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ASSESSING THE REPEATABILITY OF SEDIMENT CLASSFICATION METHOD AND THE LIMITATIONS OF USING DEPTH RESIDUALS

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Abstract—Knowing the morphology and sediment composition of the seabed is of high importance for various applications. In this contribution, the repeatability of acoustic seafloor classification (ASC) results obtained from MBES backscatter value is investigated. The unsupervised classification algorithm based on Principal Component Analysis has been applied to the MBES backscatter acquired in the Cleaver Bank, Netherlands Continental Shelf, during five different surveys with two vessels. In general, there is good repeatability between surveys demonstrating the potential of using backscatter for marine environmental monitoring. To increase the discrimination performance the so-called depth residuals can be used. These are derived from the bathymetric measurements and considered to be representative for the sediment roughness. The challenge is that the small-scale depth variations are not solely dependent on the sediment roughness but also on the intrinsic uncertainties inherent to the MBES system. An A-Priori Multibeam Uncertainty Simulation Tool (AMUST) has been developed to predict the depth errors induced by various contributors. Correcting the measured depths for these uncertainties, as predicted by AMUST, theoretically provides information about the actual sediment roughness and this should improve the ASC algorithms. This was first tested on a MBES data set from Shallow Survey Conference Plymouth, 2015. It was shown that for the water depth of 20 m the standard deviation of the depth measurements was in agreement with AMUST predictions indicating a smooth seafloor, however, discrepancies between the predictions and real measurements occurred for the water depth of 8 m which is an indication of roughness or morphological features. This indicates the necessity of knowledge about the uncertainties when the objective is to derive the sediment roughness from MBES measurements.

Keywords: Multibeam derived bathymetry, Acoustic seafloor classification (ASC), MBES inherent uncertainties, depth residuals

1. INTRODUCTION

Modern seafloor mapping techniques using multi-beam echo-sounders (MBES) have improved scientific understanding of the physical structures of the seafloor. The main information delivered by the MBES are backscatter and bathymetry data. Several acoustic seafloor classification (ASC) methods have been developed to analyse the MBES data for sediment characterization [1].

We start with showing the results of applying an unsupervised sediment classification method referred to as Principle Component Analysis (PCA) in conjunction with k-means clustering to the backscatter data of the Cleaver Bank, Netherlands Continental Shelf. The MBES data was acquired during five different survey campaigns in the period from 2013 to 2015 using two vessels both equipped with a single-head Kongsberg EM3002. These results have been presented in earlier contributions [2], but are repeated here to illustrate the current performance in MBES backscatter sediment classification and indicate the need for further improvements. A very detailed explanation of the application of PCA to MBES data can be found in [3].

Monitoring the time-varying behaviour of the seafloor requires repeatable ASC results. Factors affecting the ASC results have been highlighted in [4]. Hence, it is important to assess the consistency and repeatability of ASC results derived from MBES data affected by these factors. This well-known problem was assessed in [2] by applying ASC to MBES backscatter data acquired by different vessels during different surveys carried out in various time periods. Generally, good repeatability between surveys using a single ASC method is found indicating the potential of using ASC for marine environmental monitoring. However, a limitation of sediment classification using backscatter only is related to an ambiguity in the backscatter for coarser sediments decreasing the discrimination power for these sediment types.

As a solution, depth residuals derived from bathymetric measurements can be used to improve the discriminative performance and solve the ambiguity. Depth residuals are obtained by fitting a plane to the MBES depth measurements and calculating the least square residuals between the depth measurement and the fitted plane. Theoretically, the depth residuals are representative for the sediment roughness. This can be seen from [3] and [5] where backscatter data are combined with depth residuals to improve the ASC. However, depth variations are not solely caused by the actual bottom roughness, but are also influenced by the intrinsic uncertainty in the MBES measurements, and hence this issue is to be considered.

To predict these intrinsic uncertainties, a software tool called AMUST (A priori Multibeam Uncertainty Simulation Tool) is employed. It will be used to assess the expected uncertainty in the bathymetric measurements from one of the Shallow Survey Conference 2015 MBES dataset in the area of Plymouth Sound, United Kingdom.

2. DESCRIPTION OF THE SURVEYED AREAS CONSIDERED

The Cleaver Bank area is located 160 km north-west from Den Helder in the Dutch North Sea. The water depth in the area varies between 25m and 50m, but is divided from north-west to south-east by a 70m deep channel, see Fig. 1. The MBES surveys were carried out within the period from 2013 and 2015. Two different vessels equipped with a single-head Kongsberg EM3002 were employed. Data from this survey will be used to illustrate the

current performance of MBES backscatter data for monitoring sediment distribution and to demonstrate the need for additional information for classifying also the coarse sediments.

As explained in the introduction, depth residuals as derived from the MBES bathymetric data are expected to increase discriminative performance, although affected by the intrinsic MBES measurement uncertainty. Unfortunately, during the Cleaver Bank surveys focus was on acquiring backscatter data and consequently no high quality bathymetric data was obtained during the surveys. Therefore, to assess the information contained in the depth residuals an additional data set, from a second site, was used.

This second site is taken from one of the datasets from the Shallow Survey Conference 2015 in Plymouth, United Kingdom where various MBESs were tested (quality of S-44 Order 1A, International Hydrographic Organisation Standard). The bathymetry in the area varies between 5 m to 35 m and is shown in Fig. 2. These measurements were acquired with a Reson Seabat 7125.
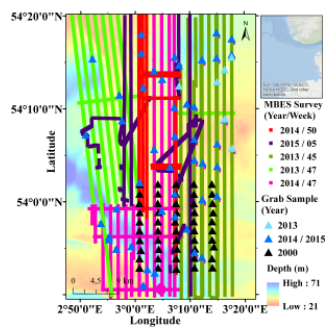

Fig. 1. MBES tracks of different surveys plotted over the bathymetry of the Cleaver Bank. Bathymetry is received from EMODnet [6].
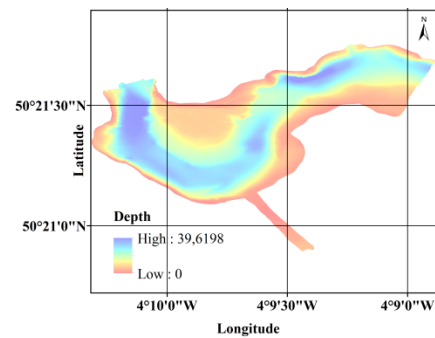
Fig. 2. Bathymetry of the Plymouth Sound, United Kingdom.

3. COMPARISON BETWEEN DIFFERENT ASC APPROACHES

For the sediment classification of Cleaver Bank area, the PCA method was applied to the receiving beams between 20° and 60°. The inner beams were not used due to their lower sensitivity to sediment properties. The beams larger than 60° were excluded because they were unusably noisy in these data sets. For the PCA approach, eight statistical backscatter features from surface patches of the size 10 m×10 m were derived. Application of PCA to backscatter values indicates that the first 3 PCs contain around 85% of the data variability. Using the correlation analysis, it was found that the mean, median, mode and minimum are the most informative features and hence a second PCA was applied to these four remaining features. Finally, the first PC (accounting for 98% of data variability) was used in the k-means clustering assuming seven clusters, see [2]. Fig. 3 shows the zoom in of the resulting ASC map with 10 intersections of track lines from different surveys. Clearly, there is a high agreement in the classification obtained from the data from different surveys. However, discrepancies also occur, for example in the area shown by the black rectangle in Fig. 3 where 2013 and 2015 surveys indicate the presence of acoustic classes 2 and 1, respectively. Still a high degree of repeatability and consistency is demonstrated considering different time spans, vessels, crews and environmental conditions.

The matches between acoustic class and sediment type at the grab sample location are plotted in Fig. 4, where the ordering of classes is such that the lowest acoustic class represents finer sediment. The PCA results represents a good match of acoustic class 1 with

the sediment type sandy mud. However, with regards to muddy sand to sandy gravel the correspondences are less clear, indicating that additional factors affect the backscatter data, such as the change in the relation between the backscatter value and the mean grain size for coarse sediments referred to the ambiguity in backscatter.
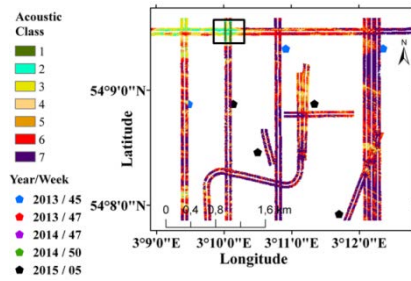

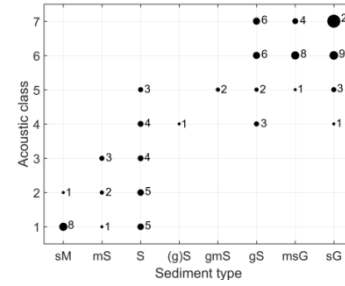Fig. 3. Zoomed in area of acoustic classes map generated by PCA. The grid size is 10 m by 10 m

Fig. 4. Correlation between acoustic class and sediment type.

To solve for this ambiguity, but also to increase the discriminative power in general, one can use the depth residuals derived from the least squares fit to the depth measurements in a small patch, since this parameter is theoretically representative of the seafloor roughness. However, depth residuals are affected by the intrinsic noise inherent to the MBES and hence an understanding of the magnitude of these uncertainties is imperative. For the Cleaver Bank area, the bathymetric measurements suffered from low quality. Therefore, the remainder of the paper focuses on the Plymouth Sound dataset to investigate the possibility of using depth residuals for improving classification methods.

4. AMUST DESCRIPTION

The A-priori Multibeam Uncertainty Simulation Tool (AMUST) is the result of collaboration between TU Delft and the Ministry of Infrastructure and the Environment of the Netherlands (Rijkswaterstraat). AMUST calculates the vertical and horizontal uncertainties in operational circumstances assuming a flat seafloor and is based on the error analysis of [7]. The total propagated uncertainty is derived assuming independent uncertainty contributors. The water depth d is related to the oblique distance from the MBES to the seafloor, r, by the following equation

$$d = r \cos P \cos \theta \qquad (1)$$

where P and θ are the pitch angle and beam angle with respect to the depth axis respectively. The model for depth uncertainty prediction is based on application of the error propagation to Eq. (1). In AMUST, the contributors considered are: 1) range error, 2) across track angular error, 3) along track angular error, 4) error due to beam opening angle, 5) heave related error, 6) error due to variation in water level and 7) GPS error. The contribution of each source to the total uncertainty is determined separately and assumed independent, resulting in the following expression for the total vertical uncertainty, where the subscripts $d_1, \dots, d_7$ correspond to the just mentioned error contributors.

$$\sigma_d = \sqrt{\sigma_{d_1}^2 + \sigma_{d_2}^2 + \sigma_{d_3}^2 + \sigma_{d_4}^2 + \sigma_{d_5}^2 + \sigma_{d_6}^2 + \sigma_{d_7}^2} \qquad (2)$$

As an example, the predictions for the vertical uncertainty (68% confidence level) for the water depths of 8 m and 21 m using Eq. (2) are shown in the left panel of Fig. 5. The right panel illustrates the vertical uncertainty for a range of depths for five beam angles. The characteristic of the Reson 7125 together with attitude and Global Navigation Satellite System (GNSS) sensor information during the survey were used as the input parameters for AMUST ([8]). Clearly, the outer beams have higher uncertainties and the maximum uncertainties for water depths of 8 m and 20 m are equal to 5 cm and 11 cm, respectively.
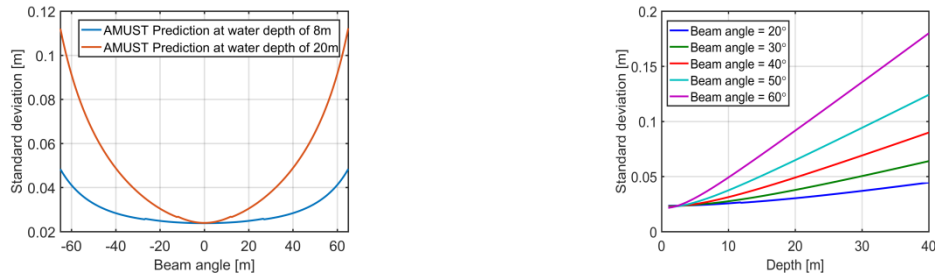

Fig. 5. Angle dependency (left) and depth dependency (right) of the uncertainty in the bathymetric measurements as predicted by AMUST.

5. COMPARING MODEL AND MEASUREMENT UNCERTAINTIES

Here, the comparison between the uncertainties derived from AMUST and those of real measurements has been made. Two areas with the water depth of 8 m and 20 m from the Plymouth Sound survey have been chosen. Shown in Fig. 6 are the standard deviation of depth measurements at 8 m (left) and 20 m (right) depths and AMUST predictions. The number of pings used to calculate the standard deviation was set to 50. This number is large enough to give a robust estimation of standard deviation and small enough to ensure that the seafloor topography does not change.

It is seen from Fig. 6 that for the shallower depth the measured standard deviation is higher than those predicted for the beam angles from -55° to 55°. The reverse situation holds for beams outside this range. This discrepancy can be due to the seafloor morphology or presence of stones. With regard to a small area chosen at 20 m depth, it is seen that there is a good agreement between the standard deviation derived from measured depth and those of AMUST. Theoretically, this indicates that the area has a smooth surface or homogenous seafloor as the AMUST predictions are derived assuming a flat seafloor. This information is required for determining sediment roughness.
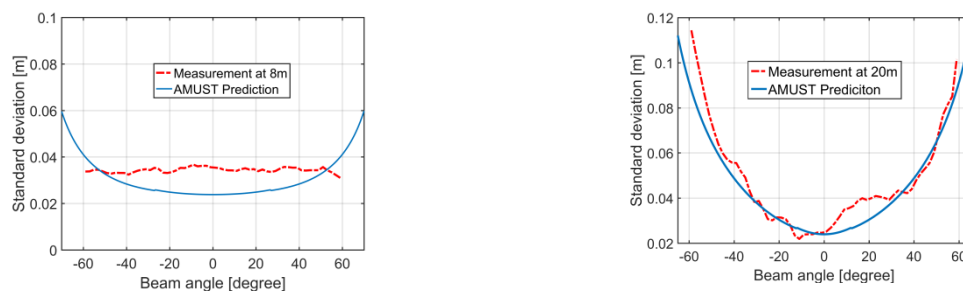

Fig. 6. Standard deviation of depth measurement and AMUST predictions at the water depth of 8 m (left) and 20 m (right)

6. CONCLUSION

From applying ASC methods based on MBES backscatter measurements, it is known that there exists an ambiguity for coarse sediments. For these sediments, different sediment types can result in similar backscatter values, hampering the discrimination between these sediment types. To solve for this ambiguity, but also for increasing the discriminative performance in general, one can use the depth residuals. However, as this parameter is contaminated by the intrinsic noise inherent to MBES, an insight into the depth uncertainties is required. This knowledge can then be used for calculating the actual sediment roughness. In this contribution, use is made of AMUST for the uncertainty prediction. The AMUST predictions are compared to the variations in the depth measurements derived in a flat area from the real measurements. While the discrepancies between these two indicate morphology effects, the agreement is an indication of smooth seafloor. A good agreement is found between the AMUST predictions and the measurements for small areas. This indicates the possibility of using AMUST predictions to extract the actual sediment roughness from the MBES bathymetric measurements.

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