The Accuracy of the Depth Information of the Nautical Chart

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Abstract

The aim of this article is to contribute to the discussion on the description of the quality of depth information, as presented in the nautical chart, by combining the effects of the bathymetric uncertainty due to the line spacing, the dynamic behaviour of the seafloor and the accuracy of the measurements.

Because of the following developments, the quality description and assessment of depth information has become of increasing importance:

a. Higher accuracy requirements for hydrographic surveys as a result of increasing accuracy demands by the user of the nautical chart, due to the increasing draught in relation to the available water depth.
b. The development of new hydrographic positioning and depth measuring systems.
c. The improvement of positioning systems which enables the mariner to navigate with great accuracy.

The total deviation of the depth, reduced to chart datum, as depicted in the nautical chart, from the true (safe) least depth, can be described by the sum of:

- the error in the actual measurements, processing and manipulation of the data,
- the error as a result of the (limited) data density,
- the deviation caused by the dynamic behaviour of the seafloor.

Quantification of the statistical properties of the total error is described as the total accuracy. It is assumed that the total accuracy is a normal distribution with an expectation value equal to zero and a standard deviation of σ.

Allowance for the total accuracy of the depth information of the nautical chart, will enhance safe navigation. The implementation of this procedure is only possible when necessary data can be derived from older surveys, and future surveys are planned with respect to the total accuracy. It is recommended that the total accuracy, as defined in this article, should first be determined and applied in those areas where the available depth in relation to the expected draught is critical.

Résumé

Le but cet article est de contribuer à la discussion sur la description de la qualité de l'information relative à la profondeur, telle qu'elle figure sur les cartes nautiques, combinant les effets de l'incertitude provenant de l'espace entre les lignes de sonde, la dynamique du fond marin et la précision des mesures.

Etant donnés les progrès énumérés ci-après, la description et l'évaluation de la qualité de l'information relative à la profondeur ont acquis une importance croissante:

a. Nécessité d'une meilleure précision dans les levés hydrographique, résultant d'une exigence croissante de précision de la part des utilisateurs de cartes nautiques par suite de l'augmentation du tirant d'eau comparé aux profondeurs disponibles.
b. Développement de nouveaux systèmes de position et de mesure de profondeur.
c. Perfectionnement des systèmes de position qui permettent aux navigants une navigation d'une grande précision.

La déviation totale de la profondeur, réduite au datum de la carte et représentée sur la carte nautique, comparée à la profondeur minimale réelle (de sécurité) peut être décrite comme la somme de

- l'erreur dans les mesures réelles, dans le traitement et la manipulation des données,
- l'erreur résultant de la densité (limitée) des données,
- la déviation résultant de la dynamique de fond marin.

L'évaluation des propriétés statistiques de l'erreur totale est décrite comme la précision totale. On suppose que la précision totale est une distribution normale avec un valeur attendue égale à zéro et une déviation normale de σ.

La possibilité de disposer d'une précision absolue dans l'information relative à la profondeur dans les cartes nautiques, augmentera la sécurité de la navigation. La réalisation de ce procédé est seulement possible lorsque les données nécessaires peuvent être issues d'anciennes levées et que les levées futures sont programmées en respectant une totale précision. Il est recommandé que la précision totale, telle qu'elle est définie dans cet article, soit déterminée et appliquée en priorité aux zones dans lesquelles la profondeur disponible est critique comparée au tirant d'eau bâtiments.

Resumen

El propósito de este artículo es contribuir a las discusiones sobre la descripción de la calidad de la información de la profundidad, tal como debe ser presentada en las cartas naúticas, combinando los efectos de la incertidumbre debida a la distancia entre lineas de sondeo, el comportamiento dinámico del fondo del mar y la precisión de las medidas.

Debido a los progresos que se enumeran a continuación, la descripción y valoración de la información sobre la profuindidad ha adquirido una importancia creciente:

a. Necesidad de una mayor precisión en los levantamientos hidrográficos como resultado de una creciente demanda de preción por los usuarios de las cartas naúticas, debido al incremento de los calados con respecto a las profundidades disponibles.
b. El desarrollo de neuvos sistemas de posicionamiento hidrográfico y de medición de profundidades.
c. El perfeccionamiento de los sistemas de posicionamiento, lo que permite a los navegantes navegar con gran precisión.

La diferencia total entre el fondo, reducido al datum de la carta, representado en la carta y la verdadera mínima profundidad (de seguridad), se puede describir como la suma de:

- el error real de las medidas, procesado y manipulación de los datos,
- el erro resultante de la (limitada) densidad de datos,
- la desviación causada por la conducta dinámica del fondo marino.

La cuantificación de las propiedades estadísticas del error total se describe como la precisión total. Se supone que la precisión total es una distribución normal con un valor de esperanza igual a cero y una desviación normal de σ.

La provisión de una precisión total en la información sobre la profundidad de klas cartas naúticas, aumentarián la seguridad en la navegación. La implementación de este procedimiento es sólo posible cuando los datos necessarios se derivan de antiguos levantamientos, y se programan futuros levantamientos para una precisión total. Se recomienda que la precisión total, tal y como se define en este artículo, debe ser determinada y aplicada con prioridad en aquellas zonas en las que la profundidad disponible es crítica con repesto a los calados de buques.

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Preamble

1.1 Until recently the choice of depth measuring systems was limited; e.g. a single beam echosounder or a leadline. As a result of the introduction of new measuring systems, among which: swathe sounding, remote-sensing and in the near future surveys using models of the vertical component from DGPS for tidal reduction, an additional differentiation in the accuracy of the depth measurements is introduced, and thus a demand for an unambiguous approach to the accuracy of depth information of a hydrographic survey and the related nautical chart.

1.2 Single beam echosounders only measure a narrow path, directly under the track of the vessel. In a water depth of 20 metres and a line spacing of 50 metres, only 6% of the bathymetry is collected. A traditional survey is only a random spot check of the seafloor which leads to uncertainty with respect to the depths between the lines. This problem, combined with the requirements for higher accuracy standards, has initially resulted in reduction of the line spacing and has eventually led to the development of swathe systems. A swathe system will provide 100% coverage, but as the range of a swathe system is a function of the depth, it will not always be practical or economical to use a swathe system and therefore the traditional single beam echosounder survey, with its limitations, will continue to be an important survey technique.

1.3 The reliability of charted depths is a function of the dynamic behaviour of the seafloor. In certain critical sandwave areas (expected draught in relation to the existing water depth) the survey frequency should be high. However, survey capacity is not always sufficient to meet this need. In other words it may be assumed that the charted depths do not always represent the actual situation with the required accuracy. Determining a statistical value for the dynamic behaviour, and applying this value to the charted depths will enhance safe navigation.

1.4 A comprehensive description of the accuracy of depth information is given by the total accuracy (σ_{tot}).

$$\sigma_{tot} = \sqrt{(\sigma^2_{fm} + \sigma^2_{dd} + \sigma^2_{dyn})}$$

- σ_{fm}; the accuracy of the actual measurements, processing and manipulation of the data of a survey,
- σ_{dd}; the bathymetric uncertainty caused by the limited data density,
- σ_{dyn}; the bathymetric uncertainty caused by the dynamic behaviour of the seafloor.

1.5 The two most important reasons for the absence of a comprehensive quality description were:

a. lack of sufficient redundancy,
b. lack of computer capacity.

By adjusting hydrographic procedures and planning of surveys, redundancy can be increased. Due to developments in the automation industry, computer capacity currently covers the needs.

1.6 *Safe under keel clearance*
Apart from ship related and meteorological effects, a safe under keel clearance is a function of the accuracy of the depth information of the nautical chart.

1.7 The nautical chart is a compilation of hydrographic surveys which have been executed over several years with different line spacings and different measuring systems, from different platforms under different circumstances using different techniques and procedures.

1.8 An indication of the reliability of the depth information of a nautical chart can be derived from a "source diagram" as function of the year and the scale of a survey. However, the year and the scale only have a limited relation with the accuracy of the depth information.

1.9 The average user of the nautical chart will have no knowledge of the data density nor the accuracy of the measurements. It is also expected that the user will not have any knowledge of the dynamic behaviour of the seafloor.

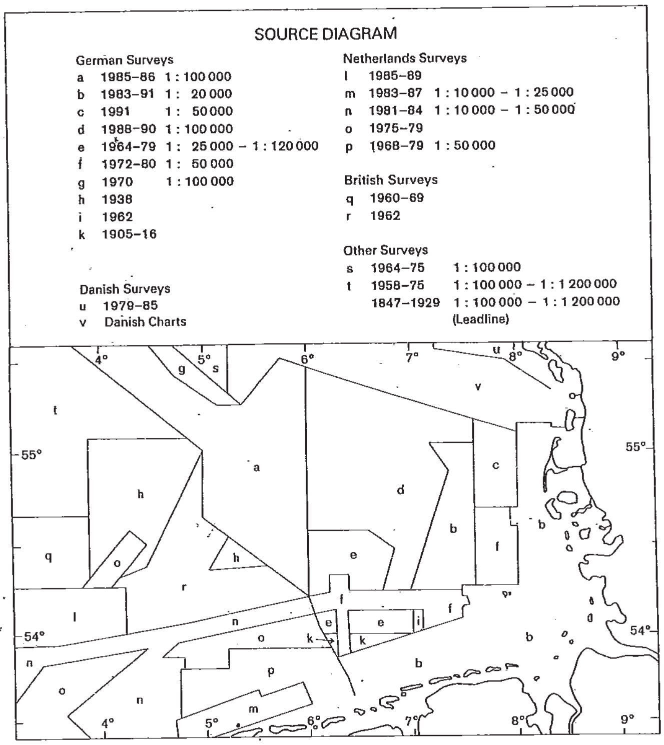

Fig. 1: A compilation of different surveys

1.10 *Application of the total accuracy*
There are two ways to apply the total accuracy to the depth information of the nautical chart:

a. In the long term, the most secure policy would be to adjust all charted depths in the nautical chart, to the safe side, at a 90% confidence level.
b. In the short term, the most practical way is to adjust the source diagram to show the total accuracy at a 90% confidence level.

1.11 Application of the total accuracy in the nautical chart will result in a generally shallower appearance. This is not surprising. It has been proven that due to the absence of the bathymetric uncertainty as a result of the line spacing swathe surveys generally give a more shallow result than traditional surveys, and above that the dynamic behaviour of the seafloor can be significant.

1.12 The following paragraph will specify how the total accuracy can be obtained. The described procedures have been tested with data from the "Twin" surveys. The Twin area is located in a sandwave region approximately 60nm WSW from Hook of Holland in the Selected Route, for vessels with a draught up to 74 feet, leading to the entrance of Europoort. Although this area is supervised by the Northsea Directorate of the Ministry of Transport, Public Works and Water Management (RWS-DNZ), it has been surveyed by *HNLMS Buyskes* of the Hydrographic Service of the Royal Netherlands

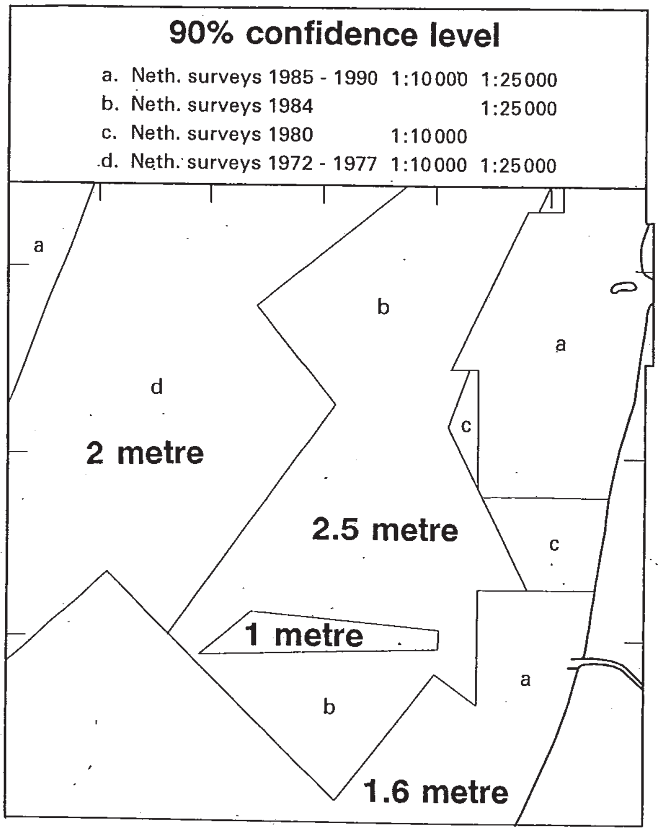

Fig. 2: (imaginary) values for a 90% confidence level for the charted depths

Navy, under the terms of reference of the Netherlands Hydrographic Institute (NHI), since 1986.

1.13 The surveys have been executed with a single beam echosounder (Deso 10/25) utilizing the same standard tracks and a line spacing of 50 metres every year. The data processing has been carried out with the automatic onboard system HYDRAUT. For the reduction to MSL, real tidal data from the DAG 6000 offshore tide gauges have been used. Hyperfix positioning was used with a RMS smaller than 5 metres.

1.14 The statistical calculations for this article have been carried out by, and in collaboration with, RWS-DNZ.

Calculation of the total accuracy

2.1 *The accuracy of the measurements*
The accuracy of the measurements is related to the environment from which the measurements have been derived. Apart from the measuring system, the accuracy is a function of the water depth, the weather conditions and the morphology. An assessment of the accuracy of the measurements cannot be detached from the experienced environment.

2.2 Systematic errors are, to the best knowledge of the surveyor, eliminated by prescribed procedures, bar checks, accurate measurement of the propagation of sound, choice of the correct line direction, and the best possible assumption of mean sea level etc. In spite of these measures, every survey will contain a certain constant anomaly. The larger part of this anomaly is caused by the difference between the true and the assumed (calculated) value of mean sea level. This anomaly is not systematic but differs with each survey.

2.3 The measuring system encompases the following components:
a. The platform used.
b. The depth measuring system.
c. The positioning system.
d. The automation system and the algorithms used.
e. The tide measuring system and the reduction procedure used.

2.4 The standard deviation of the accuracy of the measurements (σ_{fm}) can be divided into two components:
a. σ_{ca}; the standard deviation of the constant anomaly (this standard deviation can be determined from a series of surveys),
b. σ_{ms}; the standard deviation of the accuracy of the measuring system.

2.5 An assessment of the standard deviation of the constant anomaly (s_{ca}) can be combined with an assessment of the standard deviation of the accuracy of the measuring system (s_{ms}). This combination is representative for an assessment of the standard deviation of the measurements; s_{fm}.

$$s_{fm} = \sqrt{(s^2_{ms} + s^2_{ca})}$$

2.6 *Assessment of the constant anomaly.*

2.7 *Assumption*
Within a limited period (a decade) and within a strictly delimited off-shore area, the mean seafloor is in equilibrium. The total volume of sand and other transportable sediment will not change.

2.8 The mean depth per survey (md) can be determined by dividing the aggregate of all depths (Σ dn) within a strictly limited area by the total number of survey points within this area (n).

$$md = \sum_{i=1}^{n} \frac{dn}{n}$$

2.9 In areas surveyed with a high frequency it will be possible to derive the mean depth of the same, strictly limited area, over a number of surveys (mds).

2.10 The differences between the mean depth per survey and the mean depth over all (md – mds), leads to an estimate of the standard deviation for the constant anomaly.

$$s_{ca} = \sqrt{\left(\sum_{i=1}^{n} \frac{(md-mds)^2}{(n-1)} \right)}$$

2.11 This estimate applies only to the used measuring system and strictly speaking, only to the experienced environment.

2.12 An analysis of the data from 6 consecutive surveys of the Twin area leads to the following results:

year	number of survey points	mean depth (md) per survey
1986	52585	362.76dm
1988	53458	365.84dm
1989	53211	366.42dm
1990	53311	364.86dm
1991	53000	363.72dm
1992	53296	365.03dm

The mean over-all depth is 364.77dm and an assessment of the standard deviation of the constant anomaly was calculated to be 1.35dm.

2.13 *The accuracy of the used measuring system*
In hydrographic literature, extensive research with respect to this matter, for single beam echosounder surveys, can be found. Error budgets totalizing accuracy estimates of several error sources are known[1]. However, this approach has two significant limitations:

a. Error budgets depend on specifications from the manufacturer and single or periodic calibrations. It does not fully allow for the experienced environment.
b. The different values for the error budget are dependent on a best possible "educated guess". Hence, error budgets can lead to different assessments of the accuracy for the same survey.

2.14 By using adequate redundancy, the accuracy of the measurements in the experienced environment can be assessed. (SP44, 3rd edition, 1987 of the International Hydrographic Organisation: "The interval between cross-check lines should normally be no more than 15 times that of the principal sounding lines", i.e. 1:10.000, 100 metre line distance, every 15cm)[2].

2.15 An assessment of the accuracy of the measuring system (s_{ms}) follows from the depth differences in the intersections of the principal and the cross-check lines. However, the positional accuracy can have a significant effect on the depth differences. This effect can be reduced.

$$s_{ms} = \sqrt{\left(\sum_{i=1}^{n} \frac{(\delta i - \delta m)^2}{2(n-1)} \right)}$$

δi = depth difference,
δm = mean depth difference.

2.16 The diameter of the footprint of a hydrographic echosounder with a beam width of 8 degrees, in a depth of 30 metres amounts to approximately 4 metres. Within this footprint the least depth is determined by the first return pulse. By creating a window of 5 * 5 metres around the intersections, wherein the least depth as measured on the principal line and that on the cross-check line are compared, this positional effect will be reduced.

2.17 The above described procedure has to be carried out before the data reduction process (least depth selection for the fairsheet); i.e. using the raw data, corrected for spikes and tidal reduction.

2.18 This method assumes that the cross-check lines are surveyed directly after the primary lines. The dynamic behaviour of the seafloor will then have little effect on the results.

3.1 *Bathymetric uncertainty as a result of the limited data density*

Figure 3 shows the standard deviation of the bathymetric uncertainty due to the limited data density as used within the probabilistic calculation on the probability of seafloor disturbances by ships with a draught of 74 feet in the Selected Route to the entrance to Europoort[3]. These values have been obtained by empirical methods. The bathymetric uncertainty due to a line spacing of 250 metres in this area amounts to 12.5dm.

3.2 By using recently developed algorithms it is possible to assess the bathymetric uncertainty between the lines from the data collected along the survey tracks.

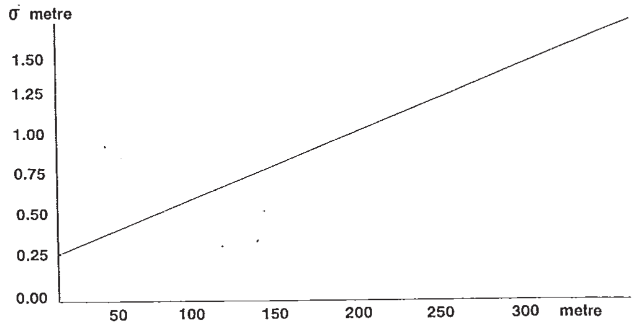

Fig. 3: Bathymetric uncertainty due to line spacing in the North Hinder area

3.3 A spot sounding only describes the depth in one position. A series of soundings does not only give this information but also the changes of the bathymetry. Since the earliest days of hydrographic surveying this information has been used to draw the depth contours. But a series of soundings contains even more information. Apart from a predictable trend, information can be obtained of the unpredictable "noise" on the trend. This noise is normative for the bathymetric uncertainty between the lines.

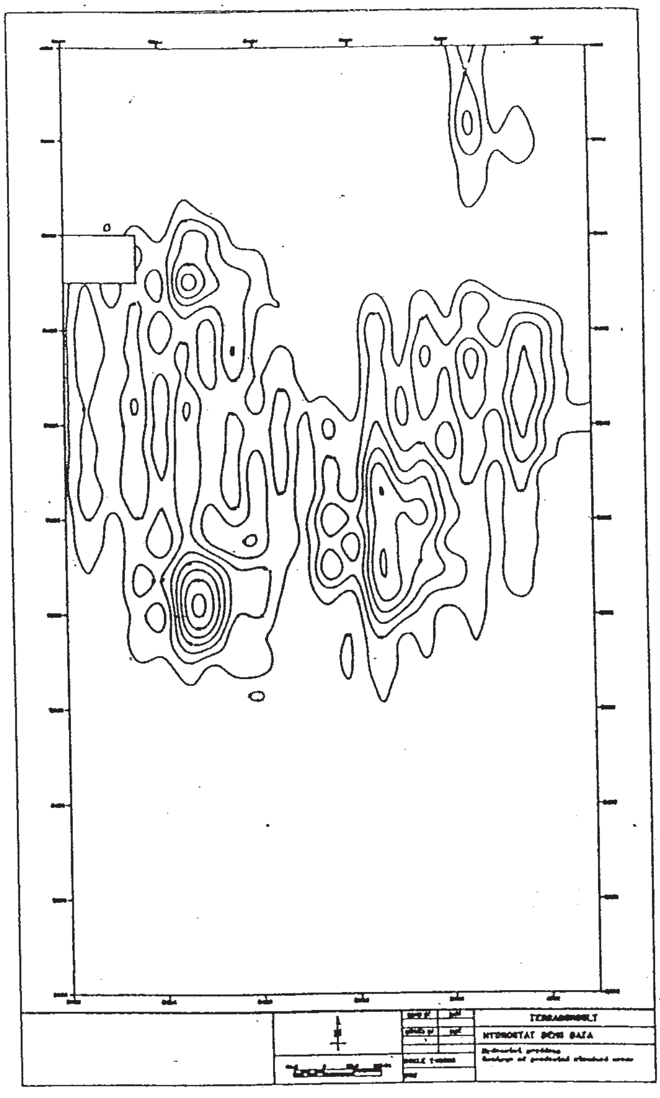

Fig. 4: IHO-stat product

3.4 The Canadian Hydrographic Service is developing the software package "IHO-stat" which uses "Variograms" and "Kriging". Both concepts are not new, but their hydrographic applications are. In this software package the determination of the statistical values of the bathymetric uncertainty as result of the line spacing is a crucial issue[4 5].

3.5 Figure 4, produced by IHO-stat, shows a contour map of predicted standard deviation resulting from the bathymetric uncertainty as a result of the line spacing. Figure 5 shows confidence envelopes; envelopes wherein the standard deviation of the bathymetric uncertainty due to line spacing remains within a predetermined value.

4.0 *The bathymetric uncertainty as result of the dynamic behaviour of the seafloor*

4.1 At present there is still much unknown about the relation between time and the mechanism that causes the dynamic behaviour of the seafloor. All changes of the seafloor, particularly movements in the vertical sense, must be treated as random effects. Figure 6 shows a typical seafloor profile in the Twin area.

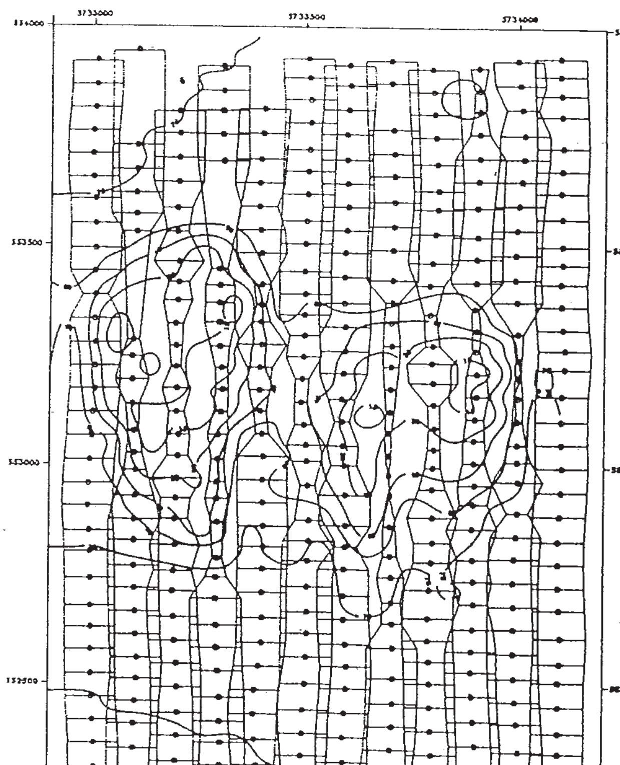

Fig. 5: IHO-stat product

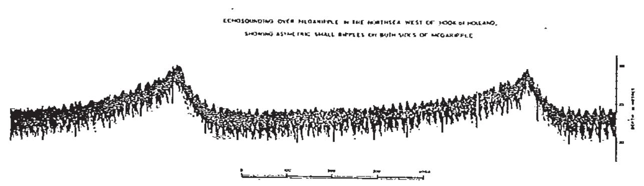

Fig. 6: Typical seafloor profile in the North Hinder area

4.2. The key to the future is found in the knowledge of the past. The most important areas of the North Sea have been surveyed with modern digital techniques. Using previous surveys or a series of small check surveys in critical areas, an historical analysis of the data is possible.

4.3 *Assessment of the dynamic accuracy of the seafloor*
For charting purposes, the changes in the most shallow areas are of the greatest significance. An analysis of the North Hinder area shows the horizontal distance, over a period of 4 years, within which nearly all significant vertical changes take place, to be 300 metres, along the crest of the sandwaves.

4.4 For the purpose of this article (analysis of the Twin area), the standard deviation of the vertical changes of the most shallow parts of the seafloor within a distance of 300 metres measured along the crest of a sandwave, is described as the dynamic accuracy of the seafloor.

4.5 *Assumption*
Within a limited area, shallowing and deepening will occur. However, the volume of sand and other transportable sediment will not change. Hence the surveys must each be corrected for the constant anomaly as derived in 2.6.

4.6 From the depth differences between two surveys, separated by a certain period of time, an assessment of the standard deviation of the depth differences can be obtained.

4.7 If the depth data of both surveys have been acquired from the same tracks, the bathymetric uncertainty due to the line distance will have no effect on the standard deviation of the differences.

An assessment of the standard deviation of the differences can be described as:

$$s_{tot} = \sqrt{(s^2_{fm1} + s^2_{fm2} + s^2_{dyn})} \text{ where;}$$

s_{fm1} : the assessment of standard deviation of the accuracy of the measurements of survey 1.

s_{fm2} : the assessment of standard deviation of the accuracy of the measurements of survey 2.

An estimate of the standard deviation of the dynamic accuracy follows from;

$$s_{dyn} = \sqrt{(s^2_{tot} - s^2_{fm1} - s^2_{fm2})}$$

4.8 An analysis of the data of the "Twin" area has been carried out using a grid size of 150 * 300 metres where the long side of the grid has been positioned along the general direction of the sandwaves. The least depth in each grid square has been selected for the comparison. This analysis leads to the following results.

comparison	number of grid squares	mean difference dm	standard deviation dm
1986 - 1990	502	0.3	6.0
1988 - 1990	504	– 0.1	5.3
1989 - 1990	504	– 0.5	4.8
1991 - 1990	504	– 1.2	4.9
1992 - 1990	503	– 0.3	5.6
1992 - 1986	504	– 0.7	5.0
1992 - 1988	507	– 0.3	4.1

From this information the following values for the dynamic behaviour of the seafloor are calculated, assuming that the standard deviation of the measurements of all surveys is equal to 2dm.

comparison	σ_{dyn} dm	period
1986 - 1990	5.29	4 years
1988 - 1990	4.48	2 years
1989 - 1990	3.88	1 year
1991 - 1990	4.00	1 year
1992 - 1990	4.83	2 years
1992 - 1986	4.12	6 years
1992 - 1988	2.97	4 years
mean:	4.22	

4.9 The mean value of the standard deviation for the dynamic behaviour in the Twin area over a number of years is assumed to be 5dm.

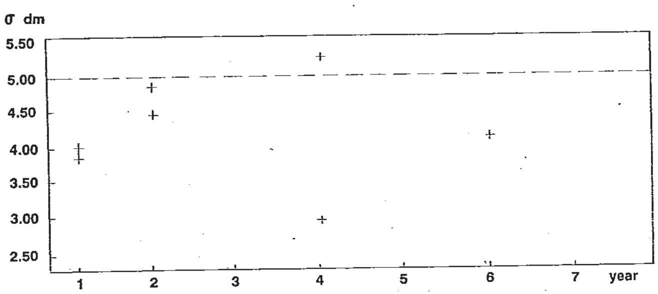

Fig. 6: Standard deviation of the dynamic accuracy of the seafloor

4.10 The values show that the bathymetric uncertainty as a result of the dynamic behaviour of the seafloor in the Twin area, compared over periods of more than a year, has no relation with time. The vertical component of the dynamic behaviour of the seafloor remains within a 90% confidence band of (±0.9 metres), measured from a mean profile of the seafloor.

Examples of the calculation of the total accuracy

For the purpose of these examples an assessment of the standard deviation (s) is assumed to be equal to the standard deviation (σ).

1. The total accuracy of the depth figures plotted in the nautical chart resulting from the single beam surveys of the Twin area can be calculated as follows:

a. The standard deviation of the measurements (σ_{fm}).

(i) The standard deviation of the accuracy of the measuring system is assumed to be 2dm (σ_{ms}).

(ii) The standard deviation of the constant anomaly is calculated to be 1.35dm (σ_{ca}).

The standard deviation of the measurements:

$$\sigma_{fm} = \sqrt{(\sigma^2_{ms} + \sigma^2_{ca})} = 2.41dm$$

b. The standard deviation of the bathymetric uncertainty as result of the used line spacing of 50 metres is 4dm (σ_{dd}, figure 3).

c. The standard deviation of the bathymetric uncertainty due to the dynamic behaviour of the seafloor has been calculated to be 5dm (σ_{dyn}).

The standard deviation of the charted depths from this survey are calculated to be:

$$\sigma_{tot} = \sqrt{(\sigma^2_{fm} + \sigma^2_{dd} + \sigma^2_{dyn})} = 6.84dm$$

Conclusion

From the previous statement it can be shown that in this example the depths in the nautical chart are accurate within a 90% confidence interval to:

±1.12 metres

2. If this area had been surveyed using a swathe system, the standard deviation of the total accuracy would have been: σ_{tot} = 5.55dm and the 90% confidence interval:

±0.91 metres

3. If this area had been surveyed using a line spacing of 250 metres the standard deviation of the total accuracy would have been: σ_{tot} = 13.68dm and the 90% confidence interval:

±2.24 metres

4. *Example*

In 1972 an area has been surveyed with a line spacing of 500 metres. The area has the same morphology as the Twin area.

a. The accuracy of the measurements are assumed to be represented by a standard deviation of 4dm.

b. The bathymetric uncertainty due to a line spacing of 500 metres is assessed by a standard deviation of 25dm (figure 3).

c. The standard deviation of the dynamic behaviour of the seafloor is estimated to be 5dm.

The standard deviation of the charted depths from this survey are calculated to be:

$$\sigma_{tot} = \sqrt{(\sigma^2_{fm} + \sigma^2_{dd} + \sigma^2_{dyn})} = 25.81dm$$

and the 90% confidence interval of the depths in the nautical chart:

±4.23 metres

In the designated area in figure 2 a value of 4.5m should be noted in this case.

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