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Adaptive, variable resolution grids for bathymetric applications using a quadtree approach

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Abstract

The spatial sampling often used to process and represent bathymetric data are of fixed grid resolution where the least depth value is stored in each grid cell. This results in Digital Elevation Models (DEMs) that are used to depict the underlying features of the seafloor. With the discretion of the user, the resulting DEMs used may either be of coarse resolution or a very fine resolution surface which provides as many details as possible. However, depending on the resolution of the data collected and the variability of the seafloor, the arbitrary user defined grid resolution is not the best option. Hence we address the problem of finding an optimal grid resolution for representing and processing the bathymetric data for the application of bathymetric risk assessment whilst maintaining computational efficiency. Here we adopt the quadtree decomposition approach.

In addition, the research suggests the optimal criteria and standard deviation threshold, σ_{th} values for this particular application. These suggestions are still flexible and can be optimized for this application depending on the end user requirements. Previous studies have focused only on the splitting criteria or the constrained criteria to ensure that there is homogeneous accuracy over the entire dataset. However, an investigation into the threshold selection for the standard deviation, σ_{th} which describes the variability in the dataset is one of the most important splitting criterion, is still lacking. Also, a new approach to store the depths in the grid in a time ordered approach for each epoch is shown.

By optimizing the criteria for the quadtree decomposition and time series algorithm, the approaches shown in this paper provide the adaptive, accurate DEM which makes optimal use of the available bathymetric data for the Netherlands Continental Shelf (NCS) as the study area. This data preparation step forms the basis for developing a probabilistic approach to assigning hydrographic resurvey frequencies in the NCS.

Keywords: Bathymetry, Quadtree, Variable Resolution Grid, Time Series, Digital Elevation Model

1 Introduction

Globally there is increasing maritime economic activity across varying sectors, ranging from ports and navigation, renewable energy, tourism, coastal defense, submarine cables, fishing, mineral extraction, military operations, among other activities. These maritime activities are currently known as the Blue Economy [1]. To ensure safe operations and safety of navigation, hydrographic surveys provide data for accurate and up-to-date nautical chart production.

With the increased mapping of the seafloor, it is important to understand the geometry of the systems used in measuring the depths. The depth is determined from the observation of the travel time of the acoustic waves from the transmitting beam, through the water column, and the return of the echo reflected from the seafloor. The techniques used to measure the depths are the conventional single beam echosounding (SBES) and the multibeam echosounding (MBES). The SBES has beamwidth of the order 30° which measure the depths directly under the vessel and the MBES is a swath system that produces multiple acoustic beams which provides increased bottom coverage. With increased swath however, this does not mean that the accuracy of the MBES measurements are better [2]. The uncertainty introduced in the MBES measurements depend on the transmit and receive angles of the beams, and hence the accuracy of the measurements decrease as the swath angle increases. Hence, the swath width is usually limited by the expected depth uncertainty in relation to the maximum allowable total vertical uncertainty (TVU). The uncertainty quantification of the depth measurements has been of research interest in [3], [4] and [5], [6].

The MBES and SBES data used in this research was acquired from the Bathymetric Archive System (BAS) provided by the Netherlands Hydrographic Service and Rijkswaterstaat in accordance to the IHO Order 1 specifications [7]. These surveys however, are costly and with limited resources of national hydrographic offices, there is a need to optimize the hydrographic survey and resurvey strategy. The study area is the Netherlands Continental Shelf (NCS) which is characterized as a shallow sea with a dynamic seafloor. Part of the NCS is covered by sand waves and is an area of interest for the national hydrographic offices and the scientific community for over a century [8]. Due to the complex behavior of the seafloor, the use of only traditional, single beam echosounding (SBES) has its limitations since it does not provide full bottom coverage and interpolation is necessary which can introduce additional uncertainties in the final DEM output. With the introduction of multibeam echosounding (MBES), there is now a combination which results in a long time series of data that can be used to yield information about the characteristics of seafloor dynamics which can include heights, wavelength, asymmetry, migration rates and direction of seabed features such as sand waves. This would provide an evidence-based approach to decision making which is necessary in order to make more reliable decisions based on shipping risks.

A digital elevation model (DEM) is the 3D representation of the seafloor which provides important information for data analysis, nautical chart development and decision making. The wide range of applications reflects the importance of accurate DEMs. To determine the priorities of hydrographic resurvey planning, the digital elevation model (DEM) of the seafloor forms the basis for further spatio-temporal analysis. Traditionally, DEMs of a regular gridded structure have been used to manage and store the bathymetry, however, depending on the dataset, intended use of the results and the accuracy requirements, this may not always be the best option. In [9] a 25×25 meter grid was chosen to guarantee sufficient data density in all areas and was considered to be sufficient resolution to reveal the bedforms at the scale of sandwaves,

in [4] the data was represented on a 50x50 meter grid. Here the focus of the application is for risk assessment due to the variation of the seafloor depths. The storage of the depths accompanied by the variances is an important step when analysing bathymetric data sets for risk assessment but the challenge presented arises from the heterogeneous nature of the data due to differences in mapping techniques and the variability of the depths.

This paper hence provides the overview of the use of the quadtree decomposition method as the approach to store the depths on a variable resolution grid, that is suitable for detecting the large scale depth variations and tidal sandwaves in the NCS and is also adaptable to the spatial resolution of the available data. The paper also focuses on the design of the algorithm to determine the optimal criteria needed to resolve these issues. This paper is, therefore, focused on the preparation step in developing a dynamic DEM which covers the entire (NCS) (except in areas where there are no hydrographic data sets available) with homogeneous accuracy. Therefore the parameters of the DEM that will support the needs of the end user or in this case the national hydrographic offices.

This paper starts with a general context of the quadtree algorithm with potential criteria settings that can be applied to other applications. The design of the algorithm for this specific application to hydrographic survey data is also described using a single epoch example which allows for more flexible criteria selection based on the end user requirements, data availability and intention of data usage. Also, for the purposes of a time series analysis to capture the changes of the seabed dynamics, a multiple epoch workflow is described. This provides an adaptive grid that compensates for the spatial and temporal changes in the depths. Finally, the implementation of the quadtree algorithm is tested on different datasets of varying spatial resolutions and seafloor characteristics to assess the flexibility of the σ_{th} and criteria settings and suggests an optimal solution for this application.

2 Quadtree approach

The general quadtree algorithm is a hierarchical spatial data structure which is based on the principle of recursive decomposition of a space into adaptable cells [10]. The quadtree decomposition method is commonly used to represent spatial data structures such as points, regions, surfaces, lines and volumes. Applications include, computer graphics, image analysis, collision detection between two dimensions, computational fluid dynamics, geographic information systems, among others. Hence, the principles guiding the decomposition process can be predefined based on the input data and the required resolution. The quadtree approach starts with a square area which is successively subdivided into four equal quadrants until the criteria for subdivision are met. Depending on the application, the algorithm is flexible in terms of the criteria for splitting the quadrants and the choice of associated thresholds. The quadtree algorithm therefore allows for improved grid representation with the spatial sampling requirements according to parameters of interest.

For example, [10] applied quadtree decomposition to image processing, [11] applied it to interferometric synthetic aperture radar (InSAR) data and related applications to bathymetry include [12], [13], [14] and [15] [10] applied quadtree and octree decomposition to image processing for the purpose of representing the data in applications such as computer graphics, computer-aided design, robotics and cartography focused on 2-dimensional region data. [11],

designed and applied quadtree decomposition to InSAR data for designing an optimal spatial sampling method applied to earthquake inversion problem. [12] developed a quadtree based solver for depth averaged shallow water computational models. The recursive subdivision in this instance was also based on a predefined flow criteria according to "boundary seeding points". This led to a hierarchical data structure. [15] showed that the multiresolution image can be subdivided by introducing the fractal imaging with limiting constraints. [13] created a prototype variable resolution surface of the seafloor using RTINs (right triangulated irregular networks) which is equivalent to a quadtree approach, except that the same result is with two binary trees of right triangles for storing, analyzing and visualizing the bathymetric surfaces. The main goal was to thin the data before performing further interpolation and analysis. To achieve this, different thresholding methods were compared; distance thresholding which produced a higher reduction and error in shallower water since the distance is constant. The other method used the error thresholding technique based on the water depth. In this technique the shallow areas are preserved.

Quadtree decomposition applied to bathymetric applications can be shown in the development of the S-100 ENC (Electronic Nautical Chart), IHO (International Hydrographic Organisation) geospatial standards for hydrographic data. In [14] it is stated that the S-100 ENC data standards require that data of several different attributes can be stored and supported. This can vary from gridded bathymetry data, seafloor classification, water levels, currents, ice information and other temporal varying information. Therefore a standardized set of data layers that can be used together has to be established. The standard only suggests different types of structures for which coverage can be achieved and the 2D quadtree is one such representation which allows for smaller grid cells and larger grid cells and in areas of little variation. Other research that include the variable resolution bathymetric grids include the works of [16] and [17]. These alternative approaches have the objective to arrive at an appropriate, variable, grid resolution during the data acquisition and processing phase of the observations. That is, to achieve a finite sampled representation from the raw observations. In our research we move from the processed data to an optimal, variable resolution grid using the density of the observations as determined by the sensor used in order to optimize the available bathymetric coverage for estimating seafloor dynamics and features of interest as input for the evaluation of shipping risks.

The goal of the quadtree decomposition applied to bathymetric data in this paper is twofold. Firstly, to define an accurate variable resolution DEM of the seafloor whilst supporting end user requirements. The user requirements are directly linked to the resolution required for detecting seafloor dynamics that contribute to shipping risks and exposure of objects on the seafloor. To address this, the design of the quadtree algorithm is assessed to determine the optimal criteria requirements for achieving the desired resolution without loss of detail. Other research can be found with a focus on different lossless compression techniques for creating digital terrain models (DTMs) from high resolution bathymetry data [18] and [19]. In addition to demonstrating how the quadtree data structure can be useful for representing bathymetric data and the relevance to hydrographic survey planning, the focus is also on the σ_{th} assessment and its flexibility based on the intended use of the final estimated DEM. Although the spatial variability of the observations is dependent on depth itself, sea state and the incidence angle of specific beams of an MBES survey, here we only take into account the effect of depth on the standard deviation of the observations, since the data provided is in accordance to the IHO Order 1 specifications [7]. All survey data used are given in WGS84 with a UTM31 projection. The data are reduced to Lowest Astronomical Tide. For SBES surveys the track distance is

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50m and for the MBES surveys there is full coverage of the sea floor with highest resolution of 5x3m. The standard deviation of the observations, σ_{obs} for a specific hydrographic survey is calculated based on the number of observations in the grid. To identify the areas of high spatial variability, the spread of the observations within the grid is considered. The optimal threshold seeks to minimize the variance within grid cells making it a more homogeneous surface by dividing the area into appropriate grid cell sizes and assigning an easting, northing and depth value to each node based on the spatial variability defined by an optimal threshold criteria for the variability of the observations in the grid. This is considered the splitting rule for the decomposition.

The predefined criteria that can be used for the general quadtree decomposition algorithm are defined as follows:

1. A square, coarse initial grid size for applying the quadtree decomposition for an area.
2. Minimum grid size, G_{min} which is also called the stopping criterion for the decomposition.
3. Minimum number of observations, N_{min} in a grid cell to allow splitting.
4. Maximum number of observations, N_{max} in grid cell.
5. Standard deviation threshold which is the threshold for spatial variability of the observed parameter, σ_{th} .

In our application, the spatial representation of the depths, the data density over time and signal variability for each quadrant are assessed. If all are exceeding a predefined σ_{th} , the quadrant will be split into four new sub-quadrants recursively, until convergence or until a certain minimum grid size is reached. This will lead to a decomposition of the DEM into grid cells, each with a low standard deviation of the depths. Hence each newly subdivided grid cell will have more or less equal variation. In this instance, the variability and the minimum grid size will be the most important criteria for splitting and indexing the depths. For each quadrant, the 10th percentile, (P_{10}) was chosen as the lower limit of the minimum set of depth values to be truncated and stored as the final representative depth value of the whole grid cell. Therefore, each grid cell is represented by a central node with indexed P_{10} depth value and the corresponding easting and northing. For safety of navigation, it is better that the DEM surface be conservative in its estimation. The P_{10} value ensures that it represents the shallowest area within the grid cell without being too conservative as some of the observations can be outliers or in the tail of the distribution.

N_{min} is a predefined value set to ensure that there are enough observations in each grid cell after splitting it. In some areas of the NCS, the availability and data density of the depth observations are very low where areas are mapped using SBES. It is assumed that in these areas the depths do not reach a critical value where it affects the safety of navigation and also exhibits the least dynamic behavior. Therefore, in these areas where variability is not critical, a larger grid is acceptable especially if the dynamic depth is set equal to P_{10} of the depths in the corresponding grid cell. N_{max} is set at a large number which adds to the stopping and indexing criteria. Therefore, if the $\sigma_{obs} < \sigma_{th}$ but there are still more observations than N_{max} , the splitting will continue.

Figure 1 shows the schematic of the quadtree decomposition algorithm for a single epoch, with the initial splitting criteria including the minimum grid size, minimum number of observations,

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maximum number of observations and the stopping and indexing criteria which is a combination of G_{min} and σ_{obs} less than σ_{th} . Figure 2 (a) shows a schematic of quadtree decomposition approach where the areas are successively divided into equal quadrants and can be represented as leaf nodes as shown in (b) exposing the hierarchical data structure. Finally (c) shows the final resulting variable resolution grid with the indexed depths at the center of each grid cell.

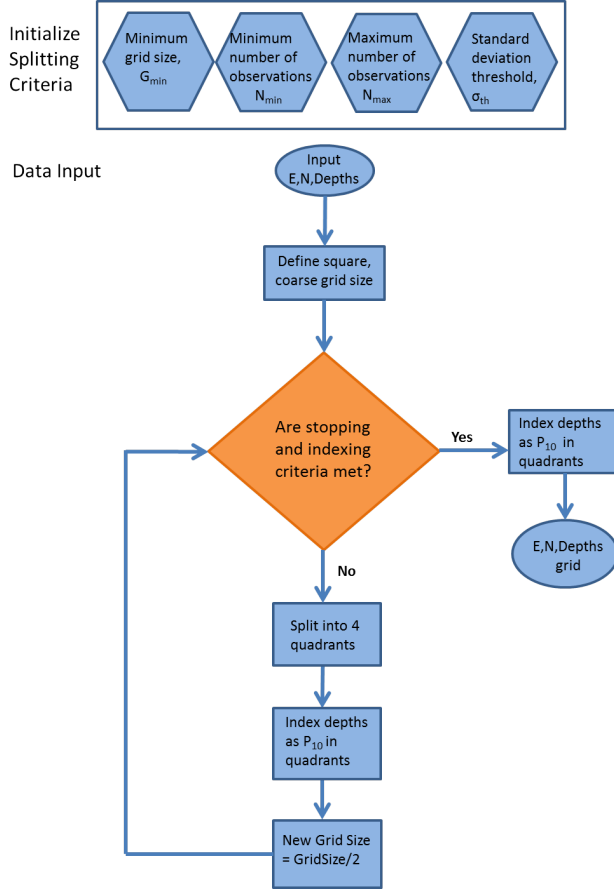


Figure 1: Single epoch algorithm with predefined criteria for the quadtree decomposition applied to bathymetry. The final DEM is a quadtree grid of indexed data (E,N,Depths) where E is the Easting and N is the Northing for each grid node.

To study the spatio-temporal dynamics of the seafloor, a time series analysis of the bathymetric surveys requires that the depths be expressed as the grid of depth values and their variances. To account for the morphological changes over time, a time ordered grid for each survey must be able to capture the changes between the intervals of each bathymetric survey. The purpose of the time ordered analysis of the quadtree decomposition process is to ensure that the grid resolution of the latest DEM in time is adaptive based on the changing dynamics over that period. To capture and retain the changing dynamics in time and space, with each new survey, the new DEM is automatically updated using the previously decomposed gridded structure as the input for the new decomposition in time. This results in the latest DEM structure capturing the evolution of the bed dynamics and hence is always representative of the

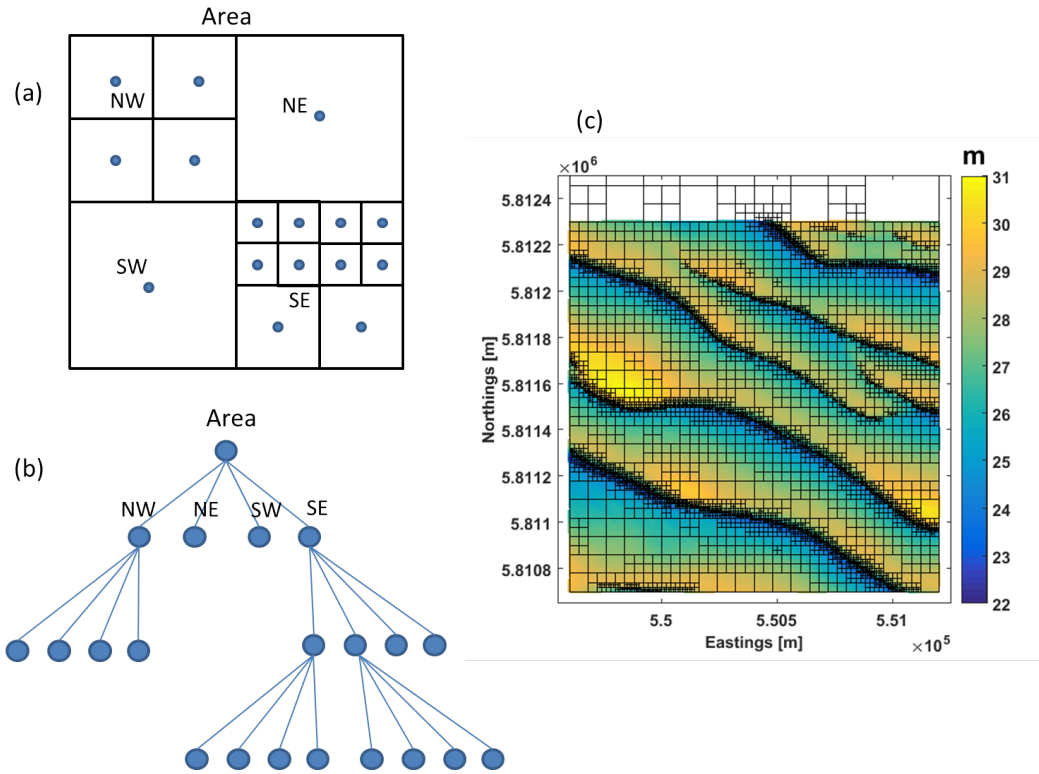


Figure 2: Example of quadtree decomposition applied to an MBES dataset. Sub-figures show (a) Subdivided quadrants of an area, (b) Quadtree representation of the quadrants. (c) Final quadtree decomposition output of an MBES dataset

latest changes in the seafloor depths (refer to figure 3). This cycle continues as new survey (data) becomes available. This is a new approach and major advantage to survey planning and risk management since the trends in seafloor features are not always well defined by a regular gridded structure where the resolution of the final estimated surface is either too large or too small and does not take into account the changes of the seafloor depths or other parameters of interest. This new time series algorithm will retain the important features such as the crests, troughs and bifurcations in all the DEMs used in the time series analysis.

Applying the quadtree analysis to a time series of bathymetric surveys results in the latest quadtree decomposition grid being used as input for the next epoch as shown in figure 3. The output quadtree structure represents changes from the previous survey where some grid cells may have been split further. If in the latest quadtree decomposed grid the cells are split further than in the previous epochs, then in the previous epochs the corresponding grid cells that were larger will now get the new grid structure with the same depth value as previously indexed. In this instance, the new grid cells will get the same value as the previous larger cell. This is justified since at the previous epochs, the variability and data density permitted the use of the same depth values. This results in the same gridded structure for each epoch which can be used in further spatial and temporal analysis methods.

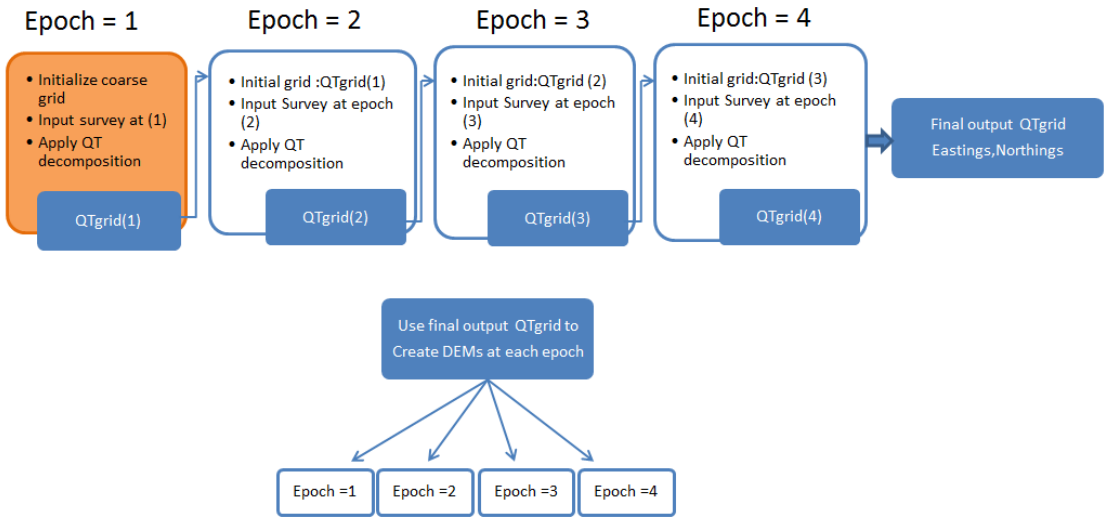


Figure 3: Multiple epoch, time series approach to the quadtree decomposition of a survey area.

3 Results

The quadtree decomposition method used to derive an adaptive, multiresolution grid is based on five criteria as listed in section 2. However, there are two very important selection criteria for optimal grid output. The first criterion is the density of observations since the data is collected using both SBES and MBES. The other criterion is the variability in observations given by the σ_{obs} in each grid cell which is a representation of the spatial variability. The experimental results show that the quadtree decomposition algorithm creates a dynamic DEM based on the data density and data variability. Smaller grid sizes are resolved in areas of high variability and larger grid sizes in areas of low variability as shown with the example of a SBES and MBES dataset where there is high variability in the depths (sandwaves are present) and the data types are of different density (refer to figures 4 and 5). Also when decomposing high resolution datasets such as MBES data, it allows for data reduction when variability in the depths is low as seen with the sloping seafloor in figure 6. This added value of the quadtree algorithm is demonstrated in figures 4, 5 and 6 for an area with different seafloor characteristics which include areas where sandwaves are present versus sloping seabed, represented by different data densities and a σ_{th} value of 0.3 m. Aside from the improvement to the storage and processing efficiency, which is outside the scope of this paper, the main outcomes of the study will be the level of detail and uniform accuracy of the valuable regions or dynamic areas of importance for further queries and analysis using the adaptive, variable resolution DEM.

3. RESULTS

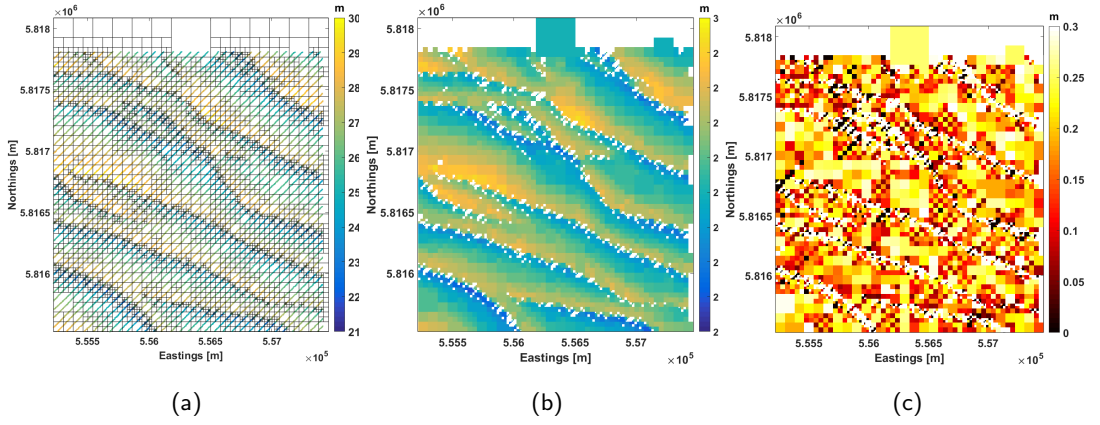


Figure 4: Quadtree decomposition results for a SBES survey (low density of observations) where sandwaves are present based on $\sigma_{th} = 0.3$ m. (a) Decomposed grid cells. (b) Indexed P_{10} depth values representative of each grid cell. (c) σ_{obs} .

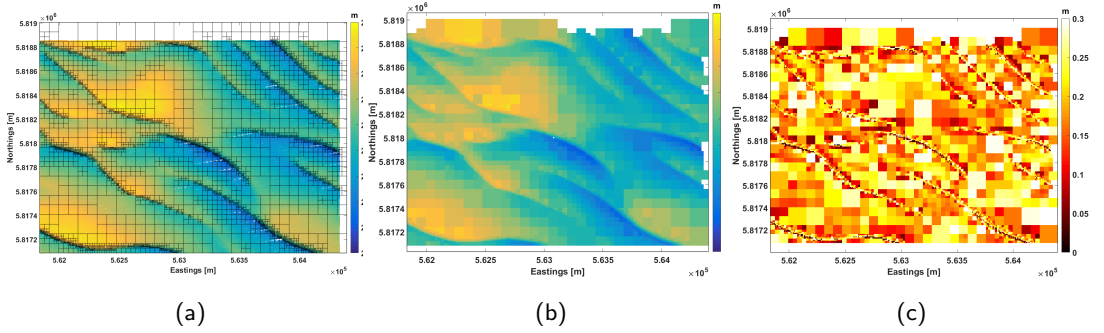


Figure 5: Quadtree decomposition results for a MBES survey (high density of observations) where sandwaves are present, based on $\sigma_{th} = 0.3$ m. (a) Decomposed grid cells. (b) Indexed P_{10} depth values representative of each grid cell. (c) σ_{obs} .

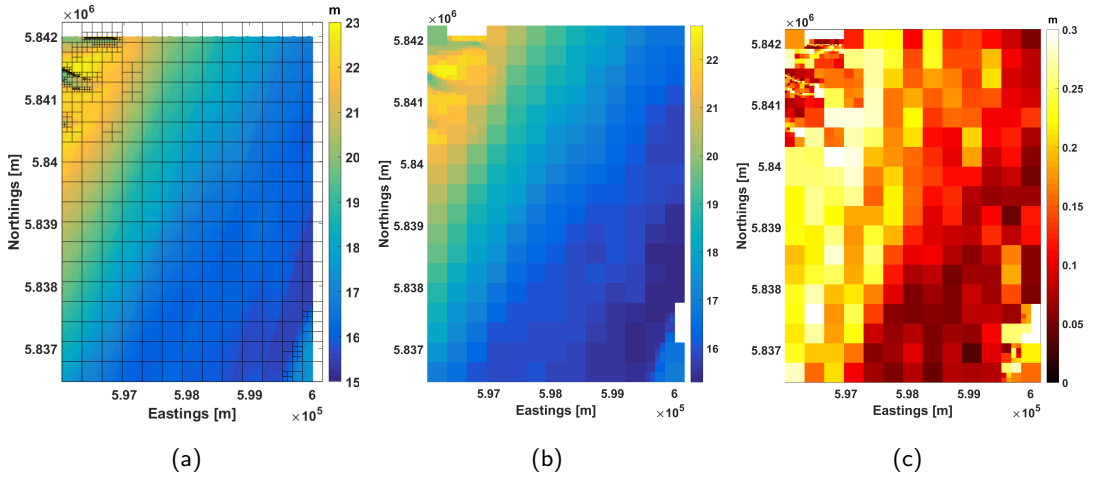


Figure 6: Quadtree decomposition results for a MBES survey where there is less variability. (a) Decomposed grid cells. (b) Indexed P_{10} depth values representative of each grid cell. (c) σ_{obs} .

3.1 Optimal Criteria and threshold selection

The method proposed in Section 3 demonstrated that without loss of data or detailed information about the underlying features of the seafloor, a dynamic DEM can be developed for further use in spatial and temporal analysis. To further quantify the advantages of the method, the number of grid nodes resulting from different σ_{th} values (refer to table 2) is compared to regular, fixed grid sizes (refer to table 1). For this, the same area as in figure 5 is used with a total number of original observations of 288,245. With a $\sigma_{th} = 0.1\text{m}$ the highest resolution DEM which accounts for the spatial variability is produced with an 88% reduction in the number of grid nodes as compared to a 38% reduction achieved with the fixed grid resolution of $5 \times 5\text{m}$. The quadtree decomposition with a $\sigma_{th} = 0.1\text{m}$ results in an accurate DEM, without loss of details by storing approximately half the number of grid nodes compared to a regular $5 \times 5\text{m}$ grid.

Table 1: Number of grid nodes for fixed, regular grid sizes for the same area.

Fixed, Regular Grid Cell Sizes (m)						
320 x 320	160 x 160	80 x 80	40 x 40	20 x 20	10 x 10	5 x 5
80	234	792	2944	11,557	45,107	178,712

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Table 2: Quadtree decomposed grid cell sizes and the resulting number of grid nodes for different σ_{th} values.

σ_{th} (m)	Quadtree Decomposed Grid Cell Sizes (m)							Total Nodes
	320 x 320	160 x 160	80 x 80	40 x 40	20 x 20	10 x 10	5 x 5	
0.1	0	0	60	700	5194	8573	19,052	33,579
0.2	0	8	222	1416	1470	2624	6944	12,684
0.3	3	26	267	806	853	2282	1672	6006
0.5	1	76	326	299	578	712	0	1992
1.0	35	32	61	67	36	0	0	231

Unlike the variability of the original data set, the variability of the quadtree grid is assumed to be only the result of the uncertainties of the observations. If the natural spatial variation within a grid cell would not be negligible, the quadtree process would need to continue. For the value of σ_{th} , this means that it should be directly related to the uncorrelated part of the error budget of σ_{obs} . The largest sources of error (water level reduction, sound speed profile) could be assumed constant within a grid cell, so σ_{th} needs to be smaller than the stated total vertical uncertainty of IHO order 1 specifications and equal to the combined effects of the uncorrelated components within that TVU.

The accuracy and quality of the DEM is essential for accurate risk assessment for safety of navigation which will be done in further research when secondary information such as shipping intensity, ship draughts, objects on the seafloor are considered. The algorithm is tested with many trials of different σ_{th} values before arriving at a suitable, fixed threshold value for this application. The selection of the optimal criteria can be seen as an experimental trial and error process to achieve the desired results from the algorithm by varying the different criteria and σ_{th} values.

The main findings of the data sets and application under consideration, suggest that the optimal criteria to be used will be the following:

1. Define an initial coarse, square grid of size 320m to capture the scale of the sandwave dynamics.
2. G_{min} which is also referred to as the stopping criteria for the splitting as 5 m. This was selected to capture the small features to be detected for risk assessment.
3. N_{min} in an area to allow splitting as 5. This number was selected since it is likely that there will be at least one observation left, however this is still not guaranteed in areas where there is lower than expected observations.
4. N_{max} in a grid cell as 30,000. This large number was chosen, in the event that there are that many observations in a grid cell. In that case, even if the $\sigma_{obs} < \sigma_{th}$ and there are more that the N_{max} , the splitting will continue.
5. σ_{th} of the observed parameter as, $\sigma_{th} = 0.1$ m. This was chosen for a more accurate, homogeneous DEM surface representation that will be used in further analysis.

Splitting is based on how the homogeneous areas can be described. Here the homogeneous areas are described in terms of the σ_{obs} . In addition to this, there must be a stopping criterion which is the G_{min} value. The indexed depths are given as the P_{10} value which gives a better indication of the distribution of the data. The mean of the values were considered to be too simplistic and does not represent the proper distribution of the depths values. Additionally, the σ_{th} value can be determined empirically to support the target requirements of the national hydrographic offices (in this case the Netherlands Hydrographic Service) in terms of the deviations.

3.2 Validation

An additional validation step was done using a MBES survey as an example for different σ_{th} values. Figure 7 shows how the selection of the cross-sections each in the Easting and Northing directions were carefully selected to show the effects of the σ_{th} criterion on the resulting accuracy of the homogeneous surface. Figures 8 and 9 show the original observations and the indexed, P_{10} value of the depths after the quadtree decomposition for different σ_{th} values 0.1 m, 0.2 m, 0.3 m, 0.5 m and 1.0 m. The smaller the threshold value leads to the dispersion of the individual depth observations from the P_{10} value being reduced. Therefore a more accurate DEM of the seafloor is obtained. This is validated in figure 10 showing the deviations of the observations from the P_{10} value for each grid cell and the corresponding P_{90} value of the deviations for each σ_{th} .

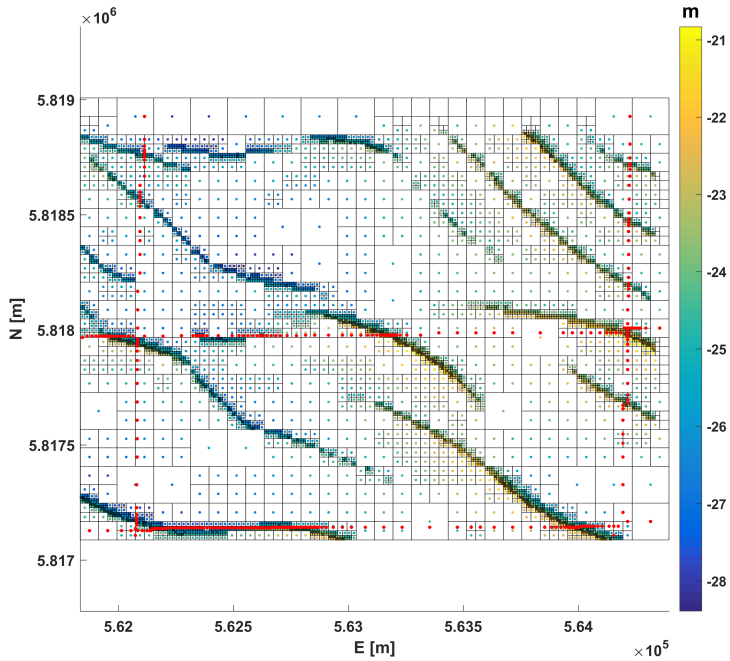


Figure 7: Example showing the selection of grid nodes along cross-sectional profiles in the E and N directions.

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Decreasing the value of σ_{th} , the P_{10} value is closer to the original observations. Values for the σ_{th} greater than 0.3m results in more than 97% data reduction (refer to table 1). The cross-sectional analysis shows there is loss of detail in the seafloor representation with σ_{th} values greater than 0.3m (refer to figures 8 and 9). Also, the peaks, troughs, lee and stoss sides of the sand wave features are not properly captured, resulting in an inaccurate DEM of the seafloor. The right choice of σ_{th} ensures the accuracy of the variable resolution grid (DEM) as the final representation of the seafloor. This is important for further analysis procedures of the sand wave parameters and detection of sandwave dynamics applied to risk assessment. This is especially useful for the peaks when important factors such as the shipping risks and objects on the seafloor need to be considered. Also the interests for marine engineering application for the spatial and temporal deformation analysis of the troughs of the sandwaves and how it affects the laying of pipelines, maintenance and other engineering applications where the dynamics of the troughs are important. Figure 10 shows the deviations of the individual observations from the indexed P_{10} depth value within each grid cell for the cross-section shown in figure 8.

Additionally, the P_{90} value of the deviations is computed for σ_{th} value 0.7m. Figure 11 gives an indication of the accuracy of the approximated surface for different values of σ_{th} . Figure 11 indicates that indeed the errors increase as the σ_{th} increases. The σ_{th} values lower than 0.3m lead to low truncation errors due to the assumption that the variability of the quadtree grid is due to the uncertainties of the observations only. The distribution of the errors continue to increase until they converge at around σ_{th} equal to 0.6m. This convergence can be explained essentially due to effect that the σ_{th} values greater than around 0.7m matches the amplitude of the sandwave features. The remarkable increase in errors greater than a threshold value of 0.3m can therefore be explained by the natural spatial variability of the depths within each grid cell.

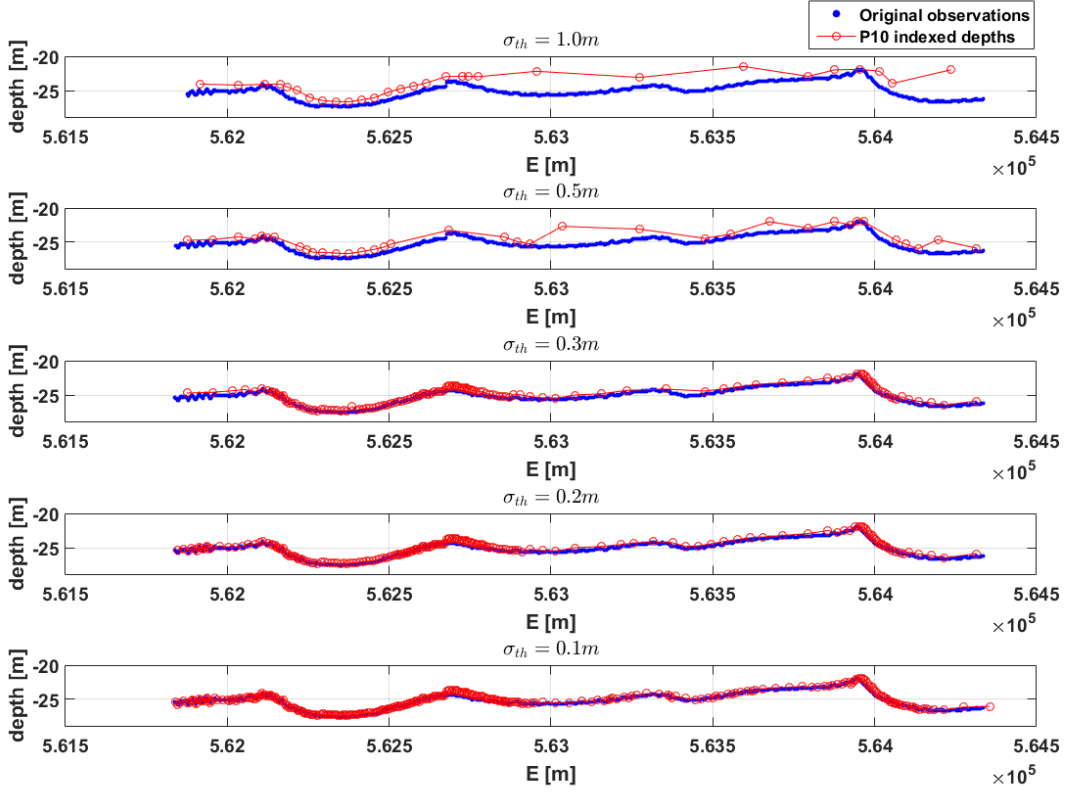


Figure 8: Depth profile (leftmost vertical cross-section as shown in figure 7) comparing the Quadtree decomposition results of indexed depths to the original observations for different σ_{th} values of $0.1m$, $0.2m$, $0.3m$, $0.5m$ and $1.0m$.

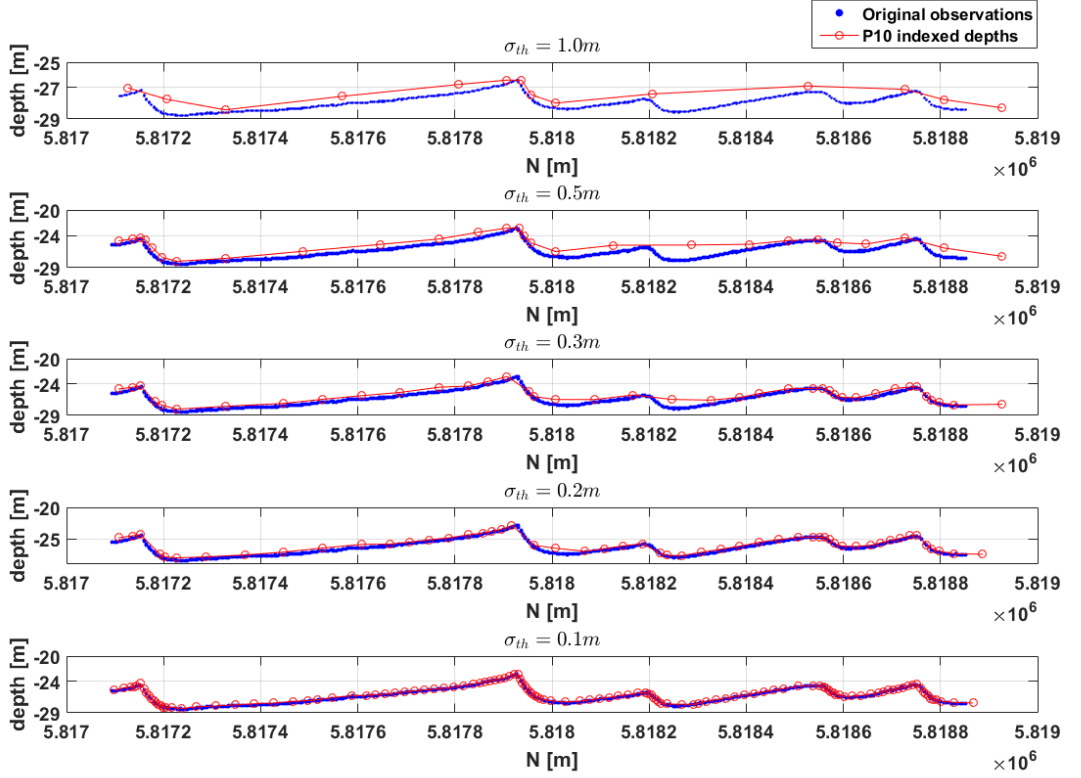


Figure 9: Depth profile (last horizontal cross-section as shown in figure 7) comparing Quadtree decomposition results of indexed depths to the original observations for different σ_{th} values of 0.1m, 0.2m, 0.3m, 0.5m and 1.0m.

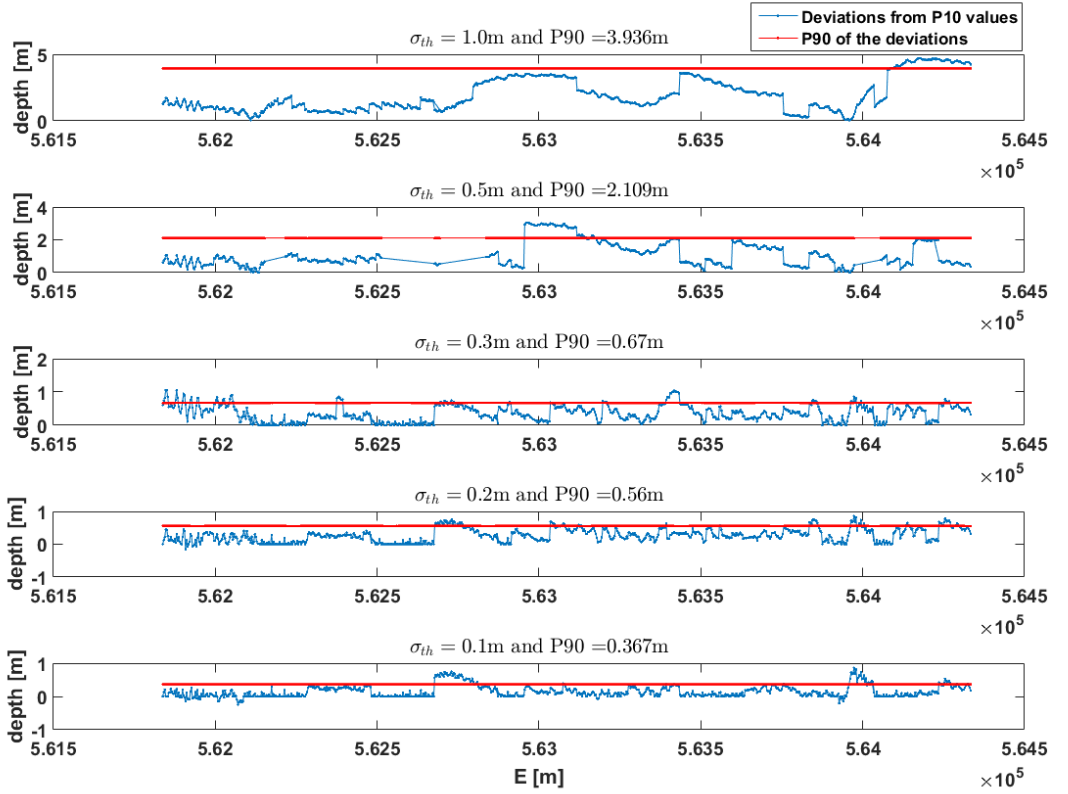


Figure 10: Deviations of the observations from the indexed P_{10} value for the cross-sectional profile in figure 8 and the P_{90} value of the deviations (red).

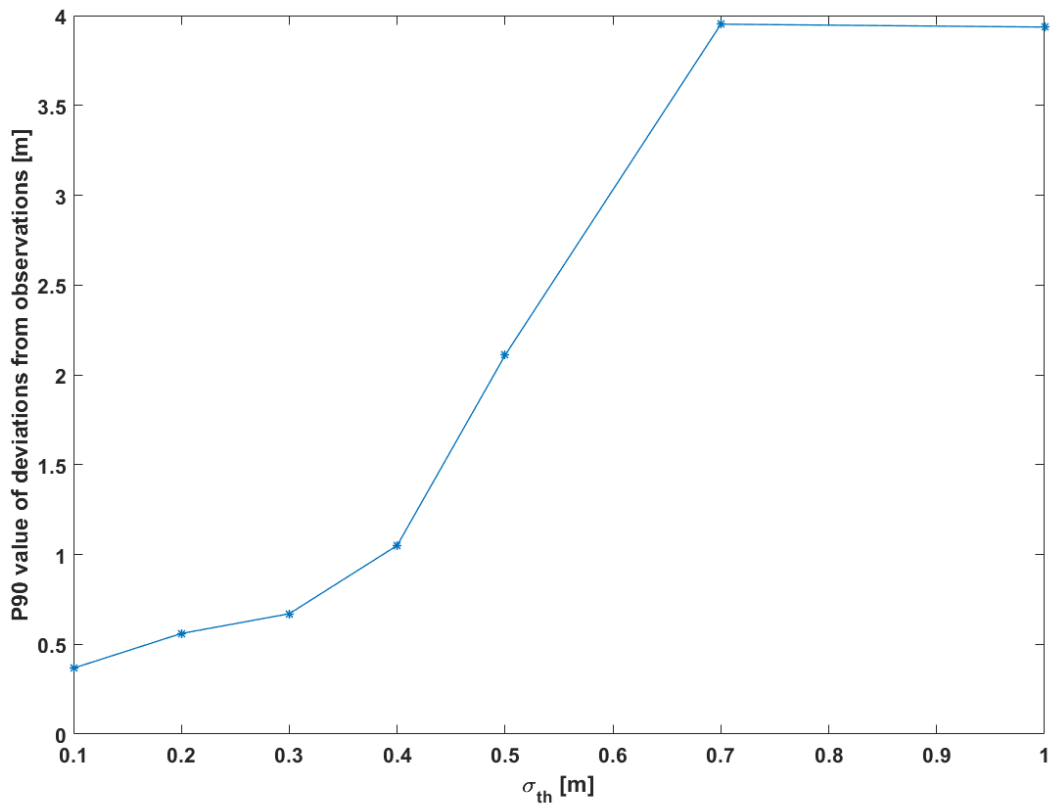


Figure 11: Effect of the different σ_{th} values on the P_{90} value of the deviations.

4 Concluding Remarks

This paper has presented a quadtree approach to obtain an adaptive, accurate variable resolution DEM of the seafloor using bathymetry data which is heterogeneous in time and space. This approach improves the creation of a dynamic, homogeneous DEM as the basis for developing a probabilistic map which assigns the hydrographic survey frequencies of the Netherlands Continental Shelf. The method and optimized approach ensures the following:

1. The final DEM accounts for the spatial and temporal aspect of the seafloor dynamics ensuring that different epochs resulting in different grids are based on the same final DEM.
2. This quadtree decomposition approach provides optimal use of the available bathymetric data for the Netherlands Continental Shelf.
3. In the case of high resolution datasets (MBES data), data reduction is achieved whilst accounting for the data variability without loss of detail. This leads to better computational efficiency by improving the sampling density of the observations.
4. The variable resolution DEM is created using a set of predefined criteria which are flexible and ensures that the DEM is adaptable and can be modified based on the intended use of the end user.

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