in the studies I have presented had characteristic shapes typical of the fine-grained sediment curve in the APL-UW model (1994).

Angle varying gain correction of the relative intensity of the signal backscattered from the seabed

The relative intensity of the backscattered acoustic signal shows a strong dependence on the angle of incidence. Fig. 5 shows an example map of the relative intensity values of backscattered signals as a function of incidence angle recorded by me in the measurement area.

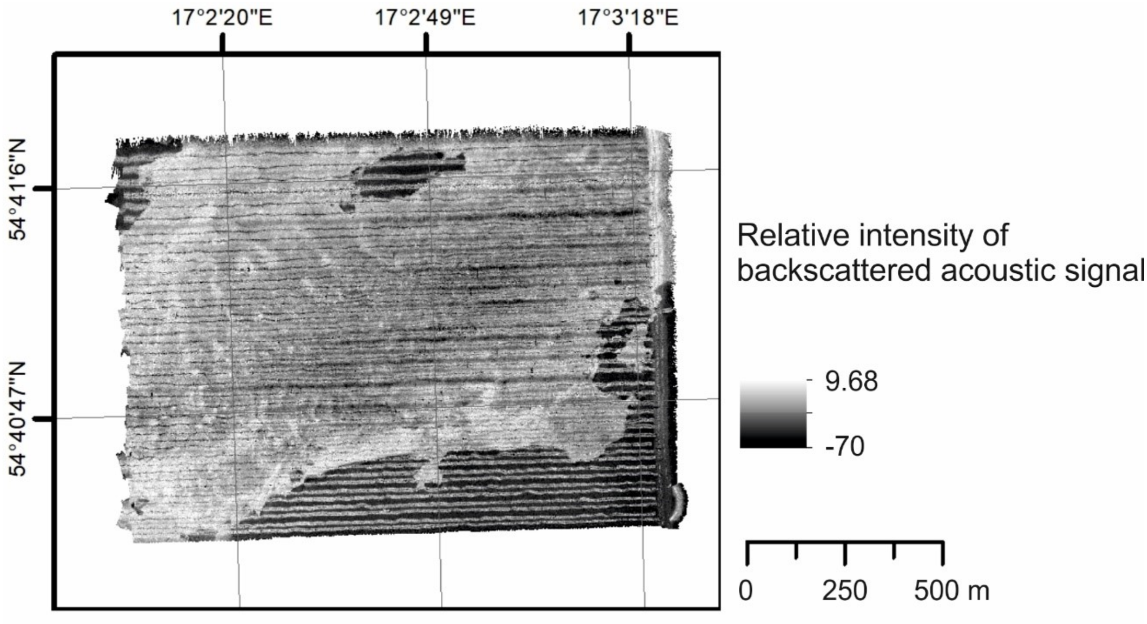

Fig. 5. Map of relative intensity values of backscattered acoustic signals recorded in the Rowy area in the southern Baltic Sea.

I developed an empirical correction method based on angle varying gain (publication 3). It uses averaged values of the measured backscattered acoustic signal intensity rather than model assumptions as is done in the standard Geocoder software. High quality backscattering maps reduced to a single angle of incidence are necessary to perform accurate benthic habitat classification. I reduced all backscattered acoustic signal intensity measurements in the study area to values corresponding to backscattering for an incidence angle of 40° in order to produce a homogeneous map that is easy to interpret and further use in programs that perform classification. The algorithm I propose makes it possible to bring the backscattering strength to any angle of incidence of the acoustic beam on the seabed.

The novel correction procedure involves dividing the data recorded by the multibeam echosounder into groups, each containing a sequence of 50 impulses and each impulse containing several hundred recorded received signals (the echosounder used operated on 512 receiver beams). For simplicity, I assumed that the backscattering properties of the acoustic signal from the seabed were constant in each sequence of recorded pulses. I assigned each recorded signal to an appropriate incidence angle interval. From all the data recorded in a given sequence, I calculated average values of the backscattered acoustic signal intensity for different incidence angles. I then checked what value corresponded to an incidence angle of 40 degrees and calculated the correction factor for each incidence angle. I multiplied each recorded backscattered acoustic signal intensity value with the correction factor appropriate for that incidence angle. The correction factors were calculated separately for each sequence of 50 impulses.

In Fig. 6, I have presented a map of the relative intensity values of backscattered acoustic signals with values converted to an incidence angle of 40°. The result of the correction procedure is shown as a map of the calculated values of the relative intensity of the backscattered acoustic signal after the correction called BBS-Coder.

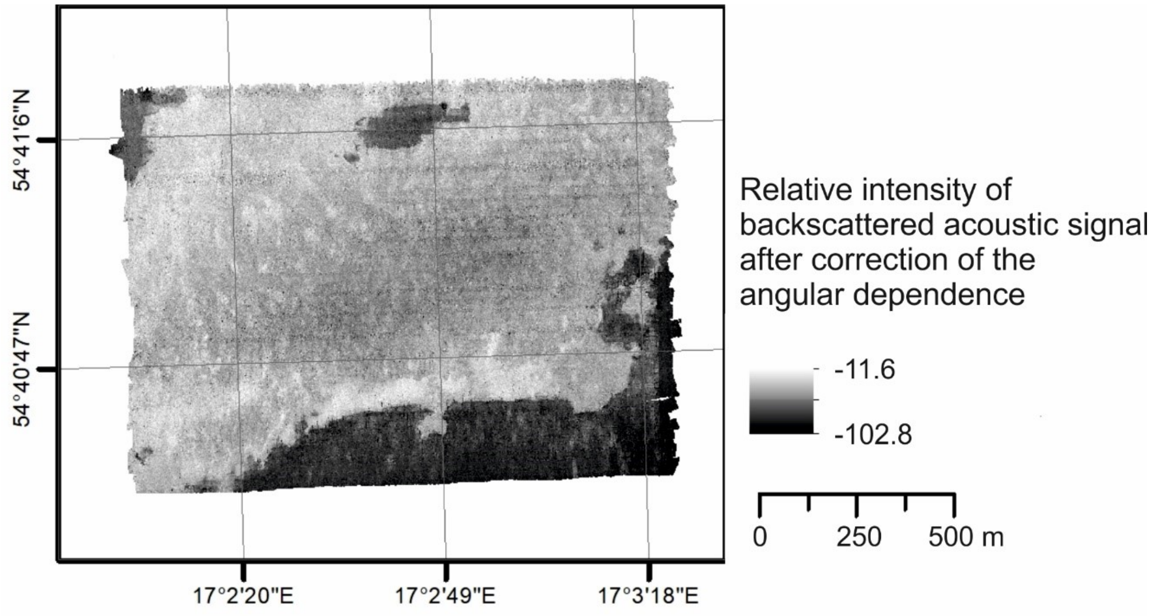

Fig. 6. Result of the BBS-Coder algorithm – a map of relative intensities of backscattered acoustic signals converted to 40° incidence angle, recorded in the Rowy area in the southern Baltic Sea.

The Geocoder tool (Fonseca and Calder 2005) allowed the preparation of maps of the relative intensity of the backscattered acoustic signal of the study area without angular dependence. However, for incidence angles close to 0°, a high standard deviation of the parameter value presented in the map was obtained. The Geocoder assigns validity information to backscattering samples. Data for incidence angles near 0° and near 90° have low validity, while samples in the middle range have higher validity values and greater influence on the final backscattering mosaic map (Fonseca and Calder 2005). In the case of the angle varying gain correction I presented (publication 3), when scattering data recorded with different incidence angles were present in a single raster map window, all values were averaged according to the spatial assignment to the raster grid. The method I have presented, based on angle varying gain, is a simple and effective tool for preparing a backscatter mosaic map useful for seabed habitat classification.

Summary and conclusions

While preparing the dissertation, I created a digital model of the seabed of the study area north of Rowy in the southern Baltic Sea and prepared maps of spectral parameters of the digital model of the seabed surface. To investigate the acoustic characteristics of the benthic habitats in the study area, I measured and calculated the real backscattering strength of acoustic signals. In the dissertation, I used a very effective classification method using object-based analysis, which I improved by using spectral parameters of the digital terrain model. In addition, I developed a method to unify the intensity map of backscattered acoustic signals, referred to in publication 3 as BBS-Coder, by bringing the signal intensities throughout the study area to values corresponding to one angle of incidence of the acoustic beam on the seabed. Using it, I prepared a backscattered acoustic signal intensity map reduced to an incidence angle of 40°.

Summary and conclusions on acoustic classification of benthic habitats

The spectral parameters describing the seafloor calculated for the digital elevation model (publication 2) are not dependent on variable environmental parameters, such as the intensity of the signal backscattered from the seafloor, and therefore fulfill well the objective set in the dissertation. They are important in developing repeatable and homogeneous methods for seafloor habitat classification. This completely novel approach makes it possible to semi-automatically and repeatably classify benthic habitats of the southern Baltic Sea (publication 2) and has also been applied in the prediction of terrestrial postglacial forms, which confirms the effectiveness and universality of the method (Janowski et al. 2021 – my co-authored paper not included in the dissertation, published in IEEE Transactions on Geoscience and Remote Sensing, IF = 5.6). The obtained results confirm the high efficiency of spectral parameters in identifying benthic habitats, which is evidenced by the high agreement (86%) of classification results with bottom sediment samples in the validation process (publication 2).

In this publication 2, I have presented eight spectral parameters describing the seafloor surface. The importance of the spectral parameters was expressed by the so-called importance score as a result of the Boruta feature selection algorithm. Seven of the eight proposed spectral parameters significantly improved the predictive power of the supervised classifiers (publication 2). The most significant parameter in this study was the intensity map of the backscattered acoustic signal from the seabed for the emitted signals at 400 kHz and 150 kHz. The next significant parameter was the fractal dimension calculated from the slope of the spectrum. Interestingly, the results of the Boruta algorithm analysis indicate that some spectral parameters are more important for correct classification than the bathymetry from which they were calculated. It is noteworthy that all other extracted features, including geomorphological, statistical and textural parameters of bathymetry and backscattered acoustic signal intensity, were not identified as significant. This result highlights that the use of spectral parameters can significantly improve supervised classification and mapping of benthic habitats. The method I presented proved its effectiveness in an area with complex geomorphology. The appropriate use of new parameters increased the classification accuracy over the work presented in publication 1. In addition, it was confirmed that there are moderate differences in the backscattering of the studied habitats for 150 kHz and 400 kHz, and both parameters have a high validity index. This confirms the utility of the multi-frequency approach in mapping benthic habitats.

A strong similarity can be observed between the spectral parameter maps and some features of the relative intensity map of the backscattered acoustic signal. It is extremely important for the predictive power of supervised classifiers. Spectral parameters can be very useful for mapping benthic habitats when only bathymetry is available. However, the inclusion of spectral parameters requires high resolution and quality bathymetric data. Any artifacts associated with errors during multibeam echosounder measurements can distort the bathymetric image and affect the calculated spectral parameter values. However, modern motion compensation systems during multibeam echosounder measurements are good at correcting these errors.

Another interesting issue may be the use of such spectral parameters for classification of digital terrain models of different origins. An example of such an application is the morphological classification of glacial forms using a digital terrain model from i.a. lidar measurements (Janowski et al. 2021 – my co-authored paper not included in dissertation, published in IEEE Transactions on Geoscience and Remote Sensing, IF = 5.6).

Further research should focus on determining the optimal size of the sliding window in which spectral parameters are calculated to have as much influence as possible on the correct prediction of habitats.

Summary and conclusions about measurements of the real backscattering strength

Acoustic calibration of the multibeam echosounder allows measurement of real values of the backscattering strength, which are an important geoacoustic feature of benthic habitats and are helpful in their differentiation. Unfortunately, the results of measuring values of the real backscattering strength recorded with a multibeam echosounder representing the entire angular relationship are extremely rare and insufficient (Wendelboe 2018; Eleftherakis 2018). Any physically correct calibration method improves data quality and provides valuable information. The methodology I present in publication 3 for obtaining real absolute values of backscattering strength makes it possible to replicate the measurement and data analysis process by using the manufacturer's calibrated echosounder and supplementing it with corrections related to the reverberation area and incidence angle corrections. The validity of absolute values of backscattering strength makes it necessary to use acoustically calibrated echosounders whenever possible.

Relative values of backscattered acoustic signal strength have been effectively used to classify benthic habitats (publication 1; Gaida et al. 2020; Buscombe et al. 2014; Preston 2009), but for more advanced environmental analyses, real values of backscattering strength are needed. An example is the study of diurnal and seasonal variability of backscattering by seagrasses, as a difference of a few dB in the backscattering strength level can determine the variability (Feldens et al. 2018). Recordings of relative values of backscatter from the seabed made at different times in different areas and often using a different multibeam echosounder model give very different results for the same benthic habitats. Using absolute values of backscattering strength will allow a comparison of these results. However, it is important to keep in mind that apparently similar benthic habitats may differ significantly in physical properties, such as the number and size of gas bubbles in the sediment, sediment density, and others, which contributes to differences in absolute values of backscattering strength. Intensive research is necessary to determine absolute backscattering strength values of different benthic habitats. Examples of measurements presented in various studies indicate a large variation in real backscattering strength, so it is important to find empirical limits of the actual backscattering strength for specific habitats in different basins. The studies presented so far describing the angular characteristics of the real backscattering strength are very rare and insufficient to know the characteristics of benthic habitats, therefore in publication 3 I described this problem, presented the method of data correction and the characteristics of benthic habitats of the study area in the southern Baltic Sea. This is one of the first works of this kind in the world.

In publication 3, I presented the angular dependence of the actual backscattering strength for five benthic habitats in the Baltic Sea at an acoustic signal frequency of 150 kHz. Corrections to the recorded scattering data included the use of an acoustically calibrated multibeam echosounder, correction of the seabed slope in the signal reverberation area, and the use of a reverberation area.

The results of measurements of the real backscattering strength as a function of incidence angle presented in publication 3 are consistent with theoretical predictions as well as with results obtained by other authors who performed measurements with a multibeam echosounder (Eleftherakis 2018; Fonseca et al. 2009). In the study I presented, for incidence angles ranging from 25 to 65, the curve of real values of the backscattering strength showed a significant decrease in values greater than that in the APL model (APL-UW 1994) at 100 kHz. This may be related to the higher frequency of the applied signal – 150 kHz.

In some studies, a trend of increasing values of the real backscattering strength with increasing frequency was observed (Williams et al. 2002; Williams et al. 2009). Higher values of the real backscattering strength for higher frequencies may be related to the strong scattering of signals on the rough bottom surface, while the degree of bottom roughness is described by the Rayleigh parameter and depends on the acoustic wavelength, the magnitude of the roughness present on the scattering surface and the angle of incidence (Ogilvy 1991).

Real values of backscattering strength are essential for characterizing benthic habitats and represent their important acoustic property. Differential angular characteristics with a known slope of the curve and a known range of values for the corresponding benthic habitats can in the future be used for classification with proper assignment of areas to habitat classes despite little or no bottom sediment sampling. Real values of backscattering strength will provide a better understanding of environmental processes on the seafloor than ever before and learning about them is part of basic research.

Summary and conclusions about BBS-Coder

For object-based analysis (OBIA), textural analysis (GLCM) or automatic classification, mapped values of the backscattering intensity without an apparent angular dependence are necessary. The most commonly used tool to reduce backscattered signal values to a single angle of incidence is Geocoder (Fonseca and Calder 2005).

Mosaic maps of the relative intensity of the backscattered acoustic signal of the study area prepared with the Geocoder tool have large errors for incidence angles close to 0°, so I developed my own correction method. It reduces the backscattering intensity to a selected incidence angle of 40° and, as a result, reduces the effect of the incidence angle.

The algorithm presented for correction involving angle varying gain BBS-Coder (publication 3) is simple and effective. It will be made available for wide use on the ECOMAP project website (https://www.bonus-ecomap.eu/). The very good quality of the backscatter maps created with BBS-Coder indicates their suitability for benthic habitat mapping and sustainable seabed resource management.

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