An equivalent bottom for navigation above irregular bottoms

M. Vantorre[(1)], E. Lataire[(1)], M. Candries[(1)], J. van Doorn[(2)], and D. van Heel[(2)]

1. Ghent University, Division of Maritime Technology, Ghent, B – marc.vantorre@ugent.be
2. MARIN, Wageningen, NL

Abstract

An algorithm is suggested for converting the raw sounding data of a sea bottom with local depth variations into manageable dredging maps and electronic chart systems (ECS). The resulting “equivalent bottom” can be considered to offer a comparable safety as a horizontal bottom with the same depth, and therefore does not jeopardize safe sailing behaviour of a vessel, even if the bottom is locally more shallow than the equivalent depth. On the other hand, accounting for the most shallow spots of a navigation area would result into a lower allowable draft for the vessels or a significant increase of dredging costs. The proposed algorithm has been developed for the access channels for maritime shipping traffic connecting the Western Scheldt estuary with open sea, which is partly characterized by ripples in the bottom. The more theoretical outlines of the principles behind the concept of the equivalent bottom are explained, followed by a more pragmatic approach offering the advantage of a more straightforward implementation.

1. INTRODUCTION

In 2012, a research project was carried out on behalf of the common Dutch-Flemish Nautical Authority to determine a scientifically based algorithm to create ECS-charts in the access channel to the mouth of the Western Scheldt. This research was carried out by Ghent University (Maritime Technology Division) and MARIN.

The presented research suggests an algorithm that converts the raw sounding data of a bottom with local depth variations into manageable dredging and ECS-charts. In general, the conversion of millions of data points resulting from multi-beam soundings to a readable chart is a challenging task. A conservative algorithm, based on the shallowest measured points of the navigation area, will result into safe charts, but will lead to a lower allowable draft for the vessels or a significant increase of dredging costs. A too progressive algorithm, on the other hand, may jeopardise shipping traffic safety.

The present research looks for a compromise by defining the “equivalent bottom”, which can be considered to offer a comparable safety as a horizontal bottom with the same depth, and therefore does not jeopardize the safe sailing behaviour of a vessel, even if the bottom is locally more shallow than the equivalent depth.

The proposed algorithm must take account of relevant parameters that determine a ship’s safety during navigation in restricted channels. The under keel clearance should be sufficient to keep the probability of bottom touch due to squat, response to waves and other causes of vertical ship motions acceptably low and to guarantee the controllability and manoeuvrability of the ship. On the other hand, the conversion of raw sounding data to charts must be possible with reasonable resources, which implies that the algorithm should be robust and simple. This suggests an algorithm that converts the original raw sounding data into one equivalent value for each grid cell. The vessels that use this equivalent water depth have enough information to transit the seaway in a safe manner. Also for maintenance dredging purposes, the resulting charts are sufficiently detailed to localize critical zones but neglect local spots without relevance.

The equivalent water depth concept is even more relevant in some very specific regions in the Belgian territory of the North Sea characterised by rippled bottoms and/or marine dunes. It is in this type of bathymetry that different algorithms can result in different water depths plotted on the charts and, hence different levels of safety.

2. BOTTOM SURVEY IN *SCHEUR OOST* ACCESS CHANNEL

The dredged channels Scheur West/Oost and Wielingen are of great importance for the shipping traffic to the Western Scheldt giving access to the ports of Flushing (NL), Terneuzen (NL), Ghent (B) and Antwerp (B). These channels are partly located on Belgian and Dutch territory, so that bottom survey is performed under the responsibility of both Rijkswaterstaat and the Coastal Department of the Flemish Government. Although both services make use of the same survey techniques, i.e. multi-beam sonar combined with a Real Time Kinematic positioning system (RTK), several post-processing algorithms can be applied to reduce the huge amount of measurements (5 to 10 data points per square meter) to a limited but relevant number that can be displayed on nautical charts and dredging maps. After filtering the data and removing irrelevant spikes, basic statistical characteristics of the measurements within grid cells of 1 m² are determined, such as average (avg1), minimum (min1), standard deviation (std1).

Further data reduction can be performed by many different algorithms. Over squares of $n*n$ 1m² grid cells, either the average or the minimum value can be taken of the n^2 individual average or minimum values; the results are denoted min*n*_min1, avg*n*_min1, min*n*_avg1, avg*n*_avg1.

In areas with a relatively flat bottom, the results are less sensitive with respect to the reduction algorithm. However, some areas are characterized by the formation of ripples with crests perpendicular to the main current direction , a "dune length" of 0.6 to 30 m and a top-to-crest height between 0.4 to 1.5 m. In such areas, different algorithms may lead to significantly different values.

An area of 419 * 464 m² in the access channel *Scheur Oost* was selected as a test case. The results of multi-beam soundings was performed by Flemish Hydrography; the 2.3 10^6 measurements, reduced with the avg1 algorithm, are displayed in Figure 1. The area contains some rather flat, uniform zones at the edges (north and south) of the channel, and a central zone with clear ripples. Bottom samples taken in this area by Rijkswaterstaat revealed that the bottom is composed of mostly clay or sand; in the troughs between the ripples mud is sometimes found. The bottom can therefore be considered as solid, non-penetrable for navigation.

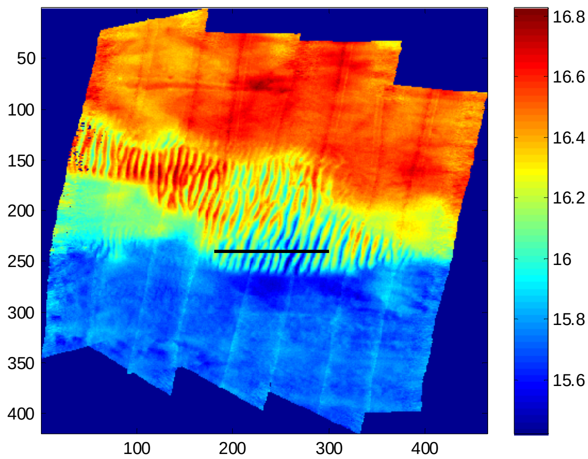

Figure 1. Test section in channel *Scheur Oost*: average values of the multi-beam soundings per grid cell of 1*1 m² (avg1). Horizontal and vertical scale: distance in m (north up); color scale: depth in m with respect to LAT.

A cross section along the east-west line shown in Figure 1 provides a typical view of the ripples, with a height of up to 0.6 m and a wave length of 7 to 10 m, see Figure 14. The difference between avg1 and min1 fluctuates between 0.04 m and 0.20 m, the lower values occurring for grid cells in the troughs and on the crests, the higher values on the slopes. Also the standard deviation over the grid cells (std1) varies correspondingly.

The values for avg1 – min1 and for std1 appear to be very small in uniform zones and on the ripple crests and troughs, so that the average value over 1 m² square grid cells, avg1, was agreed to be a suitable starting point for further analysis. The question remains how these avg1 values can be reduced to suitable values for larger areas.

3. EQUIVALENT BOTTOM FOR DETERMINISTIC CHANNEL ACCESS POLICY

3.1 Analysis of available UKC

Deep-drafted vessels are allowed to navigate in the channels giving access to the Western Scheldt mouth and the Flemish coastal harbours (see Figure 2) based on their gross under keel clearance (UKC), i.e. the difference between the water depth (as a function of place and time) and the static draft of the ship at rest in still water. For Scheur and Wielingen, a gross UKC of 15% of the ship's draft is required, for Pas van het Zand and Western Scheldt 12.5% is needed. These percentages are considered to be sufficient as an allowance for the vertical motions of the ship and as a margin for the uncertainty on the level of the bottom, the free water surface and the ship's draft. The depth of the *Scheur* channel varies between 15.4 m and 16.2 m below LAT, which implies that at zero water level ships can pass with a draft of 13.4m to 14.1m, leaving a gross UKC of 2.0 – 2.1 m.

Taking account of the type of vessels, their speed range and the local wave climate, a rough sub-division of this gross UKC can be made.The following fractions of the gross UKC are assumed to be required for the different types of allowance:

- Squat: abt. 6.0% abt. 0.8 m
- Waves: abt. 7.5% abt. 1.0 m
- Other: abt. 1.5% abt. 0.2 m

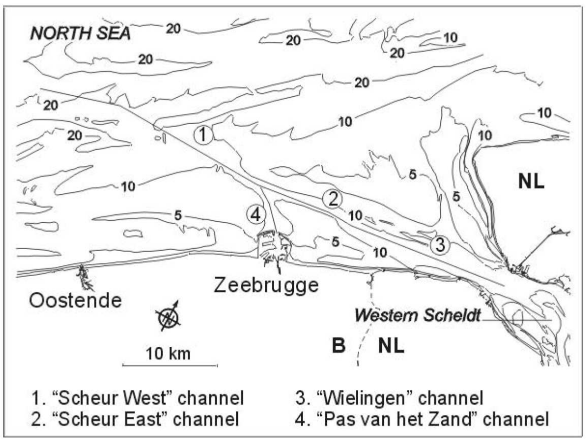

Figure 2. Access channels to the Western Scheldt Estuary and the Belgian coastal harbours (Vantorre et al, 2008).

Assuming that a gross UKC of 15% of the ship's draft offers a sufficient safety margin with respect to a horizontal, flat bottom, the effect has to be estimated of a bottom with variable depth on the required UKC.

3.2 Effect of depth variations on squat

The sinkage and dynamic trim of a ship due to her own forward motion depends on a large number of parameters: ship's speed, ship geometry, water depth, channel bathymetry, … (Briggs et al, 2010). Many empirical methods an formulae have been developed for estimating squat. The water depth is an important parameter in this respect: a decrease of water depth results into a stronger return flow, which increases the sinkage of the water level around the ship and, hence, the ship's squat. The effect of bottom variations has been investigated only sporadically; relevant studies have been carried out at BAW (Hamburg) on the effect of bottom ripples on the squat of container vessels (Uliczka and Kondziella, 2003, 2006). It could be concluded that the squat of a ship navigating above a ripple bottom is approximately equal to the squat above a horizontal bottom at the average level.

A ship navigating above an arbitrary variable bottom will therefore experience less squat compared to a situation of a horizontal bottom at a level corresponding with the most shallow point of the bottom. This squat reduction allows a somewhat smaller UKC with respect to this shallowest point, or allows to define an equivalent bottom level resulting in the same margin with respect to this shallowest point. This is illustrated in Figure 3:

- The sinkage of a ship due to squat above a real, variable bottom can be approximated by the sinkage the ship would experience above a horizontal bottom with a depth equal to the average bottom profile.
- The squat the ship would experience if navigating above a horizontal bottom above the shallowest point of the channel is greater than the squat above the real bottom.
- As a result, the margin between the keel and the bottom is larger in the case of the real bottom compared to the case of the horizontal bottom through the shallowest point.

- The equivalent bottom (with respect to squat) can therefore be defined in such a way that the real margin is kept. The equivalent bottom is located below the minimum bottom level; the level difference equals the difference in squat between the real and the minimal bottom.

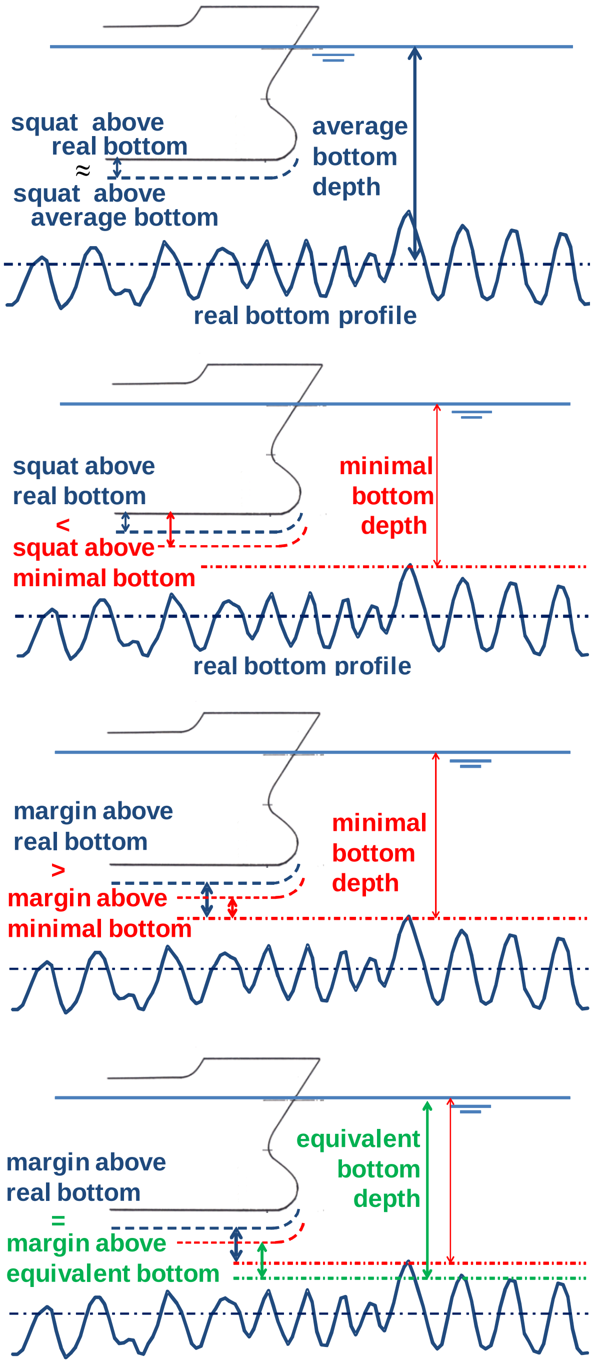

Figure 3. Equivalent bottom with respect to squat.

The effect of an average increase of the water depth on the squat of a ship within the mentioned draft range with a gross UKC of 15% resulting in a squat of 0.8 m was investigated for a number of realistic cases. It was concluded that, in the considered cases, the difference between the squat above a horizontal bottom at a level h_{min} and the squat above a real bottom with average level h_{avg} is about 10% of the difference between both levels.

This leads to the following expression for the equivalent bottom with respect to squat:

$$\begin{aligned} h_{eq}^{(squat)} &= h_{\min} + 0.10\left(h_{gem} - h_{\min}\right) \\ &= 0.90 h_{\min} + 0.10 h_{gem} \end{aligned} \tag{1}$$

For a zone with ripples with a trough to crest height of 1 m, the reduction equals 0.05 m, which is only marginal. It is important to mention that the average depth should be considered over an area with dimensions comparable to the horizontal dimensions of deep-drafted vessels.

3.3 Vertical ship motions due to waves

Principally, the fraction of the UKC needed for allowing vertical wave induced ship motions can only be determined in a probabilistic way, as the maximum wave height that will be encountered during the passage of a vessel cannot be predicted with certainty. One can only make predictions about the probability of exceeding a certain level; for such predictions the significant wave height Hs has to be known. This principle can be extended to all (linearly dependent) consequences of wave action, such as vertical ship motions. The vertical position of a point of the ship's keel oscillates about an average level; the time series of the instantaneous level of this point is characterized by a significant amplitude, which is 2.0 times the standard deviation σ_{VM} of the vertical position. The knowledge of this significant amplitude and the fraction Z_{VM} of the UKC available for wave induced motions allows to calculate the probability of bottom contact, see Figure 4. As this study aims at defining the equivalent bottom within the frame of the present deterministic access policy, the quantitative value of this probability is not considered, but realistic values for Z_{VM} and σ_{VM} will be taken as a starting point.

Figure 4. Vertical ship motion above horizontal bottom

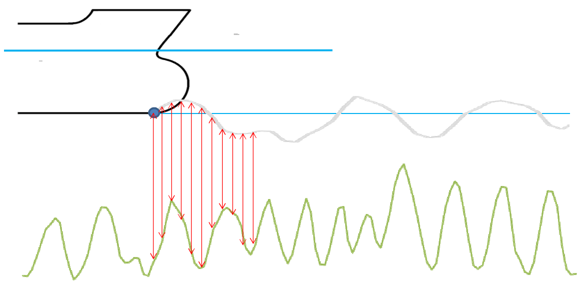

Figure 5. Relative vertical motion of a point of the ship's keel with respect to a variable bottom.

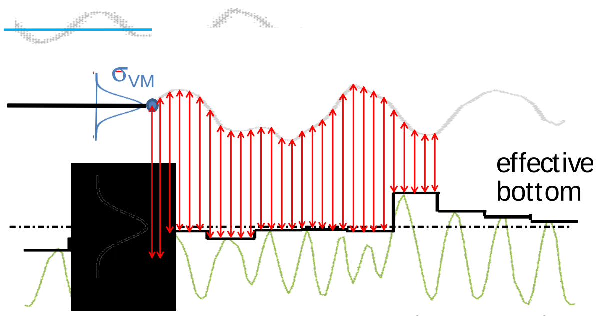

Figure 6. Relative vertical motion of a point of the ship's keel with respect to the effective bottom.

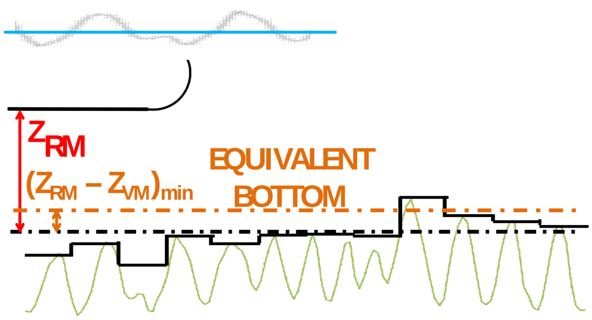

Figure 7. Equivalent bottom with respect to wave induced motions.

Instead of the absolute vertical motion of (a point of) the ship, the relative motion of such a point with respect to the bottom with variable depth can be considered, based on superposition of the the vertical oscillations of the ship and the vertical oscillations of the bottom (see Figure 5). However, this superposition does not make sense in a zone characterized by short ripples, as an arbitrary point of the ship's keel cannot fully make use of the vertical space between the ripple crests.

For this reason, the real bottom is replaced by a so-called *effective bottom*. The area is subdivided in grid cells of 10*10m²; the effective bottom in each grid cell is a horizontal plane through the min10avg1 value. This means that the real bottom is replaced by the shallowest point based on the average depth of all 100 1*1 m² grid cells of which every 100 m² cell is composed, see Figure 6.

Over a larger area, with dimensions which are relevant to the ship's main horizontal dimensions, an average effective depth h_{avg}^{eff} and a standard deviation σ_B^{eff} can be defined. For this study, rectangles of 100*50 m² were considered, containing 50 cells of 10*10m².
The relative vertical motion of the ship with respect to the effective bottom oscillates around a mean value with a standard deviation σ_{RM}^{eff} (RM denoting "relative motion"), defined as:

$$\sigma_{RM}^{eff} = \sqrt{\sigma_{VM}^{\;2} + \sigma_B^{eff\;2}} \tag{2}$$

Above a horizontal bottom, it assumed that the UKC fraction Z_{VM} results in a sufficient degree of safety for allowing a significant absolute vertical ship motion with standard deviation σ_B^{eff} . An equal degree of safety would be provided by a margin Z_{RM} between the average levels of the ship's keel and of the effective bottom equal to:

$$Z_{RM} = Z_{VM}\left(\sqrt{1+\left(\frac{\sigma_B^{eff}}{\sigma_{VM}}\right)^2}\right) \tag{3}$$

Tdhe required clearance between the average level of the ship's keel and the average effective bottom, Z_{RMmin}, is apparently larger than the required clearance with respect to a horizontal bottom, Z_{VMmin}. A ship navigating above a horizontal bottom located at a vertical distance Z_{RMmin} – Z_{VMmin} above the average effective bottom would therefore experience the same degree of safety as she would have above a realistic, variable bottom. Thus, this level can be considered to be the *equivalent bottom* (Figure 7)

$$h_{eq} = h_{avg}^{eff} - Z_{VMmin}\left(\sqrt{1+\left(\frac{\sigma_B^{eff}}{\sigma_{VM}}\right)^2}\right) \qquad (4)$$

For the considered channel, Z_{VMmin} = 1.0 m and σ_{VM} = 0.25 m appear to be suitable estimations.

3.4 Provisional proposal for equivalent bottom

Combining the effect of a bottom with variable depth on squat and on the required clearance for wave induced motions, the following proposal can be formulated for the level of the equivalent bottom, to be determined in 50*100m² rectangles.

$$h_{eq} = h_{avg}^{eff} - 1.0\,\mathrm{m}\left(\sqrt{1+\left(\frac{\sigma_B^{eff}}{0.25\,\mathrm{m}}\right)^2}\right) + 0.10\left(h_{avg} - h_{\min}\right) \qquad (5)$$

with

h_{avg}^{eff} = avg50_100min10avg1:

average value of the 50 minimum values of the depth in each of the 10*10m² grid cells composing the 50*100m² rectangle;

σ_B^{eff} = std50_100min10avg1:

standard deviation of these 50 minimum values;

$h_{\min}$ = min50_100min10avg1:

minimum of these 50 minimum values;

h_{avg} = avg50_100min10avg1:

average of these 50 minimum values;

the minimum values of the 10*10m² grid cells being based on the average values determined within each 1*1m² grid cell.

For the selected test section, Figure 8 to Figure 11 show the values for h_{avg}^{eff}, $h_{\min}$, σ_B^{eff} and h_{eq}.

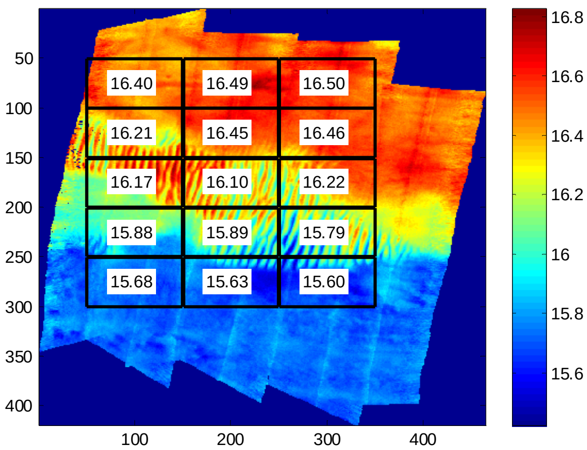

Figure 8. Test section: average effective bottom depth avg50_100min10avg1, with avg1 in the background.

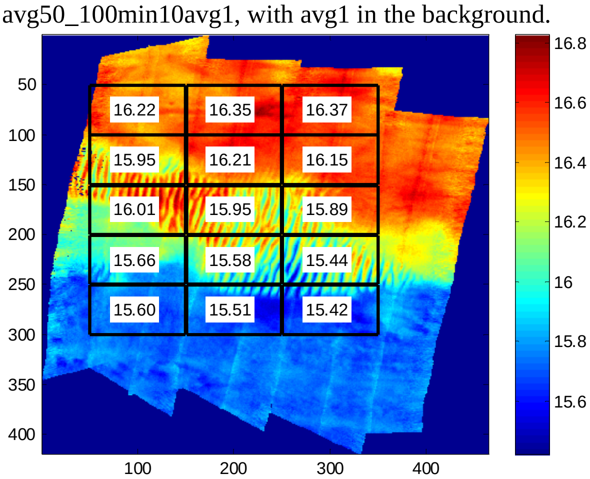

Figure 9. Test section: minimum effective bottom depth min50_100min10avg1, with avg1 in the background.

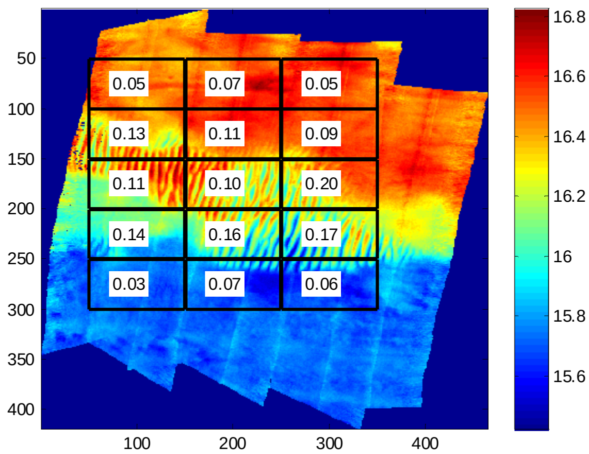

Figure 10. Test section: std50_100min10avg1 values, with avg1 in the background.

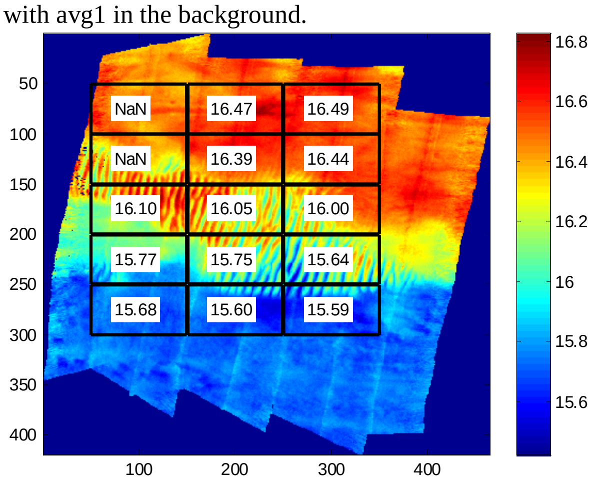

Figure 11. Test section: eq50_100 (equivalent bottom), with avg1 in the background.

4. PRACTICAL IMPLEMENTATION

Although the calculation of the equivalent bottom as described in section 3 only requires average values, minimum values and standard deviations over grid cells, the proposed algorithm deviates considerably from the present methodology for analyzing multi-beam surveys. For this reason, an alternative way of representing the bottom was sought.

The easiest way to reduce the large number of measurements is to consider average values over square grids of $n*n$ m² (avg$n$). The test section was analyzed in such a way, with n = 1,2,3,4,10. For each 50*100 m² rectangle, the minimum value of avg$n$, denoted min50_100avg$n$, was calculated and compared to the equivalent bottom depth eq50_100.

For the considered test sections, n = 3 appeared to result in slightly conservative values for the equivalent bottom depth, see Figure 12, so that avg3 was selected as an alternative practical way for calculating the equivalent bottom. Figure 13 illustrates that averaging the depth over 3*3m² squares leaves sufficient detail to recognize local variations.

The proposed avg3avg1 was implemented by the Flemish Hydrographic Services for issuing charts of the access channels in the Belgian North Sea for nautical purposes and managing dredging activities.

5. CONCLUSIONS

The implementation of the average over 3*3m² grid cells gives satisfactory results for the present practice. The implementation of the equivalent bottom as described in section 3.4 in the short run, on the other hand, is less straightforward. Firstly, the present analysis software does not directly allow such an implementation. Secondly, the implementation would imply a loss of too many details that are of interest for other shipping traffic and for dredging purposes.

In a long-term perspective, the principles of the effective bottom can be integrated in the implementation of a probabilistic access policy for deep-drafted ships, based on an acceptable probability of bottom touch (Vantorre et al, 2008). As the uncertainty of the bottom position, both spatial and temporal, contributes to the stochastic character of the relative motion of the ship's keel with respect to the channel bottom.

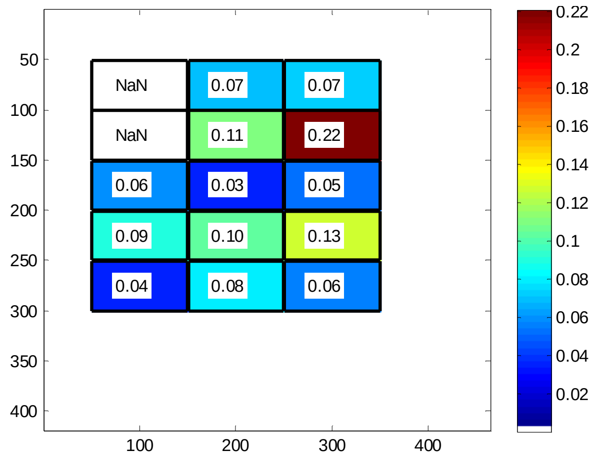

Figure 12. Test section: eq50_100 – min50_100avg3. Positive values suggest a conservative approximation of avg3 for the equivalent bottom depth.

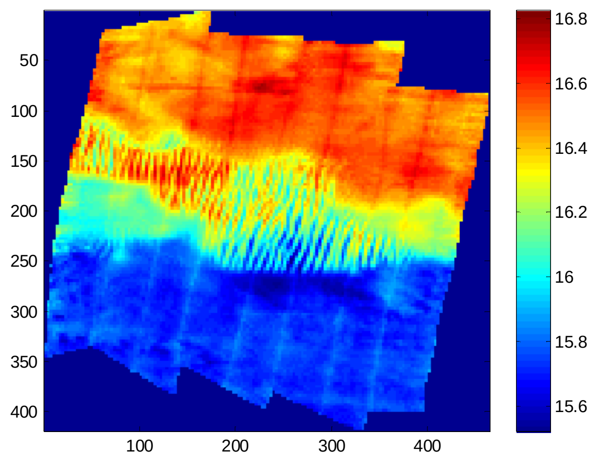

Figure 13. Test section in channel *Scheur Oost*: average values of the multi-beam soundings per grid cell of 3*3 m² (avg3avg1). Horizontal and vertical scale: distance (m, north up); colour scale: depth (m) referred to LAT.

6. ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the State of the Netherlands and the Flemish Government who commissioned the study.

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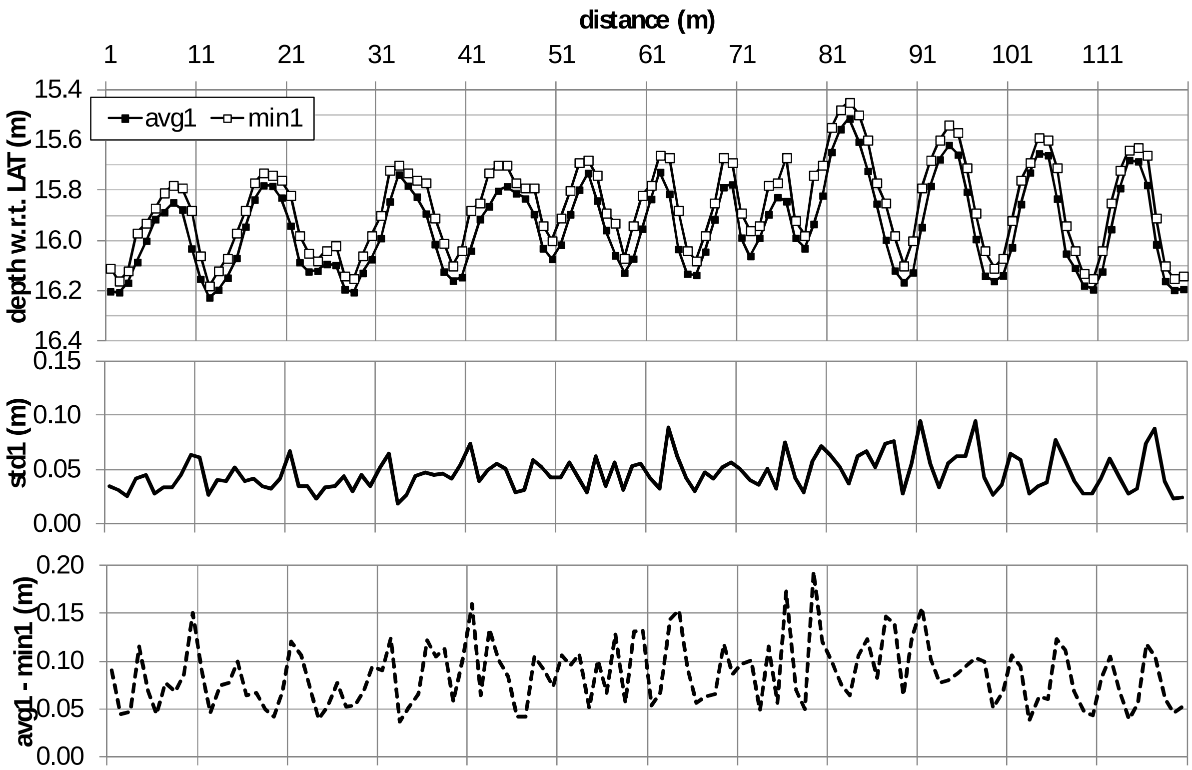

Figure 14. Variation of bottom depth parameter along line [240,180]-[240,300] (see Figure 1).