Using MBES backscatter strength measurements for assessing a shallow water soft sediment environment

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***Abstract*— Shallow water naval operations require detailed knowledge of the environmental characteristics. In this context, the BP'07 experiment was carried out in the Mediterranean Sea, south-east of Elba Island, in 2007. Measurements that were taken during this experiment employ a large set of sensors, thereby providing all information required to fully describe the environment.**

Water depths as measured by multi beam echo sounders (MBES) are found to range from 0 to about 130 meter. The finescale topography reveals that areas of different bottom morphology are present. Information about the physical sediment properties is obtained by bottom grab samples. They indicate the seafloor in the area to be composed of very fine-grained sediments with mean grain sizes ranging from 0.5 to 8 micrometer. In addition, the MBES also allows for classifying the seafloor. The MBES classification approach taken discriminates between sediments in the most optimal way by applying the Bayes decision rule for multiple hypotheses. It employs the MBES backscatter data, averaged per beam, which are assumed to be normally distributed. For shallow water situations, this assumption no longer holds due to the limited number of independent scatter pixels in the beam footprint. Averaging over a series of pings has been applied to restore this assumption.

The application of the method results in a map of the acoustic classes in this area, indicating the presence of four different seafloor types. A comparison with other results indicates a correlation between seafloor type and the presence of specific bottom features.

I. Introduction

Shallow water naval operations have become highly important for a wide range of applications, for instance mine hunting operations. Such applications require detailed knowledge about the characteristics of the underwater environment, including sediment properties.

Mainly, two types of sediment properties can be discriminated according to [1]: physical properties (e.g. grain size) and geoacoustical properties (e.g. backscatter strength). Obtaining physical properties of the sea oor sediments by taking bottom grab samples is a time consuming process and is restricted to point measurements. At maximum 30 grabs of 0.1-0.2 m^2 can be taken per day [2]. Therefore, determining geoacoustical parameters, commonly done by multi beam echo sounders (MBES), has gained a lot of interest. The geoacoustic parameters can be assigned to the physical properties by either a physical model or by using groundtruthing data.

Physical models, however, obey certain restrictions regarding the parameter range. In order to obtain results for all kinds of sediments, albeit their physical properties, we instead use ground truthing data, obtained from bottom grab samples, for comparison with a set of classified backscatter strength data.

The applied MBES classification approach itself is model-based and discriminates between sediment types in the most optimal way by applying the Bayes decision rule for multiple hypothesis. This Bayesian approach was already presented by [3]. It employs the MBES backscatter data, averaged per beam, for estimating both the number of sea oor types present in the surveyed area and the probability density function for the backscatter strength at a certain angle for each of the detected sea oor types. Thereby, it assumes the averaged backscatter strengths per beam to be normally distributed. However, for shallow water situations, this assumption no longer holds due to the limited number of independent scatter pixels in the beam footprint. We apply an averaging over a series of pings to restore this assumption. Furthermore, the number of pings for averaging is adapted to the varying water depth, to obtain comparable classification results.

Data analysed in this paper are collected during the multidisciplinary BP'07 experiment (as described in [4]) that was carried out by in the Mediterranean Sea south-east of Elba Island in 2007.

This paper is organized as follows. First, a theoretical background for the classification of backscatter stength data is given in section II. Subsection II-A brie y describes the basics of the Bayesian approach, which is choosen for classifying the MBES backscatter strength data. It is extended in subsection II-B, in order to cope with environments with large ranges in bathymetry. Thereafter, the groundtruthing of the backscatter strength classes is described in section III. In section IV, the suggested approach is applied to the data taken during the BP'07 experiment. Beside backscatter strength data, also bathymetric and morphologic information is analysed and compared for the purpose of environmental assessment. While the survey is decribed in subsection IV-A, the results of the environmental assessment are discussed in subsection IV-B. Finally, results are summarized and embedded in the context of the whole research project in section V.

II. Classification of MBES backscatter strength measurements

Since the backscatter strength of an acoustic signal provides information about the material at which the signal is scattered, it can be used for assessing the sedimental composition of the sea oor. For this purpose, a classification of the backscatter strengths is aspired. Classification involves both the assembling of classes and the decision to which class a measured backscatter value is assigned. Both are incorporated in the Bayesian approach, which was proposed for backscatter classification by [3]. It also forms the basis of the present classification approach of backscatter intensities and is described brie y in section II-A. However, due to some initial assumptions, the original method requires improvement to be capable for regions with water depth below 20 meters and for areas that show a large range in water depth. Hereto, an approach is presented in section II-B that allows for the application in such regions. It further increases the comparability of results obtained in different regions.

A. The Bayesian approach

The MBES provides backscatter strength data BS_θ in the form of averaged backscatter intensities per beam θ. These can be expressed in decibel (dB) units as follows:

$$BS_\theta = \frac{1}{N_\theta} \sum_{n=1}^{N_\theta} 10 \;\log_{10} I_n. \quad (1)$$

Here, N_θ denotes the number of independent scatter pixels and I_n is the backscatter intensity of a single scatter pixel.

A classification of the backscatter strength data, measured under a certain angle, can be performed as follows. If N_θ is large, we obtain normally distributed BS_θ according to the central limit theorem. For an area with a single sea oor type this results in a histogram of backscatter strength values per angle that can be modeled by a single scaled Gaussian probability density functions (PDF). For an area with more than one sea oor type present, the histogram of all averaged backscatter strengths, observed under angle θ, can be modeled by a sum of scaled Gaussian PDFs:

$$\begin{aligned} f(BS_\theta \; x) &= \sum_{k=1}^{m} f(BS_\theta \; x_k) \\ &= \sum_{k=1}^{m} c_{\theta k} \exp\left(-\frac{(BS_\theta - \mu_{\theta k})^2}{2\sigma_{\theta k}^2}\right). \end{aligned} \quad (2)$$

Model parameters, which are the scaling factor $c_{\theta k}$, the mean $\mu_{\theta k}$ and standard deviation $\sigma_{\theta k}$ of each of the $k = 1, \ldots, m$ Gaussians, are combined in the vector $x_k = (c_{\theta k}, \mu_{\theta k}, \sigma_{\theta k})$ and are estimated in the least squares sense. The number of Gaussians employed is equal to the number of sea oor types and is obtained empirically [3].

To decide amongst the backscatter strength classes, Bayes' rule for decision is applied. It gives the *a-posteriori* probabilities for observed BS_θ as

$$P(x_k \; BS_\theta) = \frac{f(BS_\theta \; x_k)P(x_k)}{f(BS_\theta)}, \quad (3)$$

with $P(x_k)$ denoting the *a-priori* probability. From the *a-posteriori* probabilities the backscatter class is selected which is most likely:

$$\begin{aligned} &\max \; f(BS_\theta \; x_k)P(x_k) \;\; = f(BS_\theta \; x_j)P(x_j), \\ &\text{with } k = 1, \ldots, m. \end{aligned} \quad (4)$$

In the case all classes are assumed to be *a-priori* equally likely, the *a-priori* probabilities become $P(x_k) = \frac{1}{m}$ for all $k = 1, \ldots, m$ and can be neglected in the allocation of classes.

Note that this approach results in backscatter classes. To obtain classes of sediment types, groudtruthing has to be applied.

B. Extending the applicability of the classification method

The obtained number of scatter pixels per beam footprint is the limiting factor to the applicability of the Bayesian approach, since the normal distribution of averaged backscatter strength data cannot be assumed for a small number of scatterpixels. Especially in very shallow water, beamfootprints contain too few scatterpixels, even at large beam angles (i.e. small grazing angles). The theoretical number of scatterpixels can be calculated according to the ratio of the beam footprint dA and the footprint of a scatterpixel da as

$$\begin{aligned} N_\theta &= \frac{dA}{da} \\ &= \frac{H \cdot \theta_T}{\cos^2(\theta)} \cdot \frac{2\sin(\theta)}{c\tau}. \end{aligned} \quad (5)$$

Hereby, dA depends on the waterdepth H and the beam opening angle θ_T, whereas da depends on the water column sound speed c and the pulse length τ.

The dependence of the number of scatterpixels on the waterdepth also affects the comparability of classification results, if data from different locations with varying depths are included. Therefore, a modification is applied to the above described classification method. It involves an averaging over pings, to create sets of measurements with comparable large numbers of independent scatterpixels for the entired surveyed area.

The number of pings (p) that are involved in this averaging process depends on the waterdepth H and is determined empirically by comparing the theoretical number of scatter-pixels at different waterdepths (see Eq. 5) at $44°$ beam angle. Thereby, both the pulse length ($\tau = 150\ \mu$s) and beam steering angle ($\theta_T = 1.5°$) are kept constant according to the values typically used by MBES. The water column sound speed is choosen to be $c = 1500$ m/s, since changes in these values only have a negligible effect on N_θ. For example, a difference in 40 m/s in the water column sound speed results in at most 1 pixel difference for water depths below 200 m. The obtained values for p are presented in Table I. Averaging over these numbers of pings leads to an increased theoretical number of scatterpixels of about $N_\theta = 20$. Detailed values are shown in Fig. 1.

TABLE I
PARTITION OF DEPTH VALUES AND RELATED NUMBER OF PINGS FOR AVERAGING (p)

depth range [m]	p
$<$ 10	12
10 – 15	8
15 – 20	6
20 – 25	4
25 – 35	3
35 – 60	2
$>$ 60	1

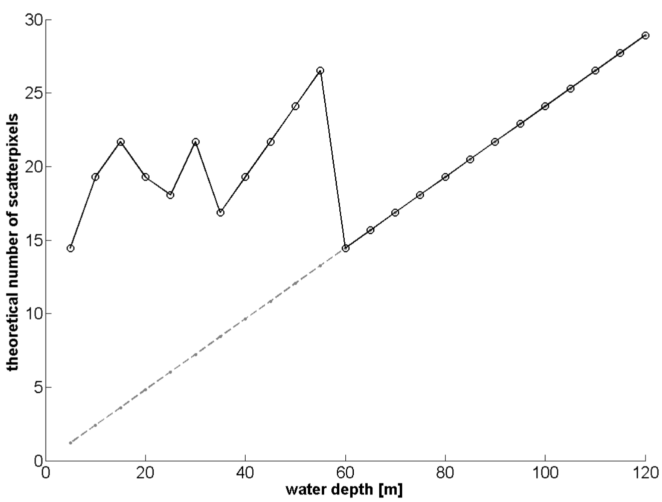

Fig. 1. Theoretical number N_θ of scatter pixels calculated at depths from 5 to 120 m in steps of 5 m for $44°$ beam angle. The dashed line indicates N_θ without averaging over pings, while the solid line indicates the corresponding values after averaging.

Applying the averaging over p pings results in the following backscatter strength values:

$$BS^*_\theta = \frac{1}{p}\sum_{l=1}^{p} BS_{\theta,l}. \tag{6}$$

Here, $BS_{\theta,l}$ denotes the backscatter strength of the l'th ping out of the set of considered pings.

III. GROUDTRUTHING OF THE ACOUSTIC CLASSES

A classification of backscatter strength data contains information about the acoustical properties of the sea oor sediments. These can be related to physical properties of the sea oor sediments (such as e.g. density, roughness and grain size), when sufficient ground truthing information is available. Such information is mostly obtained by analysing bottom grab or core samples. Commonly, the diameter of the dried sediments is measured by sieving. It is either given in millimeter units or in ϕ units. The particle size d in ϕ units results from the average grain diameter D in millimeter units according to

$$d = -\log_2 D. \tag{7}$$

However, using this value as a description of the grain size was found to be not that significant. Therefore, we use mean grain sizes instead. The mean grain size combines three different grain diameters according to

$$M_z = \frac{d_{16}\ +\ d_{50}\ +\ d_{84}}{3}, \tag{8}$$

with d_x denoting the grain size (in ϕ-unit) at which $x\,\%$ of the sediments in the sample are smaller. Mean grain sizes and grain size quantiles can easily be related to sediment types. We follow the common nomenclature of the Wentworth scale [9], which is shown in Table II.

TABLE II
SEDIMENT GRAIN SIZES.

M_z [ϕ]	maximum diameter [mm]	sediment
-1 – 0	2	very coarse sand
0 – 1	1	coarse sand
1 – 2	1/2	medium sand
2 – 3	1/4	fine sand
3 – 4	1/8	very fine sand
4 – 8	1/16	silt
8 – 10	1/256	clay
>10	1/1000	colloid

A different approach for dividing sediments into types is given by Shepard [8]. Here, sediments are differentiated by their relative composition of sand, silt, and clay (see Fig. 2). For the definition of the three composits, we again refer to Table II.

Both approaches are considered to associate backscatter strength classes with sediment types and to get an acoustic map of the sedimental composition of the sea oor. An application to survey data is presented in Sect. IV.

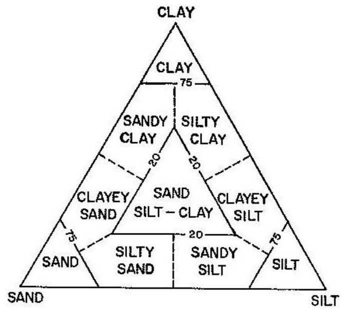

Fig. 2. Ten sediment types of fine grained sediments as introduced by Shepard, consisting of proportions of sand, silt, and clay [10].

IV. Assessing a shallow-water soft sediment environment

A classification of averaged backscatter strength data is applied for assessing a shallow water environment that extends over a wide range of water depth and features very fine-grained sediments. Both data and classification results are resented in this section.

A. Data

In the context of the Marine Rapid Environmental Assessment (MREA) project, the BP'07 experiment was carried out in the Mediterranean Sea during two weeks in spring 2007. It aimed at evaluating the in uence of changes in the surroundings on underwater acoustic operations. Since this demands a location with clearly seperable regions of homogeneous sediments, a well-known area in the south-east of Elba Island and off the coast of Grosseto (Italy) was chosen. A part of this area was already focus of several experiments such as the Yellow Shark (YS) experiments [6], [7]. The current surveying, however, focuses on a somewhat shallower area ($0 - 130$ m depth) between $10.7°$ and $11.0°$ eastern longitude and between $42.5°$ and $42.8°$ northern latitude, which features very soft sediments. Fig. 3 gives an overview over this area.

Fig. 3. Overview of the MREA BP'07 experimental area.

In-between the above mentioned bounds hydrographical (e.g. sound velocity profiles) and geophysical (e.g. seismic pro es) data have been taken. For survey details we refer to [4]. In the following, we focus on multi beam echo sounder (MBES) data and bottom grab data for assessing the environment for further evaluation purposes. MBES data were taken by a SIMRAD EM3000D that is mounted on the HNLMS Snellius, a hydrographic vessel of the Royal Netherlands Navy. This MBES operates at 300 kHz with a ping rate of 0.2 s to 0.3 s. Within an opening angle of $130°$ up to 245 beams are formed, dependent on the water depth. Per beam information about the depth (calculated from the two-way travel-time) and backscatter strength is obtained. The latter is calculated as the average over all backscatter intensities of the scatter pixels that belong to a single beam footprint, as described in Eq. 1. Due to the high frequency used, backscatter strength of the acoustic signal re ects the sediment properties of only the upper few centimeters of the sea oor.
Groundtruthing of the MBES backscatter data is guaranteed by a set of 24 bottom grabs that where taken with a Hamon grabber. These bottom grabs were analyzed at TNO, in the Netherlands, where they were dried, sieved with different sized sieves and sorted by grain size. Documented is mainly information about particle sizes and the grain size distribution.

B. Results

In the following, results of the data analysis from the MREA BP'07 experiment are presented. The focus lies on the MBES backscatter strength classification, as discussed in section II, to separate regions with homogeneous sediment types. For embedding these classes into a topographical and geomorphological context, also bathymetric data and bottom grab samples are investigated.

A bathymetric map of the MREA BP'07 research area is given in Fig. 4(a). It is calculated from the two-way travel times, measured at each beam of the MBES. As can be seen from this map, depth values vary within the wide range from 0 to 130 m. These variations occur over a horizontal distance of about 17 km. Shallowest parts occur in the north-east, near to the Italian coast. From these regions on, depth increases with distance to the coast, resulting in isobaths that tend to run parallel to the coastline. Thereby, the amount of depth increase is changing. While in most parts depth increases slowly compared to the distance (resulting in slope values of less than $1°$), accumulated isobaths between 30 and 50 m depth show a slight increase in the slope. However, even in these regions, slopes do not exceed $3°$. Fig. 4(b) shows the appearance of silghtly increased slope values also at few more locations in the MREA BP'07 area. They reveal the occurence of small-scale ripple structures that can not be seen in the bathymetric map. Knowledge about features, such as ripples, is of importance, since it can help to explain the backscatter classes.

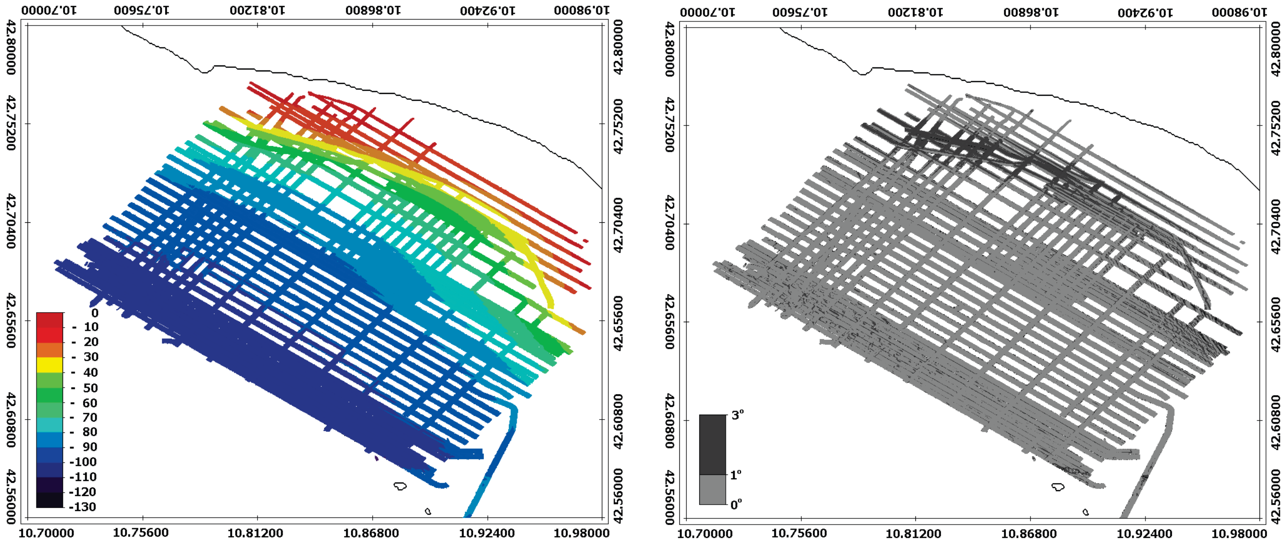

Fig. 4. Bathymetry (left) and slope (right) of the MREA BP'07 area.

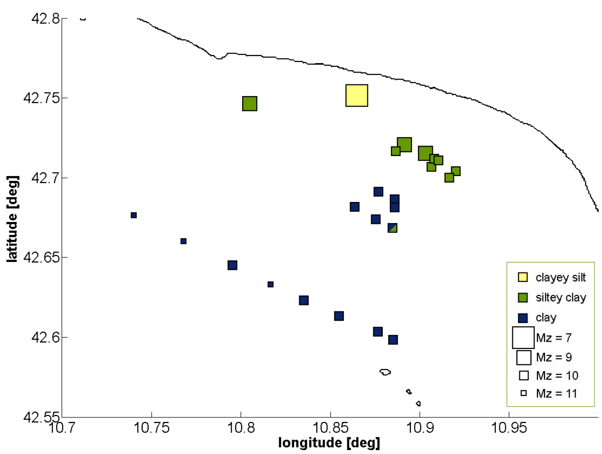

Fig. 5. Position of bottom grabs and present sedimental distribion. Mean grain size is illustrated in the marker size, while color represents Shepard's classes clayey silt, silty clay and clay.

Another way to interprete the backscatter strength classes is their comparison with bottom grab samples. According to the 24 bottom grabs that were taken during the MREA BP'07 experiment, the entire area consists of very fine grained sediments, as can be seen in Fig. 5. Despite the fact that all sediments in the area are found to be soft, they differ in composition. Furthermore, they are arranged in clearly separable patches of different sediment types.
The description of sediments by Shepard's classes shows the trend of changing sediment compositions from clayey silt (the coarsest sediment in this area) in the shallow coastal area over silty clay in the regions with higher slope to clay in the deeper part. These three classes are roughly oriented in bands parallel to the coastline, following the isobaths. Higher variability is found in the shallower parts.

A similar, but more detailed image is given by the mean grain size (M_z) distribution. Again, most of the patches with a single M_z value are aligned with the isobaths. Thereby, the M_z values increase (while the grain diameters decrease) with increasing depth, starting at 7ϕ in the shallow part and reaching the maximum of $10 - 11\phi$ in the deepest part. According to Eq. 7 the obtained M_z values equal a grain diameter of 0.5 to 8 micrometer. Additionally, a separation of sediment types in between the north-western and south-eastern part can be observed at large depths.

The sedimental distributions shown by the bottom grab samples are comparable to those of the upper sediment layers of core samples taken in the same area during previous experiments which are described in [6] and [7]. This means that no large variations took place over the last ten years. However, the bottom grab samples and cores give insight only into a small fraction of the entire area.

In the following, MBES backscatter strength data are analysed, to get a more complete image of the sedimental distribution. Backscatter values are analysed per beam angle according to the approach, presented in Sect. II. The modifications applied to the Bayesian approach enable it to deal with variations in the measurement geometry, which occur due to the wide range in water depth and the fact that parts of the measurements cover regions of less than 10 meter water depth. Basically, we are interested in a classification at large beam angles, since beams at these angles feature a larger footprint and contain more information over variations between different sediment types. However, at large beam angles measurements are provided only in shallow water regions, due to high propagation losses and low backscatter strengths at these angles.

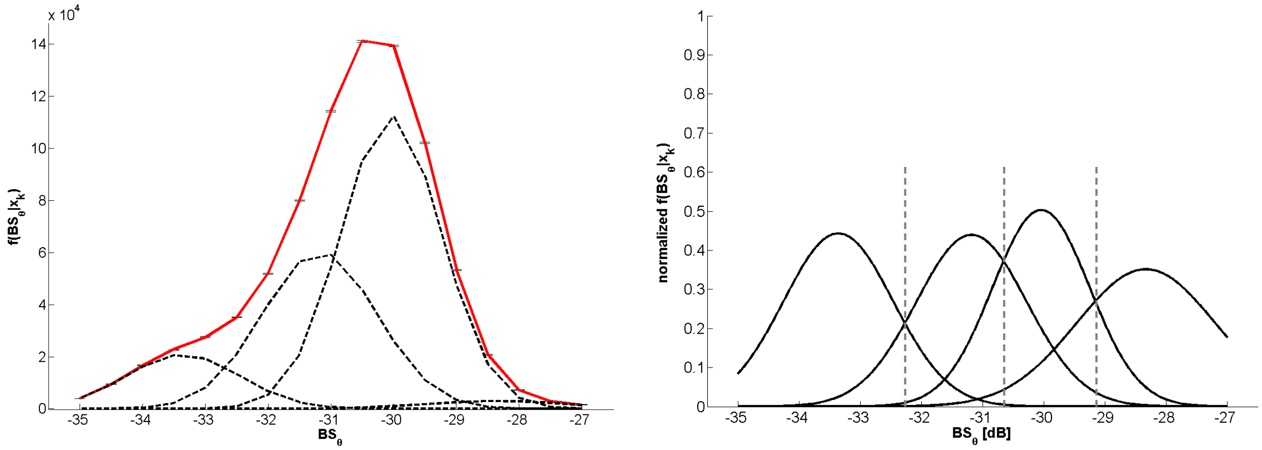

Fig. 6. Fit of scaled Gaussians to the PDF of the backscatter values BS_{44} (left) and normalized Gaussians with class boundaries (right).

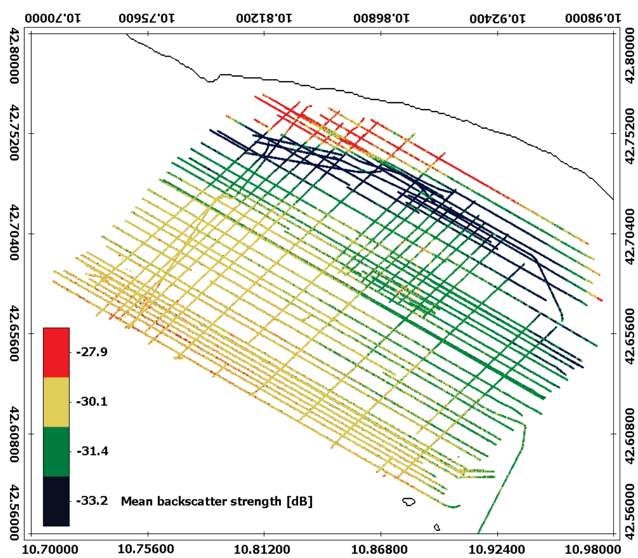

Fig. 7. Classes of backscatter strength at the beam angle of 44° in the MREA BP'07 experimental area.

TABLE III
BACKSCATTER CLASSES AT 44° BEAM ANGLE.

BS_{44}	BS_{44}			typical sediment properties	
classes	min.	mean	max.	M_z $[\phi]$	composition
1	$-\infty$	–33.2	–32.2	9–10	silty clay
2	–32.3	–31.4	–30.7	10	silty clay / clay
3	–30.7	–30.1	–29.2	10–11	clay
4	–29.2	–27.9	∞	7	clayey silt

In order to get an overview over the entire area, a beam angle of 44° is considered for classification purposes. At this angle the best fit between the histogram of the backscatter strength data and the sum of scaled Gaussians is obtained, when backscatter strength values are subdivided into four classes. At larger angles less classes might be considered, due to the lack of data in the deeper parts.

Fig. 6(a) shows the fit of the four Gaussian curves to the histogram of all backscatter strength values, obtained at this beam angle. The backscatter strength values that contribute to the histogram are averaged over several pings, according to Table I. This ensures a comparable large number of scatter pixels at all water depths. The application of the Bayesian criterion of decision then leads to class boundaries at the intersection points of the normalized Gaussians, which are depicted in Fig. 6(b). This approach results in the backscatter map shown in Fig. 7. The four classes appear not to be randomly distributed, but form patches within the area. Although these patches of backscatter strength classes roughly follow the isobaths, their distribution cannot be explained by changes in the bathymetry, since backscatter strength does not vary uniformly with depth. From the shallow to the deep part, backscatter strength decreases up to about 50 meter depth, before it increases again.

After having excluded a depth dependence of the classification results, groundtruthing can be applied to the classes. In order to map the sediment types, a comparison between the backscatter strength classes (Fig. 7) and the results of the grab analysis (Fig. 5) is made. Detailed results are given in Table III.

As expected, higher backscatter strength values in the shallow coastal part can be associated with the somewhat harder sediments. Furthermore, lowest backscatter strength values can be associated with slightly smaller grain sizes. This behavior, however, is not persistent throughout the deeper part of the research area. In this part, where the softest sediments (colloides) occur, backscatter strength increases again. About 10 dB larger backscatter values occur at these sediments with smaller grain size. Such a phenomenon might be explained by gaseous sediments with increased volume scattering [1], accumulated in the deep western part of the MREA BP'07 area.

The increase in backscatter strength both toward the coast and toward the deeper part results in spatially divided regions that are assigned to the same backscatter class. One would expect that these regions show similar bottom grab results. However, bottom grabs are available only for one region per class. Therefore, results have to be interpreted with caution. Concluding from the structure of the available grabs, we might not be able to assess each of the obtained backscatter classes by a single mean grain size value. There might be other sedimental parameters (e.g. occurence of gas) involved that condition the backscatter strength.

Furthermore, there are some parts of the investigated area which cannot be assigned to a single backscatter class, but which show two overlapping classes. This might be due to an erroneous assignment of the backscatter strength values to one of the four classes. Such a type of error cannot be excluded, since the Gaussians, which are used to model the histogram of backscatter strength values, overlap. On the other hand, the overlap of classes in Fig. 7 may also indicate the occurrence of finscale shapes and features on the sea oor. As indicated by the slope map, features such as ripple structures are present in the MREA BP'07 area.

V. Conclusions

A classification of the sedimental composition of the MREA BP'07 experimental area has been carried out by employing MBES backscatter strength data and bottom grab samples. Furthermore, bathymetric and morphologic information have been employed to allow for a comprehensive environmental assessment.

The main challenge was posed by the MBES BP'07 region itself: a region that features very soft sediment in the order of 0.5 μm to 8 μm and that ranges from very shallow waters with depths of a few meters to depths of more than 100 meters.

Regarding the wide range in water depth, averaging over several pings has proven to be a promising approach. In this way, the number of scatterpixels that contribute to an averaged backscatter strength, which is used in the Bayesian approach, can be increased depending on the prevailing water depth. However, due to the desired resolution, the averaging in along track direction cannot be extended to infimum. In future work we will investigate an extension of the present method with regard to the employment of averaging over adjacent angles. A classification at different angles also needs to be considered for validating the current results.

The present classification of backscatter strength at the $44°$ beam angle reveals the presence of four classes, which can partly be assigned to a specific mean grain size. This assessment is, however, hampered in two ways.

On the one hand, some backscatter strength values cannot be explained solely by the mean grain size. There is for instance a trend towards a larger backscatter strength from the soft sediments. Other sediment parameters have to be examined in future work, to explain this behavior. Furthermore, additional bottom grabs are needed to further compare the different regions that feature large backscatter strength values.

On the other hand, while most parts of the area are clearly separable, regions of two overlapping classes exist. Such regions with non-uniform classification results might be assigned to specific bottom features. A step towards extracting these features from a backscatter classification may lie in image processing, once a map of the classification at all angles is available.

VI. Acknowledgements

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