THE EFFECT OF BATHYMETRIC MEASUREMENT UNCERTAINTIES ON MULTIBEAM ECHOSOUNDER SEDIMENT CLASSIFICATION

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1 INTRODUCTION

In the context of the Dutch Natura2000 program, a large number (>150) of areas in the Netherlands have been designated as Natura2000 areas. Together, these areas span over 1.1 million hectares and are located both on land and at sea. Natura2000 aims at closely monitoring these environments and coordinating all activities within these areas such that their flora and fauna are not negatively affected.

The Cleaver Bank area (North Sea, The Netherlands) is one of the areas that has been designated as Natura2000 area. In this framework a number of measurement campaigns have been carried out on the Cleaver Bank. The measurements were conducted in 2013, 2014 and 2015 using a 300-kHz multibeam echosounder (MBES). In addition side scan sonar measurements and sediment samples have been collected. In this contribution focus is on the analysis of the MBES data.

Nowadays, the analysis of the MBES data for sediment classification purposes is becoming standard practice. Various approaches towards sediment classification exist.[1] These can be either model-based or empirical. Model-based methods estimate actual parameters of the sediment through the use of a forward model that predicts the received signals or signal parameters. An example of a model for predicting the backscatter strengths for a wide variety of sediment types is described in Ref. [2]. A search is then carried out to find those parameter values that provide a maximum match between modeled and measured data.[3-9] In contrast, empirical classification methods do not employ a forward model, but classify sediments as a number of acoustic classes based on features of the data. From a comparison with other measurements, e.g. samples or video recordings, sediment properties can then be assigned to these classes.[10-19]

For the research presented in this contribution, the backscatter strengths, as measured by the 300-kHz MBES, have been used for classifying the surface sediments along the Cleaver Bank area using an empirical method conform that of Ref. [14]. With this method the backscatter measurements are employed for deriving signal features, such as backscatter mean and standard deviation. Based upon these signal features, a number of principal components are derived. Through clustering, the number of acoustic classes that can be discriminated based upon these features is determined. At the same time an acoustic class is assigned to all measurements.

In addition to the backscatter measurements, also the bathymetric measurements contain information regarding the sediment properties.[15,18] A parameter often used is the so-called depth residuals parameter. This parameter is obtained by locally fitting planes through the MBES depth measurements and considering the least-squares residuals. In theory, this is a measure for the roughness of the sea-bottom. In practice, however, the variations in bathymetry are not caused by the actual bottom roughness alone, but also by the intrinsic uncertainty in the bathymetric measurements, which results from uncertainties in, amongst others, the travel time, water sound speed, and ship's attitude. To predict these intrinsic uncertainties, we employ the model AMUST (A priori Multibeam Uncertainty Simulation Tool). It will be used for assessing the expected uncertainty in the bathymetric measurements for the Cleaver Bank measurements. This knowledge is prerequisite when the aim is to derive the sediment roughness, in addition to the backscatter strength, from MBES measurements.

In section 2, the measurement area, equipment and logistics are described. Section 3 presents the classification results based on the backscatter measurements. Section 4 assesses the expected uncertainty in the bathymetric measurements, together with a comparison between this modelled uncertainty and the uncertainty derived from a first inspection of the data. In section 5, finally first conclusions are drawn.

2 DESCRIPTION OF THE MEASUREMENTS

The Cleaver Bank is located at a ~160-km distance North-West of the Dutch coast. Water depths range from 30 to 60 m. The seafloor coverage consists mainly of sand. However, there is also an abundance of coarser sediments, such as gravel, pebbles and stones. This makes the area attractive to flora and fauna, not found at other locations of the Dutch Continental Shelf.[20]
The area of the Cleaver Bank is one of the most studied areas of the Dutch part of the North Sea.[21-26] Reason is that, both in the nineteen-eighties, and around the year 2000, a need was identified for gravel and concrete sand extraction from sea. Figure 1 presents a map of the sediment distribution of the Cleaver Bank area, based on grabs that have been collected over many years.

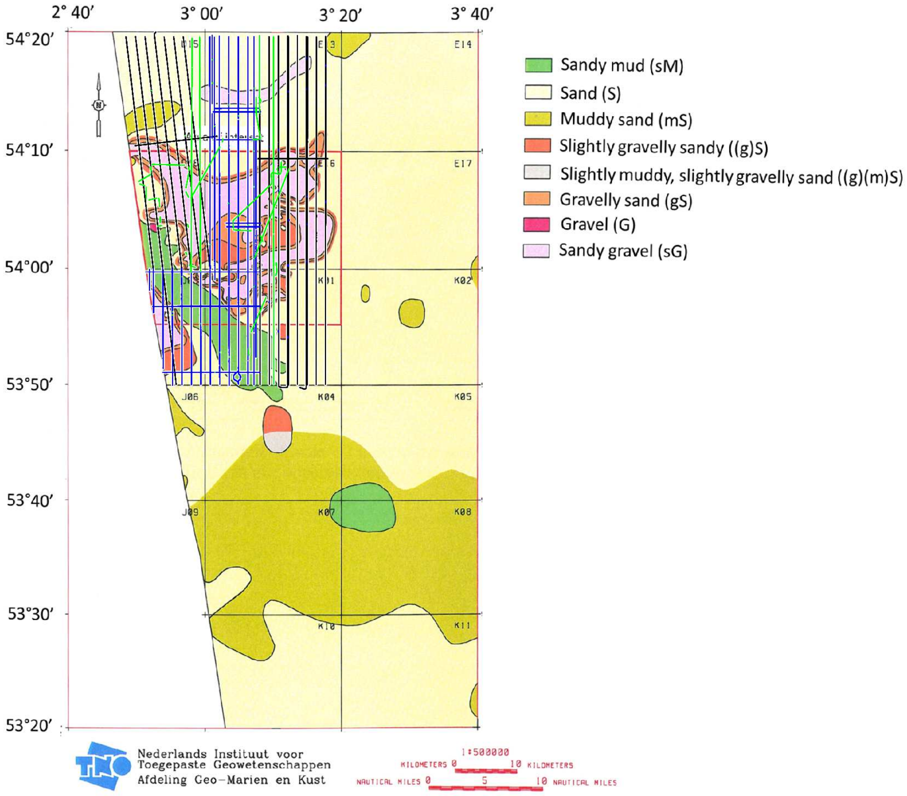

Figure 1. Overview of sediment distribution in the Cleaver Bank area (taken from Ref. [22]). The lines plotted on top of the map indicate the tracks as sailed in 2013 (black), 2014 (blue) and 2015 (green).

Measurements were taken with the Kongsberg EM3002 MBES. This is a 300 kHz system with 254 beams. Beam widths are 1.5 ° in both directions. The system is pitch and roll stabilized. Also shown in Figure 1 are the tracks sailed in 2013, 2014 and 2015, respectively. The same ship and equipment, including the MBES, was used for the 2014 and 2015 survey (Arca), but a different ship (with different equipment) was used for the 2013 survey (Zirfaea).
In addition, sediment samples and video recordings were taken. Other supporting measurements consist of a number of water column sound speed profiles in the survey area and side scan sonar recordings.

3 CLASSIFICATION BASED ON BACKSCATTER

As a first step, a classification based on the MBES backscatter strength data is performed. The datasets obtained from the different surveys were analysed separately and combined afterwards.
The classification procedure is as follows. Patches are defined, consisting of typically 7 pings in the along-track direction and approximately 5 beams in the across-track direction. Per patch, bathymetric slopes along the patch are determined. These are used for correcting the backscatter data. Based on the resulting backscatter values within a patch, the mean, standard deviation, skewness and kurtosis, together with the maximum and minimum backscatter are determined.
A principal component analysis of these features then identifies those features or linear combinations of features as the principal components that describe the majority of the variation present, i.e., those corresponding to the highest eigenvalues.
To assign sediment classes to the patches, a clustering analysis is applied. In this case, clustering is performed on the first two principal components. The number of clusters was based on a visual inspection of the maps, presenting acoustic class versus position, for an increasing number of clusters. It was found that the maps for six or more clusters show strong spatial scattering amongst classes, indicating that at maximum five acoustic classes can be determined from the backscatter measurements.
To check the consistency between the classification results obtained from the campaign carried out with the Zirfaea (2013) and that carried out with the Arca (2014 and 2015), areas surveyed by both ships are identified and their classification results are compared, as shown in figure 2, indicating a good agreement.

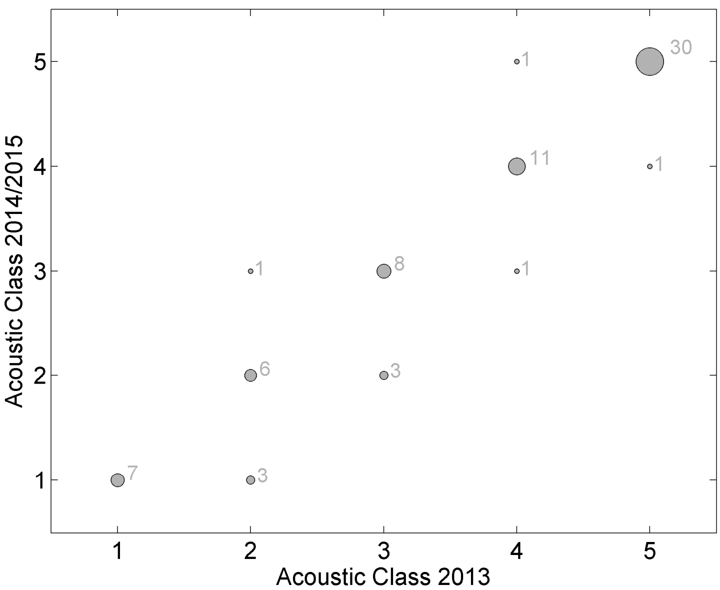

Figure 2. Illustration of the agreement between the acoustic classes obtained from the 2013 (Zirfaea) and 2014/2015 (Arca) MBES data at intersections. The size of the dots and the accompanying numbers indicate the number of intersection points corresponding to each dot in the plot.

In order to assign sediment type to the acoustic classes, use is made of sediment samples. It should be noted that, in addition to the samples taken during the 2013, 2014 and 2015 campaigns, also samples collected during a survey carried out in 2004 have been used. Figure 3 shows both the acoustic class (class number) plotted versus the sediment type as derived from the samples and the resulting classification map.

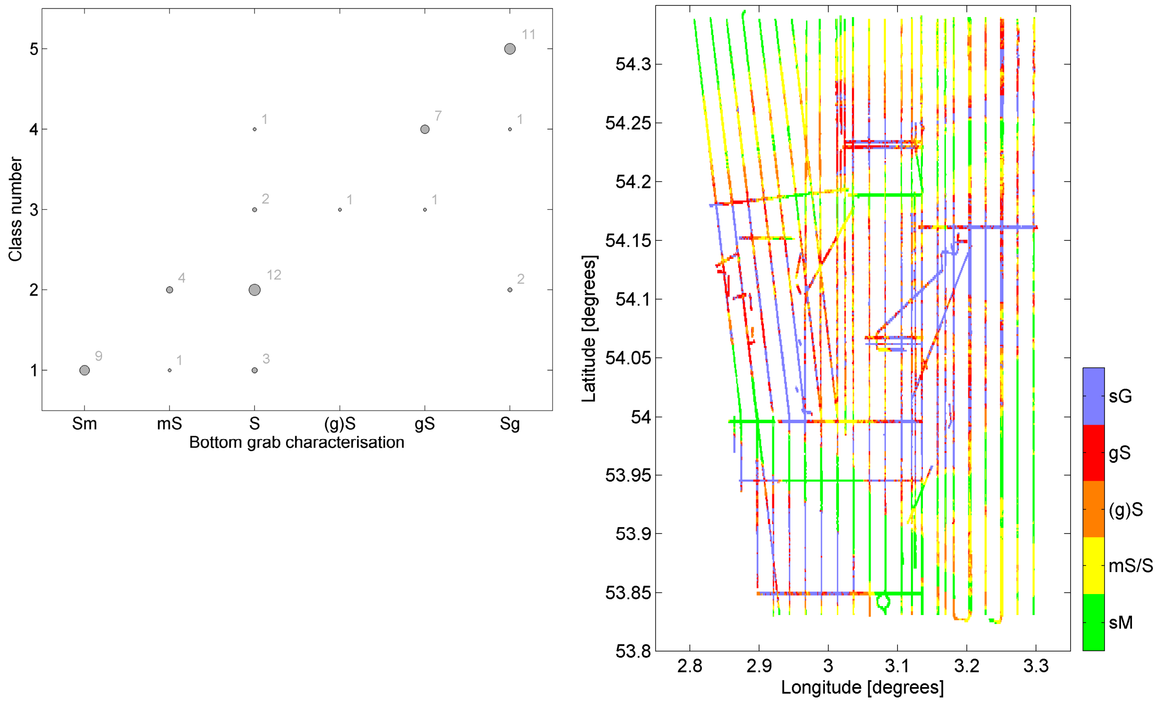

Figure 3. Left plot: class versus sediment type at grab locations. The size of the dots and the accompanying numbers indicate the number of samples corresponding to each dot in the scatter plot. The right plot shows the resulting classification map.

4 ASSESSMENT OF THE BATHYMETRIC UNCERTAINTIES

For many purposes the discriminating performance should be as high as possible, i.e., also small variations in grain size should be discernible. In addition, there should be no ambiguity where e.g. very coarse sediments are classified as fine sediments because of the correspondence in their backscatter strength. From literature it is known that a discrimination between different sediment types can be obtained also from the bathymetry. This either adds to the potential of discriminating sediments differing only little in grain size, or solving the above-mentioned ambiguity problem.[18]

A parameter often used is the so-called depth residuals parameter. This parameter is determined as the standard deviation of that part in the variations of the depths that are not captured by the plane fitted at the depths over the surface patch. In theory, this provides a measure of the roughness. For fine sediments this measure is assumed to correspond to morphological features, whereas for coarse sediments they reflect variations in bathymetry due to the actual grains.

However, care needs to be taken when considering the depth residuals as the actual measure for bottom roughness. The reason is that variations in bathymetry will be visible in all MBES measurements, even for a completely flat terrain. These variations are caused by the imprecise measurements in, amongst others, the travel time, water sound speed, and ship's attitude. This not only hampers a direct relation between a depth residual value and the bottom roughness, it also hampers the combination of depth residual values obtained from different surveys. The latter is caused by the fact that the uncertainty in the depth measurements is dependent on the measurement geometry and equipment used.

To assess the contribution of the imprecision in bathymetric measurement to the depth residuals for the Cleaver Bank survey, use is made of the A priori Multi-beam Uncertainty Simulation Tool (AMUST). This AMUST tool and its description in Section 4.1 are based on Ref. [27].

4.1 Simulating the precision in the depth measurements

Multibeam echosounders measure travel times to estimate depths and positions of an underlying surface. Using electronic beam-steering at reception, the MBES can distinguish between incoming angles of sound at the transducer. The steering angles are noted by θ_s and have an opening angle ψ_y in the across-track direction and ψ_x along-track. The geometry of the measurement is dynamic and is influenced by a number of factors, among which

- Roll: a rotation around the x-axis. The roll angle is indicated by *R* and is positive if the port side of the ship is located higher than the starboard side;
- Pitch: a rotation around the y-axis. The pitch angle *P* is positive if the bow is located higher than the stern;
- Heading: a rotation around the z-as. The heading angle determines in which direction the vessel is moving;
- Heave: a translation in the z-direction, caused by movement of the vessel on waves.

Uncertainty with regards to the exact values of these factors results in uncertainties in the depth and position that are deduced from the received signal. AMUST has been developed to provide estimates for the uncertainties.
For the depth uncertainty, the following seven contributions are distinguished.[27]

1. In multibeam echosounders the travel time of the signal and the speed of sound are used to determine the distance *r* between the transducer and the seafloor. From this distance, the depth is calculated. Consequently, an uncertainty in the measurement of the distance *r* contributes to an uncertainty in the depth. This contribution is quantified through the standard deviation $\sigma_{d,1}$.
2. An uncertainty in the angle of impact of the sound wave on the MBES will also result in an uncertainty in the depth and is due to an uncertainty in the roll angle *R* and an uncertainty in the steering angle θ_s. Its contribution to the standard deviation is indicated with $\sigma_{d,2}$.
3. The contribution from uncertainty in the pitch, indicated by $\sigma_{d,3}$.
4. The contribution from the non-zero along track opening angle ψ_x, indicated with $\sigma_{d,4}$.
5. In general, the sound speed profile will not be uniform throughout the water. Moreover, there usually exists uncertainty with regard to the sound speed profile. This contribution to the depth uncertainty is indicated with $\sigma_{d,5}$.
6. An uncertainty with regard to the vessel heave directly results in uncertainty in the depth calculation. The contribution due to heave uncertainty is denoted by σ_H.
7. Finally, uncertainties exist in the distance between the transducer and the water surface. At the beginning of a measurement the ship is usually fully fueled and docked. During the measurements, the waterline will become lower due to the vessel speed and the decreased ship mass, resulting from fuel consumption. This causes a variation in the distance between the transducer and the water surface called dynamic draft. Additionally, due to tidal variations the water level might vary during a measurement. Obviously, both effects can be predicted, but imperfections exist. The resulting contributions are written as $\sigma_{\text{dyn.draft}}$ and $\sigma_{\text{water level}}$, respectively.

The relevant equations for each of the aforementioned seven contributions can be found in [27] and [28]. Hereby, it is assumed that sound travels in straight lines, i.e., refraction due to varying speed of sound in the water column is neglected. The depth is related to the measured distance *r* by the following equation

$$d = r\cos P \cos\left(\theta_s + R + \delta\right) \tag{1}$$

where δ is the across track angle under which the MBES is mounted on the ship.
Based on this equation, expressions for contributions 1 to 4 can be determined. In Ref [27] an expression for these contributions is presented, whereas the remaining contributions are derived from operators input and product specifications. Assuming all contributions to the uncertainty in depth to be independent, the estimate for total depth uncertainty can be calculated according to

$$\sigma_d = \sqrt{\sigma_{d,1}^2 + \sigma_{d,2}^2 + \sigma_{d,3}^2 + \sigma_{d,4}^2 + \sigma_{d,5}^2 + \sigma_H^2 + \sigma_{\text{dyn.draft}}^2 + \sigma_{\text{water level}}^2} \tag{2}$$

Figure 4 shows the predictions for the uncertainty in the depth measurements for the situation of the Cleaver Bank measurements, where the water depth was taken as 30 m. In this case, as will be explained in the next section, the contributions of uncertainty in the heave, water level and dynamic draft are not considered and, therefore, not shown. The individual contributions are indicated separately, together with the resulting total expected uncertainty.

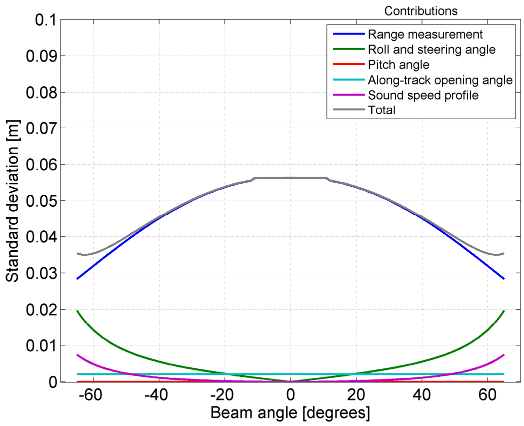

Figure 4. The uncertainty in the bathymetric measurements as predicted by AMUST. For the situation of this paper, the contributions of heave, dynamic draft and tidal corrections are not considered.

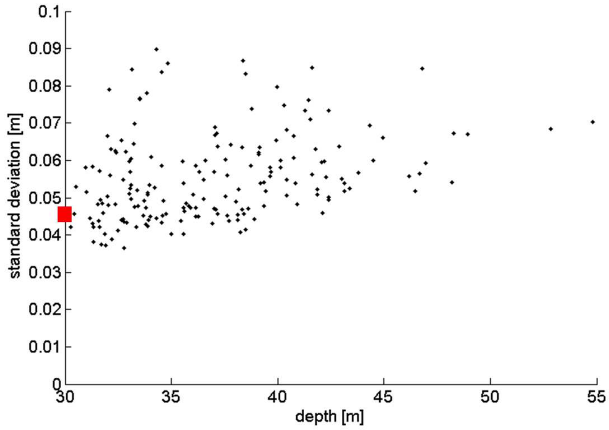

Figure 5. Standard deviation of depth measurements with the mean per ping subtracted (40° angle). The square indicates the AMUST prediction.

4.2 Comparing simulated and measured depth uncertainties

In the previous section, the expected uncertainty in the depth measurements based on the AMUST predictions is presented. As a first step to investigate the correspondence of these predictions with those in the measurements, Figure 5 shows for the data of 2013 an overview of the standard deviation as found in the measurements. These have been determined for a single steering angle (40°), where 100 subsequent pings are used. To avoid the effects of remaining heave artifacts and variations of depth in the along-track direction, the mean depth per ping is subtracted before determining the standard deviation.
As the standard deviation potentially varies also with depth, it is plotted versus depth. Indeed a dependence of depth is visible from the plot. Also shown is the AMUST prediction at 40° and 30 m

depth as derived from Fig.4. It is marked as a square in Fig. 5. This prediction includes all contributions presented above, except that for heave, dynamic draft and water level as the depths have not been reduced to a common vertical datum.
The modelled and measured standard deviations are found to be typically 5 cm. However, the measured uncertainty shows a significant spread. Standard deviations that are higher than those predicted by AMUST might be caused by effects of morphology or the presence of stones. This is valuable information that can add to the discriminative performance of the classification.

5 SUMMARY AND CONCLUSIONS

In the context of the Dutch Natura2000 monitoring program, the Cleaver Bank, located in the Dutch part of the North Sea, has been surveyed extensively in 2013, 2014 and 2015. The backscatter data acquired by a 300 kHz multibeam echosounder have been used for classifying the sediments. In addition to the backscatter, information is also contained in the bathymetric measurements. A parameter often used is the so-called depth residuals parameter. This, in theory, provides a measure for the roughness. However, the imperfectness of the bathymetric measurements also contributes to the depth residuals (as determined from the measured bathymetry). In this contribution the AMUST prediction tool that provides estimates for the uncertainty in the bathymetric measurements, resulting in variations in the measured bathymetry even for a perfectly flat seafloor, is described. The tool is used to assess the expected uncertainty in the MBES measurements taken at the Cleaver Bank. When comparing the predicted uncertainties and those derived from the measurements, a good agreement is found. It is hypothesized that deviations are, at least partly, due to the seafloor morphology. This information will be used as an additional measure to further improve the classification performance.

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