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By Ian Halls, Editor

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  Hassan Atef El. Halawani (Egypt)
  Moustafa Mohammed Hany (Egypt)
  Mohamed M. Elmelegy (Egypt)
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  by Shigeru Kato, Arata Sengoku, Hiroyuki Yoritaka, Kentaro Kaneda, Kunikazu Fukae, Yasutaka Katagiri, Yasuhiro Koso, Hitoshi Nakamura, Shinichi Toyama, Mariko Sato, Takumi Shimazaki, Yumiko Fukushima, Masayuki Fujita and Yousuke Niimura (Japan)
Editorial

The first of three Articles provides an in-depth study of multibeam survey methodology used across several spatial areas to determine an optimum cost model based on beam angles, acceptable uncertainty and other factors. The paper looks at how operator skill levels, training, multibeam parameters and the physical characteristics of the seabed and the water column affect survey results.

The second paper provides an in-depth précis of a sounding method to improve the determination of nautical depth where the seabed is composed of mud – fluid mud and consolidating mud. The authors describe a technique that has been trialled with success in the field and in a testing tank. It is their opinion that the use of the Rheocable method can provide significant savings and improved safety to dredging operations whilst determining a more reasonable estimation of the nautical depth. I hope that those involved with dredging operations may consider this method and perform your own trials to validate the method.

Our third paper discusses data encoding consistency issues in Electronic Navigation Chart (ENC) data. In the paper, the author also discusses how an ENC cell is not like a paper chart to a user and this can cause presentation problems in adjoining data to the user. In an ECDIS, the display can present several cells of ENC data, sometimes at different usage bands (or scales) to the user. This display issue requires careful consideration by the producing nation to provide data coverage that is unambiguous in terms of interpretation and use. The author also describes a preference for managing ENC data in a tiled structure rather than individual cells that mirror existing paper chart extents. I suspect that ENC cell scheming will not be consistent amongst the HO’s as they adopt a cell scheming that optimises their own geographic coverage and customer's requirements.

Included in this edition are two papers in the Notes section. The first paper provides a detailed account of the crucial work undertaken by the Japanese Hydrographic and Oceanographic Department (JHOD) as they survey and provide new charts of the ports and harbours that were ravaged by the great earthquake and ensuing tsunami of 11 March 2011. Our profession is involved in exploration, discovery, construction, economic development, research, safety of navigation and military activities but there is no more important role than providing humanitarian and disaster relief. The work undertaken by the JHOD at such a difficult time for their nation and people is a true testament to the hydrographic professionalism of their teams. The recovery of their torn communities will take many, many years and our thoughts and blessings are with them.

The second paper is an account of some personal observations from attending some recent international hydrographic conferences. It has been several years since I have attended these events and their importance cannot be understated at bringing the profession together to forge new directions and relationships between government, industry and academia. These are also important forums for students and members of developing countries to attend.

On behalf of the Editorial Board, I hope that this edition is of interest to you. Thank you to the authors for your contributions and to my colleagues who provided peer reviews for the Articles in this edition.

Ian W. Halls
Editor
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Article

MBES SWATH ANGLE IN RELATION WITH DATA PROCESSING QUALITY, TIME AND COST

By Hydrographic Survey Research Group (HSRG - Egypt), Arab Academy for Science and Technology and Maritime Transport (AASTMT - Egypt) & HYPACK Inc. (USA)

Abstract

The goal of this research was to investigate and determine the differences in uncertainty at different beam angle limits. To achieve this objective, six MBES data sets were each processed by five surveyors with different levels of experience in MBES data processing. Each project was processed three times, using 45°, 60° and 75° beam angle filter limits in the HYSWEEP MBES Editor. Each surveyor was timed to determine the total time spent editing each MBES data set, using each of the three beam angle limits. An analysis was conducted for the time taken to process each data set, along with the resultant sounding uncertainty. Finally, a virtual area was created to determine the cost of the survey as a function of swath angle.

This research was conducted in cooperation with HYPACK Inc. (www.hypack.com), and the Hydrographic Survey Research Group (HSRG) in the Arab Academy for Science and Technology and Maritime Transport (AASTMT) (www.aast.edu). HYPACK provided the project with a work station for data processing, sample MBES data, and five HYSWEEP licenses. HSRG conducted the data processing, analysis and the documentation.

Résumé

Le but de cette recherche est d’étudier et de déterminer les variations d’incertitude à différentes limites d’ouverture de faisceau. Pour atteindre cet objectif, six ensembles de données multifaisceaux ont été traités par cinq hydrographes ayant des niveaux d’expérience différents dans le traitement des données multifaisceaux. Chaque projet a été traité trois fois à l’aide des limites d’ouverture de bande de 45°, 60° et 75° dans l’éditeur HYSWEEP MBES. Chaque hydrographe devait déterminer le temps total passé à éditer chaque ensemble de données multifaisceaux, à l’aide chacune de trois limites d’ouverture de bande. Une analyse a été conduite sur le temps consacré au traitement de chaque ensemble de données, et de l’incertitude des levés. Finalement une zone virtuelle a été créée pour déterminer le coût du levé en tant que fonction d’ouverture de bande.


Resumen

El objetivo de esta investigación fue estudiar y determinar las diferencias en la incertidumbre, en límites de ángulos del haz diferentes. Para lograr este objetivo, cada una de las seis colecciones de datos MBES fue procesada por cinco hidrógrafos con diferentes niveles de experiencia en el procesado de datos MBES. Cada proyecto fue procesado tres veces, utilizando los límites del filtro del ángulo del haz a 45°, 60° y 75° en el Editor HYSWEEP MBES. Se cronometró a cada hidrógrafo para determinar el tiempo total empleado...
en la edición de cada colección de datos MBES, utilizando cada uno de los tres límites del ángulo del haz. Se efectuó un análisis del tiempo empleado en el procesado de cada colección de datos, junto con la incertidumbre de sonda resultante. Finalmente, se creó una zona virtual para determinar el coste del sondeo en función del ángulo de corte.

Esta investigación fue llevada a cabo en cooperación con HYPACK Inc. (www.hypack.com), y con el "Hydrographic Survey Research Group" (HSRG) de la "Arab Academy for Science and Technology and Maritime Transport" (AASTMT) (www.aast.edu). HYPACK proporcionó para el proyecto una estación de trabajo para el procesado de datos, de datos-muestra MBES, y cinco licencias HYSWEEP. El HSRG realizó el procesado de datos, su análisis y la documentación.
Scope of the work

The work flow consisted of four stages: training, processing, analysis and documentation. Five members of HSRG were trained in the basic theory of MBES data processing and processing MBES data in HYSWEEP. Standard Operation Procedures (SOPs) were developed for different HYSWEEP tools during the surveyor’s training and were used in the actual data processing. Two projects were processed using the SOPs and the time needed to process the data was logged. The results for the surveyor’s first two projects were used as the ‘non-expert’ basis, while the results for the surveyor’s final three projects were considered the ‘expert’ basis. Total Propagation Uncertainty (TPU) was computed and the Standard Deviation (SD) was determined and exported as a part of Phase III of the data processing. These results allowed us to analyze the time and the resultant SD associated with each data set. Finally a virtual survey area was created to compute the total cost of survey using different swath angles.

Survey Projects Data

HYPACK provided several MBES data sets that were used in conducting the research. These projects were used for either basic training of the surveyors or to measure their actual processing performance and the resultant uncertainty. The project that was used for training the survey team was named Sample HYSWEEP Survey. Projects that were used in measuring processing performance are named Philadelphia, New York, Before Dredging, After Dredging and Artificial Reef. All system offsets, described in the following sections, used the HYPACK coordinate convention.

Sample HYSWEEP Survey

The Sample HYSWEEP Survey, as illustrated in Figure 1, is one of survey projects that are included in the HYPACK training Compact Disk. The main objective for this data set was to familiarize the survey team with HYSWEEP processing module and following its SOP. The project consists of one single MBES line of 500 meter length. Hardware used in the project included the TSS Dynamic Motion Sensors (DMS) for Motion Reference Unit (MRU) and the Reson SEABAT 8101. The positioning is not known.

Table 1 lists the hardware linear and angular offsets.

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>YAW</th>
<th>PITCH</th>
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</tbody>
</table>

Figure 1: Sample HYSWEEP survey project

Table 1: Linear and angular offsets for Sample HYSWEEP Survey project
Philadelphia

Philadelphia was the first MBES survey project the team used in measuring data processing performance. The Philadelphia project, as illustrated in Figure 2, has a total survey length of 9.5km.

Hardware used in the project were an Applanix POS MV for both positioning and MRU and a Reson SEABAT 7101 MBES. Table 2 lists the hardware linear and angular offsets.

![Figure 2](image.png)

\textit{Figure 2} : Philadelphia survey project.

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>YAW</th>
<th>PITCH</th>
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<td>0.0</td>
<td>0.0</td>
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</tr>
</tbody>
</table>

\textit{Table 2} : Linear and angular offsets for Philadelphia
New York

New York was the second MBES survey project used in measuring data processing performance. The New York project, as illustrated in Figure 3, has a total survey length of 1.86 Km.

Hardware used in the project is the same as in Philadelphia project. Table 3 lists the hardware linear and angular offsets.

![Figure 3: New York survey project.](image)

<table>
<thead>
<tr>
<th></th>
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<th>Z</th>
<th>YAW</th>
<th>PITCH</th>
<th>ROLL</th>
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Table 3 Linear and angular offsets for New York project
Before Dredging and After Dredging

Before Dredging and After Dredging are two survey data sets of the same area, as illustrated in Figure 4. 'Before Dredging' was surveyed before the dredging took place and 'After Dredging' took place after the dredging had taken place.

Each project contains 30 MBES lines with total length of 10 km. the Hardware used in the project is the same as in Philadelphia project. Table 4 lists the hardware linear and angular offsets.

![Figure 4: Before Dredging and After Dredging survey projects](image)

<table>
<thead>
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<th>X</th>
<th>Y</th>
<th>Z</th>
<th>YAW</th>
<th>PITCH</th>
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<td>RTK</td>
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<td>MBES</td>
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<td>3.8</td>
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</table>

*Table 4: Linear and angular offsets for Before Dredging and after Dredging projects*
Artificial Reef
Last survey project is Artificial Reef, as illustrated in Figure 5. The project contains 24 MBES lines with total length of 100 km. The Hardware used in this project were the Applanix POS MV for both positioning and MRU and the Reson SEABAT 8101. Table 5 lists the hardware linear and angular offsets.

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<td>-1.0</td>
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<tr>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Figure 5: Artificial Reef survey project

Table 5: Linear and angular offsets for Artificial Reef project
Standard Deviation Computation
As a preparation for the data processing the Total Propagated Uncertainty (TPU) was computed for each sounding to ensure that the processed data met the International Hydrographic Organization (IHO) standards [2]. The TPU EDITOR was used in computing TPU for each project. The TPU EDITOR has 3-tabbed dialog where the user must enter the general, environmental and sensor information.

The ‘General’ tab contains over 14 parameters including angular coverage, maximum ping rate, along track beam width, across track beam width, pulse length, sector steering angle, frequency and the receive beam. All these parameter could be set to manufacturer defaults by selecting the Sonar from the TPU Editor’s database. For each project the appropriate sonar was selected. An important parameter in this tab is to configure the surveying order to the adopted standard. For the current research, IHO Special Order was selected.

The ‘Environmental’ tab of the TPU Editor contains several environmental settings. Most of the default values were used.

The ‘Sensor Information’ tab contains physical offsets and the uncertainty associated with these offsets along with other information. The uncertainty related to the positioning system and MRU were populated from TPU Editor database by selecting the appropriate sensor. Other information related to the sensor offsets have been extracted from HY-SWEEP Editor and entered in the TPU Editor.

Figure 6 illustrates the TPU graph for the last three survey projects. In the Graphs, the yellow horizontal line represents the estimated standard deviation computed according to IHO Special Order.

The IHO depth uncertainty is then extracted from the Depth Uncertainty graph (m) and then converted to one-sigma standard deviation according to the associated project depth unit. The computed one-sigma standard deviation is used in MBES data processing in Phase III of the HY-SWEEP Editor. Table 6 lists the standard deviations of the survey projects.

MBES Data Processing
MBES data processing went through several steps: applying corrections, reading parameters, raw data review (Phase I), swath-based editing (Phase II), area-based editing (Phase III) and saving the results. During data processing, the processing time was kept between the start of the first step and the end data storage.

Tide corrections and sound velocity were applied in Phase I of the HY-SWEEP Editor after reading the MBES raw data. In the second step the hardware offsets were checked. If the patch test results [3] were not applied during data acquisition, they can be applied in the second step.

In Phase I, the surveyor can examine the raw data from the sensors, checking line by line. The raw pitch, roll and heading were reviewed to make sure they are appropriate and that there is no heave drift. The track lines can also be examined and position spikes corrected. The surveyor also reviews the tide and draft corrections to make sure they are reasonable.

In Phase II, the surveyor examines the corrected MBES data swath by swath. Depth spikes can be eliminated either manually or by applying combinations of geometric filters. Available geometric filters include Min Depth/Max Depth, Beams, Port/Starboard Offset Limits, Spike Limit, Quality Limit, Intensity Limits and Savitsky-Golay.

Each survey project was edited three times by each surveyor, each time applying a different Beam Angle filter (45°, 60° and 75°). A Beam Angle filter of 45° would remove any data points that were collected with a beam greater than 45° from nadir.

In Phase III the entire survey was subdivided into cells. Based on the z-values that are contained in a cell, cell statistics were generated that can be used when applying statistical filters. The distribution of MBES data in each cell or across a collection of cells that creates a ‘profile’ can be reviewed and edited.
For each cell, the HYSWEEP Editor computes the SD, based on the distribution of z-values contained in the cell. Cells with an SD value that exceeded the value derived in Standard Deviation Computation were then visually examined in order to remove any remaining outliers. Finally the data is stored in two XYZ ASCII format files. The first file stored the depth value for each data point as the Z-value. The second file stored the SD value for each data point as the Z-value.

Uncertainty Analysis

The goal of this step was to examine the changes to the standard deviation of each data set, upon completion of processing, according to the surveyor (editor) and the beam angle limit.

The SD output HYSWEEP Editor Phase III stores the data in three columns; the X and the Y (Easting and Northing), the 3rd column represents the 1σ SD. For each data set, every surveyor generated a separate ‘SD’ file using the 45°, 60° and 75° Beam Angle limits.

The resulting files were imported into an Excel spreadsheet, converted to 2σ SD, and correlated according to its SD value from 0.00 to 0.91 (US Survey feet or metres according to the project depth unit) using separation steps of 0.02 horizontally. At the end of each column, the total number of occurrences for each SD step value is shown.

Each graph represents the relationship between the SD steps (0,0.01,0.03,…….) horizontally, and the numbers of occurrences on each of these values vertically. Since the results of the three surveyors are similar, only the graphs of the first surveyor are represented.

Before Dredging

The Before Dredging project data estimated uncertainty (2σ SD) was 0.6ft as listed in Table 6. As shown in Figure 7, the histogram for beam angle 45° for the first surveyor, most of the SD lies in a narrow range around 0.17ft. Most of the uncertainty values were within the estimated IHO Special Order limit. When the beam angle limit is increased from 45° to 60° the histogram shows a similar distribution, as illustrated in Figure 8. Increasing the beam angle limit to 75° increases the broadness dramatically, as shown in Figure 9, where most of the SD lies around 0.27ft.

<table>
<thead>
<tr>
<th>Project</th>
<th>New York</th>
<th>Philadelphia</th>
<th>Before Dredging</th>
<th>After Dredging</th>
<th>Artificial Reef</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted Uncertainty (2σ)</td>
<td>0.6 ft</td>
<td>0.6 ft</td>
<td>0.6 ft</td>
<td>0.6 ft</td>
<td>0.2 m</td>
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<tr>
<td>Standard Deviation (1σ)</td>
<td>0.3 ft</td>
<td>0.3 ft</td>
<td>0.3 ft</td>
<td>0.3 ft</td>
<td>0.1 m</td>
</tr>
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</table>

Table 6: The Standard Deviations of the survey projects

Figure 7: SD histogram of the 1st surveyor for beam angle 45°, Before Dredging.
The After Dredging project had an exceptionally rough seabed and the presence of sediment in the water column resulted in more outliers when compared with the Before Dredging project. This would lead us to surmise that it would have a higher SD.

The histogram, illustrated in Figure 10, for the 45° shows that most of the uncertainty values lies between 0.01ft and 0.33ft. Increasing beam angle limit to 60° causes the maximum SD value to jump up to 0.15ft, as in Figure 11. Processing with a beam angle of 75° causes most of the distribution to be much wider and centered around 0.53ft, as illustrated in Figure 12.
Figure 10: SD histogram of the 1st surveyor for beam angle 45°, After Dredging.

Figure 11: SD histogram of the 1st surveyor for beam angle 60°, After Dredging.

Figure 12: SD histogram of the 1st surveyor for beam angle 75°, After Dredging.
Artificial Reef
The Artificial Reef histograms show similar performance to Before Dredging, as illustrated in Figures 13, 14, and 15. The histogram shows right skew in 45° and moves more toward the right as beam angle increases indicating an increase of the uncertainty.

Figure 13: SD histogram of the 1st surveyor for beam angle 45°, Artificial Reef.

Figure 14: SD histogram of the 1st surveyor for beam angle 60°, Artificial Reef.

Figure 15: SD histogram of the 1st surveyor for beam angle 75°, Artificial Reef.
Uncertainty analysis summary
The uncertainty analysis is summarized in Table 7 where the second and third rows summarize the $\sigma$ SD of 68% and 2$\sigma$ SD 95% of the data points for each project. The last row summarizes the percentage of data points that meets IHO Special Order standards.

The Beam Angle Limit has proven to have a significant effect on achieved uncertainty. This is shown in Figure 16 where the SD increases as beam angle increases. Also the type of the survey has an effect on the uncertainty that can be achieved when comparing the Before Dredging and After Dredging survey projects. Seabed complexity, shown in Figures 17 and 18, and sea state also has a direct effect on the achieved uncertainty. This could be realized in comparing Before Dredging and Artificial Reef where a smaller oscillation has been observed during the Before Dredging project.

<table>
<thead>
<tr>
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<td></td>
<td>45°</td>
<td>60°</td>
<td>75°</td>
</tr>
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<td>maximum</td>
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<td>0.57</td>
</tr>
<tr>
<td>68%</td>
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<td>95%</td>
<td>0.08</td>
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<tr>
<td>Special Order %</td>
<td>98</td>
<td>98</td>
<td>95</td>
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</table>

*Table 7: Uncertainty summary in 2$\sigma$ SD (metres).*

*Figure 16: 68% and 95% 2$\sigma$ SD sounding uncertainty (the first three bars from the right in each project is 68% and the second three bars is 95%).*
Figure 17: Survey vessel attitude (pitch/roll/heading) in Artificial Reef survey project.

Figure 18: Survey vessel attitude (pitch/roll/heading) in Before Dredging survey project.
Figure 19 shows the percentage of the soundings that meets the IHO Special Order standard versus the Beam Angle Limit. Reducing the Beam Angle Limit from 75° to 60° or to 45° in Before Dredging didn’t make much difference, probably due to the uniform sea bottom. As the seabed becomes more complex, or the sea state becomes more dynamic, reducing the Beam Angle Limit has a significant effect in improving the uncertainty. In all cases, decreasing the Beam Angle Limit will improve the uncertainty of the survey results.

Processing Time Analysis

Table 8 provides average processing times for the three surveyors for each survey project and the three processing angles are listed as the Beam Angle Limits of 45°, 60° and 75°.

The results show that four factors can affect the processing time: Processing angle, Experience level, Type of Survey and Seabed complexity. They are discussed as follows.

Figure 19: Percentage of sounding uncertainty that meets the IHO Special Order standards.

<table>
<thead>
<tr>
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<th>Philadelphia</th>
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<td>68</td>
<td>11</td>
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Table 8: Processing time (Min per km) for the Beam angle 45°, 60° and 75°.
Processing angle
In all projects, using smaller beam angle during data collection leads to a decrease in the processing time as illustrated in Figure 20.

Experience level
Level of experience of the data processing team, in the first two projects, was elementary. The processing time decreases after getting experience with data processing generally and HYSWEEP specifically. This result is illustrated in Figure 21, where the first set shows the processing time (min/km) for both the Philadelphia and Before Dredging (processing angle limit 45°), before the surveyor team got experience with MBES data processing and the second after getting the required experience and enhancing the data processing SOPs. There was a three-fold increase (300%) in processing rates as the surveyors gained experience.
Type of Survey
After the survey team obtained the required experience, the same dredging area was processed twice (Before Dredging and After Dredging). The processing time is illustrated in Figure 22. In all processing angles (45°, 60° and 75°), the processing time for Before Dredging is less than After Dredging. The saved time is inversely proportional to the processing angle. The increase in processing time was due to two factors. First, the complexity of the seafloor increased in the After Dredging survey. Second, nearby dredging operations during the After Dredging survey caused an increase in the amount of suspended sediment in the water column.

Seabed complexity
To illustrate the seabed complexity, contour images were built for each project. The contour interval is fixed every foot. A capture of 1 x 1 Km is taken for each project as shown in the Figures 23, 24, and 25. A grid of 100m is overlaid over each plot.

Figure 22: Processing time for Before Dredging and After Dredging.

Figure 23: Before Dredging project contouring.
Figure 24: Processing time for Before Dredging and After Dredging.

Figure 25: Artificial Reef project contouring.
Comparing the Before Dredging and After Dredging contours makes it clear that the complexity of seabed has increased after dredging. This explains the increased processing times (5, 8 and 11 min/Km) vs. (7, 17 and 25 min/Km). As a conclusion, increasing the seabed complexity will increase the processing time. A contradiction to this rule is illustrated when comparing Before Dredging and the Artificial Reef project. Whilst the seabed in the Artificial Reef survey is more complex than Before Dredging (see Figures 23 and 25), the processing time is smaller (5,8 and 11 min/Km) and (2,2 and 3 min/Km). This is probably due to the size of the Artificial Reef raw data being smaller.

### Virtual Survey Area

A ‘virtual’ survey area was created to investigate the previous results in terms of time, and its equivalent cost, for both field and office work. The dimension of the survey area was taken 1km x 10km and the investigation was conducted twice; first using an average depth of 30m and then using an average depth of 10m. It is assumed that the area is parallel to the coastline along with its 10km side. Three scenarios were used for conducting the survey by using the Beam Angle Limits of 45°, 60° and 75°. In all the three cases the swath to swath overlap was set to 30%.

Using the equation:

\[ v_{\text{swath}} = \min(v_{\text{min}}, \frac{C \tan(\alpha)}{2}) \]

- First, for a simple seabed and standard survey operation where the average processing times are 5, 8 and 11 min/km. (45°, 60° and 75° degree Beam Angle Limits, respectively)
- Second, for a complex seabed or dredged area survey where the average processing times are 7, 17 and 25 min/km.

According to a 2010 survey conducted by HYPACK on several private hydrographic survey agencies, it was found that the average daily rate for a MBES survey ship is $5,000 and the office work is $1,200. This is based on 8 working hours per day. Based on this cost model, the estimated costs of collecting and processing the data from our virtual area could be computed and compared, using each of the Beam Angle Limits.

<table>
<thead>
<tr>
<th>Project</th>
<th>Raw Data Size (Mb per km)</th>
<th>Processing time (Min per km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Dredging</td>
<td>81.5</td>
<td>5, 8 and 11</td>
</tr>
<tr>
<td>After Dredging</td>
<td>67.5</td>
<td>7, 17 and 25</td>
</tr>
<tr>
<td>Artificial Reef</td>
<td>30</td>
<td>2, 2 and 3</td>
</tr>
</tbody>
</table>

**Table 9:** Raw data size along with the equivalent processing time.

### Raw Data Size

Raw data size has a direct impact on the processing time. The raw data size per Km is computed for the last three projects and is listed in Table 9 along with the processing time.

Comparing the Before Dredging and Artificial Reef surveys, the effect of the raw data size on processing time is dominant over the seabed complexity. Comparing the Before Dredging and the After Dredging surveys, the effect of type of the survey and seabed complexity is dominant over the raw data size.

#### Virtual Survey Area

<table>
<thead>
<tr>
<th>Project</th>
<th>Raw Data Size (Mb per km)</th>
<th>Processing time (Min per km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Dredging</td>
<td>81.5</td>
<td>5, 8 and 11</td>
</tr>
<tr>
<td>After Dredging</td>
<td>67.5</td>
<td>7, 17 and 25</td>
</tr>
<tr>
<td>Artificial Reef</td>
<td>30</td>
<td>2, 2 and 3</td>
</tr>
</tbody>
</table>

According to sonar configuration, the computed limits of the survey speed are very high. However, as a quality control measure, we have limited the maximum speed for our ‘virtual’ survey to 5 knots (9.26 km/hr).

According to the processing time analysis, there are several factors that could affect the estimated processing time for the virtual area other than the processing angle. For the purpose of illustrating the effect of processing angle on the office cost, two different scenarios were studied:

- First, for a simple seabed and standard survey operation where the average processing times are 5, 8 and 11 min/km. (45°, 60° and 75° degree Beam Angle Limits, respectively)
- Second, for a complex seabed or dredged area survey where the average processing times are 7, 17 and 25 min/km.

According to a 2010 survey conducted by HYPACK on several private hydrographic survey agencies, it was found that the average daily rate for a MBES survey ship is $5,000 and the office work is $1,200. This is based on 8 working hours per day. Based on this cost model, the estimated costs of collecting and processing the data from our virtual area could be computed and compared, using each of the Beam Angle Limits.
Average depth of 10m

The costs for collecting data over our virtual area with a uniform depth of 10m, using different beam angle limits and our estimated cost of $5,000 per survey day are shown in Table 10.

<table>
<thead>
<tr>
<th>Swath (angle)</th>
<th>Depth (m)</th>
<th>Line Spacing (m)</th>
<th>line spacing with 30% overlap</th>
<th>Number of lines</th>
<th>Total Length (km)</th>
<th>Time (hr)</th>
<th>Time (Days)</th>
<th>Field Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>10</td>
<td>20</td>
<td>17</td>
<td>60</td>
<td>598</td>
<td>65</td>
<td>8</td>
<td>40,000</td>
</tr>
<tr>
<td>120°</td>
<td>10</td>
<td>35</td>
<td>29</td>
<td>35</td>
<td>350</td>
<td>38</td>
<td>5</td>
<td>25,000</td>
</tr>
<tr>
<td>150°</td>
<td>10</td>
<td>75</td>
<td>63</td>
<td>17</td>
<td>168</td>
<td>38</td>
<td>2</td>
<td>10,000</td>
</tr>
</tbody>
</table>

Table 10: Field cost computation for average depth of 10 metres.

The costs for processing this data collected over our virtual area with a uniform depth of 10m are shown in Table 11.

<table>
<thead>
<tr>
<th>Swath (angle)</th>
<th>Total Length (km)</th>
<th>Processing time (hr)</th>
<th>Processing time (Days)</th>
<th>Office Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>598</td>
<td>50</td>
<td>6.3</td>
<td>7,560</td>
</tr>
<tr>
<td>120°</td>
<td>350</td>
<td>47</td>
<td>5.9</td>
<td>7,080</td>
</tr>
<tr>
<td>150°</td>
<td>168</td>
<td>31</td>
<td>3.9</td>
<td>4,680</td>
</tr>
</tbody>
</table>

Table 11: Office cost computation for standard survey operation in average depth of 10 metres.

Table 12 summarizes the total data collection (Field) and data processing (Office) costs, along with the total cost for each Beam Angle Limit.

<table>
<thead>
<tr>
<th>Swath (angle)</th>
<th>Field Cost ($)</th>
<th>Office Cost ($)</th>
<th>Total Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>40,000</td>
<td>7,560</td>
<td>47,560</td>
</tr>
<tr>
<td>120°</td>
<td>25,000</td>
<td>7,080</td>
<td>32,080</td>
</tr>
<tr>
<td>150°</td>
<td>10,000</td>
<td>4,680</td>
<td>14,680</td>
</tr>
</tbody>
</table>

Table 12: Total cost computation for standard survey operation in average depth of 10 metres.

The costs for collecting data over our virtual area with a complex bottom and an average depth of 10m would be the same as the costs for collecting the data over the uniform bottom.

The costs for processing this data collected over our virtual area with a complex seabed and an average depth of 10m are shown in Table 13.

<table>
<thead>
<tr>
<th>Swath (angle)</th>
<th>Total Length (km)</th>
<th>Processing time (hr)</th>
<th>Processing time (Days)</th>
<th>Office Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>598</td>
<td>70</td>
<td>8.8</td>
<td>10,560</td>
</tr>
<tr>
<td>120°</td>
<td>350</td>
<td>99</td>
<td>12.4</td>
<td>14,880</td>
</tr>
<tr>
<td>150°</td>
<td>168</td>
<td>70</td>
<td>8.8</td>
<td>10,560</td>
</tr>
</tbody>
</table>

Table 13: Office cost computation for dredging survey operation in average depth of 10 metres.
Table 14 summarizes the total data collection (Field) and data processing (Office) costs for a complex bottom with an average depth of 10m, along with the total cost for each Beam Angle Limit.

<table>
<thead>
<tr>
<th>Swath (angle)</th>
<th>Field Cost ($)</th>
<th>Office Cost ($)</th>
<th>Total Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>40,000</td>
<td>10,560</td>
<td>50,560</td>
</tr>
<tr>
<td>120°</td>
<td>25,000</td>
<td>14,880</td>
<td>39,880</td>
</tr>
<tr>
<td>150°</td>
<td>10,000</td>
<td>10,560</td>
<td>20,560</td>
</tr>
</tbody>
</table>

Table 14: Total cost computation for dredging survey operation in average depth of 10 metres.

Average depth of 30m
The analysis is repeated, using a uniform bottom with the average depth increased to 30m. The results for data collection and data processing costs are shown in Table 15 and Table 16. The Total Cost is shown in Table 17.

<table>
<thead>
<tr>
<th>Swath (angle)</th>
<th>Depth (m)</th>
<th>Line Spacing (m)</th>
<th>line spacing with 30% overlap</th>
<th>Number of lines</th>
<th>Total Length (km)</th>
<th>Time (hr)</th>
<th>Time (Days)</th>
<th>Field Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>30</td>
<td>60</td>
<td>51</td>
<td>21</td>
<td>206</td>
<td>22</td>
<td>3</td>
<td>15,000</td>
</tr>
<tr>
<td>120°</td>
<td>30</td>
<td>104</td>
<td>88</td>
<td>12</td>
<td>123</td>
<td>13</td>
<td>2</td>
<td>10,000</td>
</tr>
<tr>
<td>150°</td>
<td>30</td>
<td>224</td>
<td>190</td>
<td>6</td>
<td>63</td>
<td>7</td>
<td>1</td>
<td>5,000</td>
</tr>
</tbody>
</table>

Table 15: Field cost computation for average depth of 30 metres.

<table>
<thead>
<tr>
<th>Swath (angle)</th>
<th>Total Length (km)</th>
<th>Processing time Time (H)</th>
<th>Processing Time (Days)</th>
<th>Office Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>206</td>
<td>17</td>
<td>2.1</td>
<td>2,520</td>
</tr>
<tr>
<td>120°</td>
<td>123</td>
<td>16</td>
<td>2</td>
<td>2,400</td>
</tr>
<tr>
<td>150°</td>
<td>63</td>
<td>11</td>
<td>1.4</td>
<td>1,680</td>
</tr>
</tbody>
</table>

Table 16: Office cost computation for standard survey operation in average depth of 30 metres.

<table>
<thead>
<tr>
<th>Swath (angle)</th>
<th>Field Cost ($)</th>
<th>Office Cost ($)</th>
<th>Total Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>15,000</td>
<td>2,520</td>
<td>17,520</td>
</tr>
<tr>
<td>120°</td>
<td>10,000</td>
<td>2,400</td>
<td>12,400</td>
</tr>
<tr>
<td>150°</td>
<td>5,000</td>
<td>1,680</td>
<td>6,680</td>
</tr>
</tbody>
</table>

Table 17: Office cost computation for dredging survey operation in average depth of 10 metres.
The analysis is repeated, using a complex bottom with the average depth increased to 30m. The results for data collection were the same as in Table 15. The data processing costs are shown in Table 18. The Total Cost is shown in Table 19.

<table>
<thead>
<tr>
<th>Swath (angle)</th>
<th>Total Length (km)</th>
<th>Processing time (hr)</th>
<th>Processing time (Days)</th>
<th>Office Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>206</td>
<td>24</td>
<td>3</td>
<td>3,600</td>
</tr>
<tr>
<td>120°</td>
<td>123</td>
<td>35</td>
<td>4.4</td>
<td>5,280</td>
</tr>
<tr>
<td>150°</td>
<td>63</td>
<td>26</td>
<td>3.3</td>
<td>3,960</td>
</tr>
</tbody>
</table>

*Table 18: Office cost computation for dredging survey operation in average depth of 30 metres.*

<table>
<thead>
<tr>
<th>Swath (angle)</th>
<th>Field Cost ($)</th>
<th>Office Cost ($)</th>
<th>Total Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>15,000</td>
<td>3,600</td>
<td>18,600</td>
</tr>
<tr>
<td>120°</td>
<td>10,000</td>
<td>5,280</td>
<td>15,280</td>
</tr>
<tr>
<td>150°</td>
<td>5,000</td>
<td>3,960</td>
<td>8,960</td>
</tr>
</tbody>
</table>

*Table 19: This conclusion is supported by both the uniform and complex seabeds shown in Figures 26 and 27.*

Decreasing the Swath Angle Limits from 150° to 120° to 90° increases the processing efficiency but it also increases the total processing time. Reducing the Beam Angle Limit requires you to decrease the line spacing, resulting in an increase to the total survey length. These results will give an increase to both the data collection and processing times. This conclusion is supported by both the uniform and complex seabeds shown in Figures 26 and 27.

*Table 26: Field, office and total survey cost for both Standard (uniform) survey (S) and dredging (complex bottom) survey (D) for three processing Swath Limits 90°, 120°, and 150° on average depth of 10m.*
Uncertainty vs Cost

Uncertainty versus cost could be inferred by combining the uncertainty results and virtual survey area costs for standard and complex area.

Standard Area

Using the 95% of Uncertainty values for the Before Dredging study (as listed in Table 7):
- At 45° the 95% 2σSD: 0.08m
- At 60° the 95% 2σSD: 0.08m
- At 75° the 95% 2σSD: 0.15m

Total Costs for the Dredged, Complex Area over the 10m deep seabed (as listed in Table 10):
- 45° Beam Angle Limit = $48,000
- 60° Beam Angle Limit = $32,000
- 75° Beam Angle Limit = $15,000

Savings vs. Uncertainty:
- Moving from 45° to 60° Beam Angle Limit
  Savings = $16,000
  Increased Uncertainty = 0 m
- $16,000 is saved and the uncertainty was not affected.
- Moving from 60° to 75° Beam Angle Limit

Savings = $17,000
Increased Uncertainty = 0.07m

Increasing the beam angle limit from 45° to 60° did not affect the uncertainty of the survey results and yielded a saving of $16,000. Increasing the beam angle limit from 60° to 75° yielded a saving of $17,000, but resulted in an increase of 7cm to the average uncertainty of each sounding.

Complex Area

Using the 95% of Uncertainty values for the Artificial Reef study (as listed in Table 7):
- At 45° the 95% 2σSD: 0.13m
- At 60° the 95% 2σSD: 0.29m
- At 75° the 95% 2σSD: 0.33m

Total Costs for the Dredged, Complex Area over the 10m deep seabed (as listed in Table 10):
- 45° Beam Angle Limit = $51,000
- 60° Beam Angle Limit = $40,000
- 75° Beam Angle Limit = $21,000

Savings vs. Uncertainty:
- Moving from 45° to 60° Beam Angle Limit
  Savings = $11,000
  Increased Uncertainty = 0.16m
- Moving from 60° to 75° Beam Angle Limit
  Savings = $19,000
  Increased Uncertainty = 0.04m

Table 27: Field, office and total survey cost for both Standard (uniform), survey (S) and Dredging (complex) survey (D) for three processing swath limits of 90°, 120°, and 150° on average depth of 30m.
Increasing the beam angle limit from 45° to 60° resulted in a cost savings of $11,000, but increased the average uncertainty of each sounding by 16cm. Increasing the beam angle limit from 60° to 75° resulted in an additional saving of $19,000, but increased the average uncertainty of each sounding by an additional 4cm.

Conclusions

Although using smaller MBES swath angles will reduce the processing time per km, the number of survey lines will increase causing both the total field and office times to increase. This results in a higher total survey cost.

Sounding uncertainty should be taken into account when selecting the swath angle. Different factors could affect the uncertainty such as seabed complexity, type of the survey and sea state. In all aspects, decreasing the Beam Angle will improve the uncertainty.

Factors that influence the time required for MBES data processing include the Beam Angle Limit, seabed complexity, and raw data size. Increasing the beam angle limit for a survey will result in lower overall survey costs (particularly data collection costs), but will result in a greater average depth uncertainty for each sounding.

References


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PRODUCTION AND VALIDATION SOLUTIONS FOR IMPROVING ENC CONSISTENCY
By Frank HIPPmann
(L-3 Nautonix - AUSTRALIA)

Abstract

Paper charts have traditionally been produced as discrete entities. With the advent of the Electronic Navigation Chart (ENC) and the Electronic Chart Display and Information System (ECDIS) it has become possible to view multiple “charts” of varying scales on one seamless display. The ECDIS display has revealed that some of the assumptions and processes used to produce stand alone chart products are no longer valid for ENC production, and result in data inconsistencies and a disjointed chart display.

The ENC is not a chart in the traditional sense. From the mariner’s point of view, the dynamic and seamless ECDIS display is the chart. Cartographic principles that apply to individual charts need to be applied to the seamless display, whether it is composed of one or multiple ENCs. The challenge for ENC producers today is to ensure consistent encoding of features that span multiple ENCs. The growing need for hydrographic offices to implement spatial data infrastructures (SDI) and the current development of the S-101 ENC Product Specification provide the perfect opportunity to address ENC consistency.

With the aid of modern enterprise production suites, production guidelines and validation software, ENC producers will be in a position to produce high quality and consistent ENCs.

Résumé

Les cartes papier ont traditionnellement été produites en tant qu’entités distinctes. Avec l’arrivée des cartes électroniques de navigation (ENC) et des systèmes de visualisation des cartes électroniques et d’information (ECDIS), il est devenu possible de visualiser des « cartes » multiples d’échelles variées sur un seul écran en continu. L’affichage ECDIS a révélé que certaines des hypothèses et des processus utilisés en vue de produire des produits cartographiques indépendants ne sont plus valables pour la production des ENC et aboutissent à des incohérences dans les données et en un affichage cartographique décousu.

L’ENC n’est pas une carte au sens traditionnel. Du point de vue du navigateur, l’affichage dynamique et continu de l’ECDIS représente la carte. Les principes cartographiques qui s’appliquent aux cartes individuelles ont besoin d’être appliqués à l’affichage continu, qu’il soit composé d’une ou de multiples ENC. Le défi pour les producteurs d’ENC est d’assurer un codage cohérent des éléments qui s’étendent sur de multiples ENC. Le besoin grandissant des Services hydrographiques d’implémenter les infrastructures des données spatiales (SDI) et le développement actuel de la spécification de produit pour ENC S-101 fourni l’occasion parfaite d’aborder la cohérence des ENC.

Avec l’aide des méthodes de production des entreprises modernes, des guides de production et des logiciels de validation, les producteurs d’ENC seront capables de produire des ENC cohérentes et de grande qualité.
Resumen

Las cartas de papel han sido producidas tradicionalmente como entidades diferenciadas. Con la llegada de la Carta Electrónica de Navegación (ENC) y del Sistema de Información y Visualización de Cartas Electrónicas (ECDIS) ha sido posible visualizar múltiples “cartas” de diferentes escalas en una visualización continua. La visualización del ECDIS ha revelado que algunas de las suposiciones y procesos utilizados para producir productos cartográficos independientes ya no son válidos para la producción de ENCs, y resulta en incoherencias en los datos y una visualización disociada de cartas .

La ENC no es una carta en el sentido tradicional. Desde el punto de vista del navegante, la visualización dinámica y continua del ECDIS es la carta. Los principios cartográficos que se aplican a las cartas individuales tienen que ser aplicados a la visualización continua, independientemente de si está compuesta por una o por múltiples ENCs. El desafío actual para los productores de ENCs es asegurar una codificación coherente de los objetos, que abarque las múltiples ENCs. La creciente necesidad de que los servicios hidrográficos implementen Infraestructuras de Datos Espaciales (SDIs) y el desarrollo actual de la Especificación de Producto para ENCs S-101 proporcionan la ocasión perfecta para tratar la coherencia de las ENCs.

Con la ayuda de modernos sistemas de producción empresarial, de directivas de producción y programas de validación, los productores de ENCs estarán en situación de producir ENCs de alta calidad y coherencia.
Introduction
The production and validation of individual Electronic Navigation Charts (ENC) is well established. The S-58 standard, *Recommended ENC Validation Checks* (IHO 2010a), defines a set of validation checks that need to be met in order for an ENC to be published by a national hydrographic office. Producers of ENCs have the necessary procedures and software in place to ensure that their ENCs comply with S-58.

The challenge facing ENC producers today is the consistent encoding of ENCs of the same geographic area. Features that are common to adjacent ENCs, and overlapping ENCs of different scale bands, are often encoded from different data sources, potentially leading to inconsistencies in the encoding of a feature’s spatial geometry and attributes. These inconsistencies become apparent when multiple ENCs form a seamless display in an Electronic Chart Display and Information System (ECDIS).

Background
The introduction of the *IHO Transfer Standard for Digital Hydrographic Data*, S-57 (IHO 2000) during the 1990s generated a great effort on the part of hydrographic offices to publish their chart portfolios as ENCs. A number of commercial ENC validation software tools became available and formed an integral part of the ENC production workflow. As production of ENCs increased, the International Hydrographic Organization’s (IHO) Transfer Standard Maintenance and Application Development (TSMAD) working group identified a number of technical inconsistencies in data encoding. The need to standardise the testing and validation of ENC datasets led to the development of the S-58 standard by the IHO in the late 1990s.

S-57 does not provide much guidance on the consistent encoding of adjacent and overlapping ENCs. Similarly, S-58 is only focused on the validation of individual ENCs in isolation. The International Centre for ENCs (IC-ENC) highlighted a number of inconsistencies in data encoding. The need to standardise the testing and validation of ENC datasets led to the development of the S-58 standard by the IHO in the late 1990s.

Methodology
Tackling the problem of ENC consistency is not a trivial task and requires standards bodies, data producers and industry to work together. The solution to the ENC consistency problem is three-fold:

1. **Data Management and Production Environment**
   Data producers should endeavour to adopt enterprise GIS solutions for their ENC capture and management. Rather than compiling individual ENCs from varying sources, data producers should focus on building up an enterprise spatial database of hydrographic data from the best possible source data. This will eliminate the need for duplicate and redundant encoding of spatial features, which are the source of many inconsistencies.

2. **Production Specifications and Guidelines**
   Specify additional ENC production guidelines that address the various issues surrounding ENC consistency.

3. **Validation**
   Include, within S-58, a standardised set of checks for cross cell validation that can be implemented in ENC validation software.

Types of Inconsistencies
This section provides examples of the most common types of inconsistencies found in ENC cells.

Inconsistent Spatial Geometry

Spatial inconsistencies occur when the geographic location of real world features, encoded in multiple ENCs, do not match. *Figure 1* shows an example of a navigation line that is encoded in two overlapping ENCs of different scales.

![Figure 1](image-url). This example shows a partially transparent view of two overlapping ENCs. The same real world navigation line feature is encoded in both. A clear NE / SW shift can be seen.
Attribute Encoding

The inconsistent encoding of attributes on features that refer to the same real world object does not only result in logical errors. Attributes are a main driver of the S-52 (IHO 2010b) display engine, so there is potential for these features to be symbolised inconsistently (Figure 2).

![Figure 2. The same navigational mark has been encoded on two ENCs of different scales. Aside from having its position encoded inconsistently, the attribute specifying the beacon’s shape (BCNSHP) has been encoded differently, resulting in the differing symbolisations of the mark.](image)

SCAMIN Encoding

The inconsistent encoding of SCAMIN across cell boundaries results in a chart display that is cluttered in parts and uncluttered in others (Figure 3).

![Figure 3. The two ENCs depicted here use different SCAMIN encodings for their soundings, resulting in soundings being displayed in the northern, but not the southern ENC.](image)

Inconsistent Contour Intervals

Adjacent ENCs need to have the same depth contour intervals encoded. Inconsistent encoding of contour intervals leads to a disjointed safety contour and depth display (Figure 4).

![Figure 4. The northern ENC has the 15m contour omitted. This results in a broken and disjointed safety contour.](image)

Edge Matching

Line and area features need to be continuous at cell boundaries (Figure 5). As far as the mariner is concerned, the seamless ECDIS display represents a chart, whether it is composed of one or multiple ENCs. Basic cartographic principles, such as having continuous contours and unbroken area boundaries, should apply.

![Figure 5. This example depicts broken contours and area boundaries. Note the inconsistent use of SCAMIN on soundings.](image)
Use of M_CSCL

The use of “compilation scale of data” regions (M_CSCL), i.e. the combining of small and large scale data into a single ENC, can lead to a grossly over scale display when the M_CSCL regions are viewed at their compilation scale (Figure 6). ENCs that have M_CSCLs encoded contain a combination of high and low density vertex data, resulting in inefficient ECDIS displays. Given the problems associated with the use of M_CSCLs, and the fact that they can be encoded as separate large scale ENCs, their use should be avoided.

Figure 6. This example depicts a single ENC, whose compilation scale is 1:90000, being viewed at 1:12000. The northern part of the ENC lies within an M_CSCL and generates no over scale warning. The southern portion of the ENC is grossly over scale and should not be viewable at the current scale. If data contained within the M_CSCL were encoded as a separate ENC, only the large scale data would be displayed, as intended.

Holes in Data Coverage

Small scale ENCs sometimes have areas of “no data coverage” encoded where there is large scale data available. This leads to holes in the display when the ECDIS only has the small scale ENCs installed (Figure 7).

Figure 7. This particular ENC display only has small scale data installed. Note the area of no data coverage that is only filled once the large scale data is installed. The hole could easily have been filled with generalised data compiled from the large scale source.

Gaps and Overlaps

Gaps and overlaps between adjacent ENCs can lead to unpredictable results in an ECDIS display (Bisset & Fowle 2003). Whilst it is not difficult to avoid gaps and overlaps within a country’s jurisdiction, they are more difficult to avoid at national boundaries.

S-57 has the concept of a coordinate multiplication factor (COMF). Positions are stored as integers and are converted to real world coordinates by dividing by the COMF. ENCs need to have the same COMF encoded to ensure that cell boundaries are matched according to the same spatial precision (IHO 2009).

Addressing the Problem

Issues surrounding the consistent encoding of ENCs can be addressed by dealing with the following topics:

1. ENC Production
2. Production Guidelines
ENC Production

The most effective way to deal with inconsistencies within ENCs is to establish a production environment that prevents these errors from occurring in the first place.

The vast majority of errors associated with inconsistent encoding of ENCs are the result of duplicate and redundant encodings of vector objects. ENCs of the same region often have the same real world features encoded from different data sources, often paper charts of varying scales. For example, a particular navigational mark is encoded onto a large scale ENC from a large scale paper chart, whilst the same navigational mark is encoded onto a small scale ENC from a small scale paper chart. This can lead to inconsistencies in the spatial and attribute encoding of that navigational mark feature.

Hydrographic offices have traditionally compiled individual paper charts and the paper chart represented a unit of work (Figure 8). ENCs should not be viewed as charts in this traditional sense, and data compilation should not be focused on producing individual ENCs. An ENC should simply be thought of as a tile whose extents may or may not overlap one or more traditional charts. The World Geographic Reference System (GEOREF) as implemented in the Vector Product Format (VFP) (US DoD 1996) is a good example of such a tiling mechanism.

Figure 8. The traditional method of ENC production involves the compilation of individual ENCs from source data. There is no database and the ENC functions as both product and data repository.

An ENC is an end product that should be generated from a higher order data store. The data store itself is compiled from the best possible data sources. ENCs of themselves should not be compiled or edited, and should not form the basis of a data repository. Larger hydrographic offices are starting to migrate their ENC production environments to enterprise GIS solutions for the hydrographic domain. The focus behind such systems is the compilation and management of digital hydrographic databases, rather than the production of individual ENCs (Figure 9). Scale independent features, such as navigational marks, soundings, wrecks, etc. are only encoded once. Scale dependent features, such as contours, can be encoded for multiple scale bands or be generalised automatically from large scale data. A careful application of SCAMIN ensures that only the desired features are visible at a particular scale. It is important that the enterprise GIS allow for the encoding of continuous line and area features that span across multiple ENCs. Only when the ENCs are generated are the features clipped to the ENC extents.

The product generation service of the enterprise GIS is responsible for generating the resultant ENCs, or data sets of other formats, such as the Geography Markup Language (GML) (OGC 2007) and S-101 (IHO 2011a). An enterprise GIS such as this removes the need for the redundant encoding of data and therefore avoids many of the issues surrounding ENC consistency.

The draft S-101 specification provides the ability to encode scale dependent and scale independent cells. This fits in well with enterprise GIS systems that already support scale dependent and independent data.

Figure 9. An enterprise GIS production system consists of one or more databases, which are accessed via enterprise services. These services are responsible for the maintenance and discovery of data, and for the generation of multiple products. Note that the ENC is only one of many possible products; it is not edited and doesn’t form a data repository.

In addition to ensuring more consistent encoding of data, enterprise GIS solutions for ENC production allow for a smooth transition to marine spatial data infrastructures (SDI). Digital maritime data is very rich in content and has many uses beyond navigation (IHO 2011b), including:

- coastal zone management
- exploration
- environmental protection
- maritime defence.
Government bodies are increasingly seeking the data interoperability that SDIs offer and are keen to realise the full potential of digital maritime data.

**SCAMIN**

S-65 provides a comprehensive recommendation for the encoding of SCAMIN for S-57 features. The encoding of SCAMIN can be automated accordingly within the production environment. Manual fine tuning of SCAMIN for certain features may be necessary; for example, a large scale ENC may encode a cluster of underwater rocks, whereas the respective small scale ENC may represent the hazard by a single underwater rock feature.

**Inconsistent Contour Intervals and Edge Matching**

VPF (US DoD 1996) provides a practical mechanism of how adjacent data sets (tiles) are to be matched. First of all, tile boundaries are well defined by the GEOREF system. The GEOREF system will not allow for all of the scale ranges that are possible under S-57, but it does serve as a useful example on how to avoid data gaps and overlaps.

VPF also has the concept of "cross-tile topology", where geometry common to multiple tiles can be referenced by each tile. S-57 does not have the concept of "cross-tile topology", but features that span multiple ENCs can be assigned the same feature object identifier (FOID). S-65 states:

- Editing should also only be done within a specific tolerance so that the accuracy of the data is not impaired to too great a degree (IHO 2009, p. 18).

For adjacent ENCs, it is possible to go one step further and say that features that span cell borders need to join at the exact location(s) on the cells' borders. In ISO-8211 (ISO 1994) encoding this is possible since coordinates are stored as integers, before being translated to latitude and longitude via a coordinate multiplication factor.

Edge matching for overlapping ENCs of different scales is more complex. If the line work of a small scale ENC is generalised from data sourced from a larger scale, edges will match within a small tolerance. Of particular interest are depth contours. Not only can depth contours match particularly poorly between different scales (Figure 5), they are often encoded at different intervals. Data producers need to ensure that consistent contour intervals are displayed, throughout the seamless display, no matter what scale the data sets are being viewed at. For example, a data producer may decide that for a particular region, within the scale range of 1:22000 and 1:45000, the following contours are to be displayed, 0, 5, 10, 20, 30 and 50. Any ENC (large or small scale) that is viewable within that scale band needs to have the above mentioned contours encoded. This will necessitate careful encoding of SCAMIN on depth contours.

**Large to Small Scale Transition Areas**

Imagine the situation where a large scale ENC partially overlaps a small scale ENC. The large scale ENC has a series of 10 metre shoals encoded near its cell extents. The overlapped small scale ENC has the shoals generalised into a single contour. The contours are broken when the ENCs are displayed side by side (Figure 10).

To resolve this situation, a transition area can be encoded at the boundary of the large scale ENC (Figure 11). The transition area provides the missing link between the large and small scale ENCs.

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**Figure 10.** This is an example of a large scale ENC (left) overlapping a small scale ENC (right). The large scale ENC has a number of 10m shoals encoded, whilst the small scale ENC has the shoals generalised into a single 10m contour. The display is discontinuous at the boundary of the large scale ENC.

**Figure 11.** This is an example of a large scale ENC (left) overlapping a small scale ENC (right).
Encoding the transition area removes the inconsistency and the display is now seamless (Figure 12).

**Vertical Reference Datum**

It is important to note that, in order to match depth contours at cell boundaries, each ENC needs to have its depth values encoded relative to the same vertical datum. Lowest astronomical tide (LAT) is the recommended vertical datum (Hecht et al. 2006, pp. 75-76).

**M_CSCLs and Holes in Data Coverage**

Areas of large scale data need not be encoded in small scale ENCs as M_CSCL areas. It is better to encode such areas as separate large scale ENCs. The M_CSCL areas can be replaced with data generalised to the appropriate scale range of the ENC. Similarly, holes in data coverage (Figure 7) can be filled with appropriate generalised data, where available. The ENC production system should be capable to perform this generalisation as part of the ENC generation process.

**Proposed Production Guidelines and Validation Checks**

The implementation of the following production guidelines will result in greater consistency of ENC data. The guidelines also serve as validation checks, which can be included in S-58 and incorporated into ENC validation software packages. The current development of the S-101 ENC Product Specification provides a good opportunity to adopt these recommendations.

**Overlapping Cells**

This set of guidelines applies to cells that share the same geographic region and have different compilation scales:

1. Scale independent features that refer to the same real world feature must:
   - share the same geographic location;
   - have an identical set of attributes;
   - share the same feature object identifier (FOID).

2. Navigable water of a small scale cell must not overlap non-navigable areas of a large scale cell.

3. Navigable water of a small scale cell must be shallower or equal in depth to overlapping areas of navigable waters of a large scale cell.

4. Small scale cells should not have areas of no coverage (M_COVR with CATCOV=2) where there is coverage available in a larger scale cell (IHO 2009).

5. Small scale cells should not have areas of a higher quality rating (M_QUAL) than overlapped features of a larger scale cell.

6. Features that cross the cell boundaries of a large scale cell should have a corresponding match in the overlapped small scale cell. The corresponding features must:
   - meet at the cell boundary (within a small tolerance) (IHO 2009);
   - have an identical set of attributes;
   - share the same FOID;
   - have their exterior boundary edges masked (IHO 2009).

**Adjacent Cells**

This set of guidelines applies to cells that are of the same scale and are adjacent to one another:

1. Features that are continuous across shared cell boundaries must:
   - meet at the cell boundary (IHO 2009);
   - have an identical set of attributes;
   - share the same FOID;
   - have their exterior boundary edges masked (IHO 2009).

2. There should be no gaps or overlaps between cell boundaries (IHO 2009).

**General Consistency**

The following guidelines are applicable for all cells:

1. SCAMIN should be applied consistently, as set out in S-65 (IHO 2009).

2. The coordinate multiplication factor COMF should be the same for all cells and is recommended to be set to 10^7 (IHO 2009).

3. The vertical datum should be the same for all cells within the same geographic region.
Conclusions
Addressing ENC consistency is important for the overall quality of data, the ECDIS display, and ultimately the confidence that the mariner places in the underlying datasets. Guidelines for the production of individual ENCs are well established and the process of validating these has been achieved with great success. The challenge remains for HOs to produce ENCs that have data encoded consistently along cell boundaries and throughout the scale bands. The use of modern enterprise GIS systems, production guidelines and the ability to automate cross cell validation will result in consistent and higher quality ENCs. Enterprise GIS systems are required not only for the production of consistent ENCs, but also to meet the increasing government and inter-government requirements to develop spatial data infrastructures.

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NAUTICAL DEPTH SOUNDING -
THE RHEOCABLE SURVEY METHOD
By ir. Marc DRUYTS (Belgium) and dr. ir. Peteralv BRABERS (Belgium)

Abstract
Since 1984, research and development activities have been undertaken in Belgium comprising in situ measurements and sea trials with TSHD 'Vlaanderen 18' in Zeebrugge. Towing tank experiments and sludge test tank experiments have also been performed in the laboratories of the Flanders Hydraulic Research. This work has enabled the authors to conclude that mud on the seabed consists of two different physical states occurring in the same configuration - fluid mud on top of solid (consolidating) mud.

Fluid mud is navigable, solid mud is not. The interface between both is characterized by a drastic increase of rheological parameters, in particular, the yield stress. However, for the time being, this phenomenon cannot be fully interpreted scientifically.

The Rheocable sounding method is designed to detect the interface between fluid and solid mud. A towed object, when kept in a velocity window, is always positioned at this interface between fluid and solid mud. This method makes it possible to develop a new maintenance dredging strategy - leave/ignore the fluid mud and remove only the solid mud.

The dredging of fluid mud is therefore unnecessary – it is navigable (!) – and extremely uneconomical. Solid mud on the other hand is not navigable, is immobile and will absolutely maintain its position on the seabed unless removed by dredging action. Furthermore, the deployment of the Rheocable implies many operational and contractual advantages, including transparency of dredged quantities etc.

The Rheocable cable sounding method allows for a considerably improved focus, smaller quantities and easier planning of the maintenance dredging activities, resulting in lower budgets and improved safety for shipping traffic.

Résumé
Depuis 1984, des activités de recherche et de développement ont été entreprises en Belgique, qui comprennent des mesures in situ et des essais à la mer sur le TSHD 'Vlaanderen 18' à Zeebrugge. Des expériences dans des bassins d’essais de carène et des expériences dans des bassins de boue ont également été réalisées dans les laboratoires de la Flanders Hydraulic Research. Ces travaux ont permis aux auteurs de conclure que la boue du fond marin consiste en deux différentes compositions physiques qui se présentent sous la même configuration – boue fluide sur un sommet de boue solide (en consolidation).

La boue fluide est navigable, la boue solide ne l’est pas L’interface entre les deux est caractérisée par un accroissement drastique des paramètres rhéologiques, en particulier le seuil d’écoulement. Toutefois, pour le moment, ce phénomène ne peut pas être entièrement interprété au niveau scientifique.

La méthode Rheocable de sondes est destinée à détecter l’interface entre la boue solide et la boue fluide. Un objet tracté lorsqu’il est maintenu dans une fenêtre de vitesse est toujours positionné à l’interface entre la boue fluide et la boue solide. Cette méthode rend possible le développement d’une nouvelle stratégie de dragage d’entretien. – de laisser/ignorer la boue fluide et d’enlever seulement la boue solide.

Le dragage de boue fluide n’est donc pas nécessaire – c’est navigable – et extrêmement peu économique. D’un autre côté, la boue solide n’est pas navigable, est immobile et
dragage. En outre, le déploiement du Rheocable implique des avantages opérationnels et contractuels incluant la transparence sur les quantités draguées, etc.

La méthode de levés Rheocable permet une mise au point considérablement améliorée, de plus petites quantités et une planification plus aisée des activités de dragage d’entretien, ce qui a pour résultat une réduction des budgets et l’amélioration de la sécurité du trafic maritime.

Resumen

Desde 1984, se han emprendido en Bélgica actividades relacionadas con la investigación y el desarrollo, comprendiendo medidas in situ y pruebas en el mar con el TSHD ‘Vlaanderen 18’, en Zeebrugge. Se han llevado a cabo también experimentos en canales de pruebas hidrodinámicas y experimentos de canales de prueba para sedimentos en los laboratorios de Investigación Hidráulica de Flandes. Este trabajo ha permitido a los autores concluir que el lodo del fondo marino consta de dos estados físicos diferentes en la misma configuración - el lodo fluido en la parte superior del lodo sólido (que se consolida).

El lodo fluido es navegable, el lodo sólido no lo es. La interfaz entre ambos está caracterizada por un aumento drástico de los parámetros reológicos, en particular la elasticidad. Sin embargo, por el momento, este fenómeno no puede ser interpretado del todo científicamente.

El sondaje empleando el método de flujo ha sido diseñado para detectar la interfaz entre el lodo fluido y el sólido. Un objeto remolcado, cuando se mantiene en una ventana de velocidad, está siempre posicionado en esta interfaz entre el lodo fluido y el sólido. Este método hace que sea posible desarrollar una nueva estrategia de mantenimiento del dragado - dejar/ignorar el lodo fluido y retirar sólo el lodo sólido.

El dragado del lodo fluido es pues innecesario - es navegable (¡!) – y extremadamente costoso. Por otra parte, el lodo sólido no es navegable, es inmóvil y mantendrá absolutamente su posición en el fondo marino a menos que sea retirado mediante el dragado. Además, el despliegue del método flujo dependiente implica muchas ventajas operacionales y transaccionales, incluyendo la transparencia de las cantidades dragadas etc.

El sondaje empleando el método de flujo permite un enfoque considerablemente mejorado, cantidades inferiores y una planificación más sencilla de las actividades de mantenimiento del dragado, dando como resultado presupuestos inferiores y una mejora en la seguridad del tráfico marítimo.
Introduction
The problem of the determination of the Nautical Depth in mud environments is illustrated in Figure 1 which represents a classical vertical bathymetric section across a channel using a dual-frequency echosounder with two different acoustic sounding frequencies: 210 kHz and 33 kHz. In the port of Zeebrugge, the difference between both can vary between approximately 2 and 4 m. Such a marked difference between 210 and 33 kHz signals is characteristic for the presence of mud.

Figure 1. [1]

The following questions arise from these observations:
Which depth has to be communicated to a captain or pilot of a deep draft ship?
Which depth is meant by the PIANC definition of the Nautical Bottom (PIANC-IAPH 1997)? [16]

'The level where physical characteristics of the bottom reach a critical limit beyond which contact with a ship’s keel causes either damage or unacceptable effects on controllability and manoeuvrability' [16]

In Zeebrugge, this problem received much attention during the period 1984 – 1988 [2]

An ongoing extensive research programme revealed two important facts:

The existence of a transition zone in terms of rheological behaviour in the mud layer, implying the presence of two different physical states of the same sediment: fluid mud for the top layer and consolidating mud (soil) or solid mud for the lower layer. This transition zone more specifically expresses itself as a very sudden and drastic increase of the mud yield stress.

Trials with the TSHD ‘Vlaanderen XVIII’ in Zeebrugge, navigating with an under-keel clearance close to zero with respect to the rheological transition zone, showed a stark decline in maneuverability and steerability of the ship [3], totally unacceptable in terms of safe navigation.

Two different physical states
1.1 Initial observations

The existence of a rheological transition implies the presence of two different physical states of the same material: fluid mud and solid mud (soil). This can be experienced on board of any trailing suction hopper dredger carrying out dredging operations. At a certain point when lowering the draghead, the mixture velocity will be drastically reduced within a depth interval of a few decimetres when the draghead passes the interface between fluid and solid mud. Figure 2 shows pump – and pipe resistance curves where the mixture velocity drops from 5 m/s to 2 m/s when passing through the transition zone.

Figure 2.
Another observation also confirms the existence of mud in two different physical states. Figure 3 shows the mixture density and the mixture velocity histograms of the same dredging operation. While the density histogram shows a single density population, the mixture velocity histogram clearly shows two different populations.

1.2 Further Research and Development

Since these early observations, more facts and details have become known. Ongoing research carried out by Malherbe et al [14] provided the important discovery of the rheological transition in mud as early as 1986.

At that time (1988), the interface between the fluid state of the mud and the solid state was called the rheological transition zone.

This transition from a watery suspension into a soil structure with measurable shear stress, is influenced by density, water content, and by the sand content of the mud (Figure 4). This occurs at any location where sedimentation / flocculation of fine grained material takes place.

In more recent years, reference has also to be made to the research and experiments of Wurpts [4]. He describes the phases in the process of mud formation and shows the different properties of fluid mud and solid mud (soil):

- aerobic versus anaerobic
- organic versus inorganic
- absence of gas versus presence of gas
- difference in colour
- process of flocculation versus process of consolidation
- fluid dynamics versus soil mechanics
- low yield stress (25 Pa) versus high yield stress (1000 Pa)

An extremely important observation by Dr. Wurpts is that in a navigation channel, it is inefficient and useless to dredge fluid mud - only solid mud needs to be dredged (or treated). Hence the importance of locating, or sounding the interface between fluid and solid mud in relation to maintenance dredging activities. This interface can be made visible as shown in the Figures 5, 6 and 7, taken in the DEME harbour at low tide along the river Scheldt at Antwerp.

As soon as ‘decantation’ process is accomplished, the fluid mud is gone with the tide and the solid mud shown in the pictures will stay and not move unless removed eventually by some dredging process.
An exhaustive description of the sedimentation process and the consolidation process of cohesive sediment has been made by Toorman [5]. Significant research in this field has also been carried out by the Waterway Experimental Station (WES) of the US Army Corps of Engineers. [6] They reported that, at the end of the sedimentation process or at the beginning of the consolidation process (meaning the interface between fluid mud and solid mud), the water content is equal to the liquid limit (Atterberg), multiplied by 2.5.

This observation is significant. It relates the density at the fluid / solid interface to the nature of the mud: silt, clay [15]. It shows that density as a parameter for the Nautical Depth is basically inappropriate, because it depends on the mud composition (refer to Figure 4: the influence of sand content on the density at the rheological transition). Furthermore, it was found that in the upper layer of 30 cm in the fluid mud, the water content is about 5 times the liquid limit.
1.3 Rheological transition / discontinuity: some examples

In the laboratory, during the Rheocable and Accelero probe tests [8], the rheological profile in the sludge test tank (SST) was measured with great accuracy (Figure 8). The transition / discontinuity can be observed between a depth of 85 cm and 97.5 cm. The part of the profile lower than 100 cm, did not allow in situ measurements. The measuring instrument is unable to penetrate in the solid mud.

The density profile shown in Figure 9, shows a similar transition at the same location. This is unlike the in situ situation where the density transition is normally positioned in a position lower than the rheological transition. Figure 10 shows the shear stresses versus depth, at the shear rates of 0.1 and 1000 (1/s).

Both profiles have different values above and below the discontinuity, but in both cases the discontinuity occurs at the same level. In an interval of 12.5 cm, the shear stress increases drastically with a factor of about 10: from about 50 Pa up to 500 Pa for the 0.1 shear rate, and from about 80 Pa up to about 800 Pa for the 1000 shear rate.

The rheological transition from fluid mud to solid mud is therefore perfectly detectable. The difference will show up, independently from the applied shear rate, even at varying shear rates.

The existence of two different physical states of the mud is also confirmed by the relation yield stress – density. Figure 11 shows this relation density – shear strength at an applied 0.1 1/s shear rate. At this low shear rate, the stresses measured are as close to the yield stress as possible. (See also the similarity with the laboratory results reported by Haecon in 2008 [7]).

It confirms and illustrates the existence of two different physical states: a fluid mud state and a solid mud state. At the interface, the yield stress increases very quickly. In situ, this will be recorded as a discontinuity in the yield stress profile.
Figures 12 and 13 illustrate the rheological discontinuity that has been picked out of a series of prick soundings in the Central Part of the New Harbour in Zeebrugge, carried out for the Department of Flemish Hydrography on the 8 of June 2009 using the Rheotune (Stema).

The interface between fluid mud and solid mud is easy recognizable: observe the fact that the interface has a density of 1180 g/l.

1.4 Rheological transition/discontinuity - (absence of) scientific background

During the Rheocable and Accelero probe tests in laboratory conditions [8], the rheological profile was measured with great accuracy (see Figure 14), where shear stress is recorded versus shear rate at different depths in the SST.

The rheological difference between the levels of 85 and 95 cm depth – the red (above the discontinuity/transition zone), respectively the green line (below the discontinuity/transition zone) – is striking. Both lines are to be associated with Bingham fluids, but the line at a depth of 95 cm reveals an initial yield stress which is about 10 times higher.

At the level of 105 cm and further down in the solid mud, the relation shear rate / shear stress changes its profile: the yield stress is higher, but the shear stress falls with increasing shear rate, reaches a minimum and continues like a Bingham fluid. In this case, the yield stress is named ‘static’ yield stress, the minimum is called ‘dynamic’ yield stress.

Figure 12

Figure 13

Figure 14
This phenomenon widens the already existing rheological gap. Toorman [13] describes this phenomenon (see Figure 15) and makes reference to a secondary structure in some cases. But an explanation for its occurrence in some clay suspensions is unknown.

Apparently, the mud in the test tank is part of this category of clay suspensions showing static and dynamic yield stresses. The mud is a direct sample from the seabed which implies that potentially all mud in our harbours and shipping channels belongs to this category. This wide rheological gap between fluid and solid mud lacks a satisfactory scientific explanation.

This is further evidence for the existence of two different physical states of the mud, with very different rheological properties and separated by a small transition zone, which in situ is recorded as a discontinuity.

1.5 Summary and discussion

Figure 16 represents schematically the properties of the two different physical states of the mud as known.

![Figure 15](image_url)

![Figure 16](image_url)
The corresponding average density and rheological profiles (in Zeebrugge) are represented in Figure 17 [7].

With regard to the relation between both, following details are important to notice:

- The lines AB and EF are positioned near the 210 kHz level
- The point of articulation G in the density profile is situated below the point C (= rheological transition point)
- The point of articulation G is positioned above the 33 kHz level.

In section 4.1, the Rheocable soundings in Zeebrugge exactly show and repeat these observations.

In Emden a yield stress of 70 Pa is momentarily used as the definition of the Nautical Depth, with the perspective / hope of changing the definition to 100 Pa in the future - density definitively has been put aside. We agree with Wurpts to choose the parameter of the yield stress to define the Nautical Depth, but for different reasons. We will not use a particular value of the yield stress, but rather the discontinuity of the yield stress between fluid and solid mud as the main criterion defining the Nautical Depth.

2. A ship’s behaviour: TSHD ‘Vlaanderen XVIII’

Trials with the TSHD ‘Vlaanderen XVIII’ in Zeebrugge (Figure 18), navigating with an under-keel clearance of about zero with respect to the rheological transition, showed a very stark decline in manoeuvrability and steerability of the ship [3], totally unacceptable with respect to normal and safe navigation. The vessel kept moving on, but was unmanageable!

![Figure 17](image)

**Figure 17**

**Figure 18**

Conclusion

As reported by Wurpts [4], and confirmed by the laboratory observations, the yield stress shows a major discontinuity in the transition between fluid mud to solid mud and he proposes the yield stress as the parameter to specify the Nautical Depth.

The yield stress is a measure of the force needed to start the fluidisation of the mud: 25 N per m² (2.5 kg) in the fluid mud state, 1000 N per m² (100 kg) in the solid mud state. Wurpts [4] characterizes the fluid mud as ‘navigable’ (i.e. a vessel is able to navigate in a sea of homogenous fluid mud) and the solid mud as ‘not navigable’.
With the ship’s bottom in contact with the solid mud at the interface level, the normal flow of water / mud to the propellers is severely hindered and quasi interrupted due to the high yield stress of the solid mud. Consequently, the propeller’s thrust is significantly reduced, including its effect on the rudder: the ship completely loses her manoeuvrability and steerability.

On the other hand, the contact of the vessel’s keel with the interface generates quasi no frictional forces: the vessel keeps going her own way, completely out of control.

It is clear that the under-keel clearance with respect to the rheological transition of the mud is an important parameter when analyzing the behaviour of a deep draft vessel navigating above a seabed of mud. However, the position of the Nautical Depth and the properties of the fluid mud layer are not the only parameters influencing the behaviour of a deep drafted vessel. Ship related parameters have to be considered as well such as speed, keel clearance, squat, type of manoeuvre etc.

The interaction between ship and fluid mud layer has been investigated extensively by Vantorre and his team in the specially build towing tank in Flanders Hydraulic Research, Borgerhout Antwerp [9].

An important result of this research is that although the keel clearance relative to the Nautical Depth is extremely important, keel clearance relative to the water/fluid mud interface has significant effects as well.

For safe and fluent navigation, pilots, captains and ship’s officers need to know both levels: the 210 kHz level and the level of the rheological transition zone, meaning the yield stress discontinuity level in the mud. As the 33 kHz and the 1.2 density signals fail in providing the latter level, there is an urgent need to find a valid sounding method capable of detecting the Nautical Depth!

### 3. The Rheocable Method

#### 3.1 Principles

Any object, towed on a cable through water, will meet resistance. The depth of the object will depend on the towing speed through the water. The same applies for a Bingham or Herschel–Bulkley fluid, with this difference that an extra force is required to overcome the yield stress and extra energy for the liquefaction of the mud displaced by the object.

For a fluid mud, with low yield stress, friction forces are low, the energy for liquefaction is low, therefore the resistance and towing force are low, and the corresponding position of the object, when towed in an homogenous fluid mud environment is low (Figure 19).

For a solid mud, with high yield stress, friction forces are high, the energy for liquefaction is high, therefore the resistance and towing forces are high, and the corresponding position of the object, when towed in a homogenous solid mud environment is high (Figure 20). In reality, the object will come out of the solid, gel-like mud.
A second principle used by the Rheocable sounding method is the fact that fluid mud and solid mud have different electrical resistivity values. The resistivity of the fluid mud layer is low (especially higher above the transition zone), compared to the resistivity of the solid mud layer. By measuring resistivity of the towed object whilst underway, the Rheocable method is able to verify (and record) continuously whether or not the towed object is in contact with the solid mud, i.e. that the towed object is not floating. If the object leaves the fluid/solid mud interface and starts floating above it, this results in an instantaneous decrease of the measured resistivity value.

Finally, the depth of the towed object is recorded by measuring the hydrostatic pressure – with measures in place to compensate for variable density values within the fluid mud layer – and by measuring the density of the water column at different levels.

### 3.2 Measuring array

The towed object consists of a weight and a pressures sensor, tightly wrapped in a protective rubber hose, and a resistivity cable attached to it (see Figure 22). The resistivity cable includes 4 electrodes, used to measure the resistivity. This combination is connected to the survey vessel by an umbilical cable. It has several functions: towing the combination, bringing DC current to the resistivity cable, and transmitting signals to the computers on board the survey vessel.
Figure 23 shows the resistivity cable attached to the towed object. Figure 24 shows the complete towed object with the umbilical cable. Figure 25 shows the AC/DC Converter and the attached computer for monitoring and recording the resistivity values. Measurements and recordings are carried out with a frequency of 1 Hertz.

The length of the cable is approximately 3 times the depth to be surveyed - for a channel depth of 20 m, a 60 m long umbilical cable will be used at velocities up to 4 knots.

During a working day of 8 hours, a length of about 30 to 50 km can be surveyed. This is about 3 to 6 times more than would be possible with a prick probe, taking a prick every 100 m - 70 pricks per working day being a standard for this kind of activity. Consequently the cost of the Rheocable method versus prick probe survey – ship, surveyors, etc. can be estimated at 1 versus 3 to 6. Furthermore, considerably more information and detail will be available with the Rheocable method of sounding because every second a depth sounding is recorded.

Any vessel can be used as a platform for the survey. The Rheocable equipment is self sufficient, including generator, positioning system, 210 kHz survey system, etc. A well equipped survey vessel, handled by a survey crew, is the ideal platform. Moreover, after 1 or 2 surveys and with some instruction and assistance, the crew will be able to carry out a Rheocable survey without any assistance from the THV Nautic.

3.3 Analytical model

In order to investigate the behaviour of the cable combination during towing, an analytical model was developed. This model enables the study of the different parameters – cable length, cable diameter, cable weight, additional weights etc. and their influence on the ‘performance’ of the cable. Performance in this context is defined as the ability of the cable to keep its ‘tail’ on the seabed and in contact with the solid mud, at a towing speed as high as possible.

The model can be calibrated easily by towing the cable in a floating condition at different velocities whilst recording speed and depth. Figures 26 and 27 show two examples of such a calibration carried out in IJmuiden and Zeebrugge.
The model is sufficiently accurate to assist with the clarification of some questions and problems put forward [10].

3.4 Resistivity

Resistivity is a key feature of the Rheocable system to ensure the cable is effectively in contact with the fluid/solid mud interface. During the survey trials in October 2009 in Zeebrugge, a resistivity test was carried out. The same survey line was run with different speeds in order to determine the velocity beyond which the cable started floating and losing contact with the solid mud.

Figure 28 shows the frequency distribution of the survey velocity values recorded. With each velocity recorded, a resistivity value is associated, measured and recorded at the same time. Figure 29 shows the frequency distribution of these resistivity values and clearly indicates, contrary to the Figure 28, two different sets of resistivity values, sharply separated at a resistivity value of 0.300. Figure 30 shows the frequency distribution of two sets whereby the velocities are associated with resistivity values lower than 0.300 and higher than 0.300.

Both are apparently normally distributed, with medians respectively 2.6 knots and 4.4 knots. The 2.6 knots set is associated with resistivity values higher above 0.300 Ohmm whilst the 4.4 knots set has resistivity values lower than 0.300 Ohmm.

For this particular type of cable used and for the given depth range, the velocity of 3.6 knots appears to be the limit between both sets and is the difference between the rheocable being in contact with solid mud or floating.

There is an area of overlap around the 3.6 knots interface: this is due to the fact that with increasing velocities, the Rheocable ‘sticks’ somewhat longer to the solid mud and with decreasing velocities, the Rheocable takes more time to re-establish contact with the solid mud.

Figure 29 proves that the parameter resistivity ($\rho$) can be used to establish, unequivocally, the fact that the Rheocable is in contact with the solid mud and therefore indicating the Nautical Depth. Figure 30 indicates that this contact can be guaranteed / secured by keeping the survey velocity below a certain level.

All sounded depths, associated with resistivity values lower than 0.300 Ohmm, will be deleted when producing survey charts. This eliminates all ‘false’ sounded depths (associated with a floating cable situation) and guarantees true Nautical Depths to be represented in the charts.

4. Rheocable method results

4.1 In situ Nautical Depth surveys

Figure 31 shows an example of a Nautical Depth survey carried out in Zeebrugge with the Rheocable [11]. The survey took about 6 hours to complete – mobilization and demobilization excluded, and was otherwise simple, transparent and straightforward.
The results of other survey techniques using acoustic methods at 210 kHz and 33 kHz and the density pricks, with reference to the Rheocable survey are shown in Figures 32 and 33. Figure 32 relates to the area ZP1 which is the most southern area of the port whilst Figure 33 relates to the central part of the new outer port (CDNB).

The blue graph is the frequency distribution of the depths measured using the Rheocable. The grey graph is the 33 kHz frequency distribution, the green graph shows the 210 kHz and the red graph represents the 1.2 density depths by the prick probe.

In the area ZP1, the distributions have roughly the same characteristics, only that the modes are significantly shifted. The most important is the shift between the Rheocable (interface fluid/solid mud) and the 1.2 density distribution (official Nautical Depth). The interface fluid/solid mud is shallower than the 1.2 density by 0.5 m, meaning that the ‘real’ nautical depth is 0.5 m shallower as compared to the ‘official’ nautical depth. The distributions in the CDNB have a considerable higher variance and the difference between Rheocable and 1.2 density modes is smaller.
It can be seen in both areas, that the Rheocable result is positioned at shallower levels as compared to the 33 kHz results as was already recorded in the Haecon study [7] (see Figure 17).

The same observations were made during survey trials in the Port of IJmuiden (Figure 34) and also during further surveys in the Port of Zeebrugge. The observation that the position of the fluid/solid mud interface is situated at shallower levels as compared to the ‘official’ and nautical depth surveys is significant and could help to explain some difficulties of ships trying to manoeuvre in these areas.

4.2 Laboratory Tests

In June 2011, Rheocable tests were carried out in the Sludge Test Tank (STT) of Flanders Hydraulic Research (FHR) [12]. The dimensions of the STT did not allow tests to be performed with the original Rheocable. Therefore an adapted Rheocable model was used. The weight and dimensions were reduced and the resistivity function renounced. This adapted Rheocable was towed in the tank with various velocities. The result of these tests is shown in Figure 35.
The tests confirmed the existence of a velocity window. The towing velocities in the window generate the same depth position of the Rheocable with regard to the interface between fluid mud and consolidating mud. At the lower end of the window velocity, all test runs, except one, show that the Rheocable sinks into the consolidating mud at zero tow velocity and that already at a minimal towing velocity, the Rheocable moves up to its fixed liquid/solid mud interface position.

Once completed the acceleration phase, the position of the Rheocable remains fixed (within 2 to 3 cm) – fully independent of the varying tow velocity up to a velocity of about 0.75 m/s. At higher velocities, the Rheocable starts to float as experienced in both test runs with higher velocities. This proves that the cable stays on a rheological transition level for a determined speed window.

In a real environment the width of the speed window naturally depends on water depth, umbilical cable length, cable design and cable weight.

5. Maintenance Dredging: a new strategy

The procedure of sounding the Nautical Depth, as applied by a majority of maritime and port authorities, uses the method of sounding a density horizon in the mud, 1.2 in many cases. Today, it is generally accepted that this procedure is far from accurate and leaves much to be desired when used to control/quantity the necessary maintenance dredging works. More specifically it is recognized that problems exist concerning the quantification of quantities dredged and quantities to be dredged. Notwithstanding these deficiencies, most authorities are fully capable of running a safe operation, due to their vast experience and careful approach, albeit with a relatively high budget.

However, with the availability of the ‘Rheocable method’ a new sounding method capable of accurately defining the true Nautical Depth, different dredging strategies for the handling of maintenance dredging works can be introduced, leading to improved safety and reduced costs.

5.1 The Principle

The measurement of the Nautical Depth, as made possible by the Rheocable method of THV Nautic, produces the position of the interface between fluid mud and consolidated mud (Figure 36).

This distinction between fluid mud and consolidated mud, made possible by this sounding method, is very important in that principally, fluid mud doesn’t need to be removed from the seabed as it is navigable. Furthermore, fluid mud is mobile and when driven by wind, tide and currents, can travel considerable distances. It may even disappear from the area to be dredged under the effect of outgoing tidal currents. The dredging of fluid mud is therefore unnecessary and very uneconomical.

Consolidated mud on the other hand is not navigable, is immobile, will absolutely maintain its position on the seabed and is not affected by wind, tide or currents. If the guaranteed water depth is situated below the rheological transition zone (in the consolidated mud), this mud needs to be removed.

Solid mud needs to be removed

The under-keel clearance of a ship with reference to the interface fluid/solid mud and the under-keel clearance with reference to the 210 kHz level, are the critical parameters with regard to the behaviour and the safety of the ship.

Whilst the 210 kHz level cannot be influenced by dredging, the interface fluid/solid mud can, by dredging the solid mud. Therefore, the new dredging strategy proposed in this paper supposes the implementation of two important elements:

- The rheological transition between fluid mud and consolidated mud is the real Nautical Depth and must be accepted and specified as such. (Density horizons must be removed as definitions of the Nautical Depth)
- ignore the fluid mud and remove only the solid mud when necessary.
5.2 Operational Advantages

Control of the dredging activities can be carried out independently of the dredger, simply and efficiently:

Dredged quantities are calculated in m³ using in- and out-surveys.

The measurement of dredged quantities on board of the dredger, such as hopper density and /or TDM (tons of dry material) in case of a trailing suction hopper dredger, is unnecessary. Systems, automatic or not, developed for this purpose, have become superfluous.

Any dredging equipment

Abstraction made from environmental and contractual elements (such as shipping traffic, contaminations etc.) means the nature of the dredging equipment is no longer relevant - water injection dredger, cutter suction dredger, hopper suction dredger, bucket dredger, plow (with or without jets), etc. As long as the out-survey shows nautical depth levels obtained to meet the specifications, any dredge technique is acceptable.

Therefore, different dredging techniques can be used in one dredging area without consequences/comlications for the control and measurement of the dredge quantities.

Contractors can be charged to carry out intermediate soundings. It is only necessary for the Principal to carry out the in- and out-survey.

Limited or no supervision on board.

The limitation of the ‘suction tube depth’ is obtained by not paying, or even, by fining the quantities dredged below the target depth plus tolerance. ‘Overdepths’ can easily be detected and quantified using the Rheocable method. The tendency of dredging contractors to dredge deeper than required, when hopper densities are used for the calculation of dredge quantities can be avoided by the contractor, because they know it will not be paid for or even be fined. Consequently, supervision on board of the dredger is no longer required.

Dredge quantities located outside the dredging area, when made non-payable or fined can easily be detected using the Rheocable method - contractors will try to avoid this.

The disposal of dredged material within the specified areas can be checked using registrations of the existing positioning systems on board, controlled eventually by existing radar facilities ashore.

Dredge overflow, in the case of suction hopper dredgers, is not critical with the new dredging strategy and can be left to the discretion of the contractor.

Supervision on board with the purpose of ensuring a tight control of the maintenance dredging activities is no longer required.

5.3 More or less maintenance dredging activities?

Comparing dredged mud quantities, measured in tons of dry material (TDM) with dredged in situ mud quantities measured in m³, is never a simple exercise. During the dredging process, mud continuously changes density and volume on its way from the seabed up into to the hopper, during the stay in the hopper, and unless the changing densities together with the changing volumes can be measured and recorded - quod non – the exercise of comparing m³ of in situ mud with tons of dry material remains uncertain. Furthermore, a distinction between fluid mud and solid mud cannot be made.

Another imponderable element is overflowing.

The confusion, caused by the presence of fluid mud, in terms of ‘classic’ sounding data and in terms of quantities dredged, disappears when using the Rheocable.

The same applies when the contract uses a density horizon: for example 1.2. This inadequate criterion leads inevitably to more quantities dredged and paid for than strictly necessary.

For ongoing dredging contracts, which have not been based on Rheocable determined strategies, the Rheocable method can be used to determine the real efficiency of ongoing maintenance dredging activities and also to prepare for contracts based on Rheocable soundings.

It is reasonable to anticipate a considerable reduction of the dredging effort and the related budget.

The Rheocable sounding method allows for a much better focus and planning of the maintenance dredging activities.
Conclusion

The use of the Rheocable sounding method, capable of measuring directly the transition between fluid and consolidated mud, allows for a much better focused approach and control of maintenance dredging activities involving mud. The superfluous dredging of (navigable) fluid mud is avoided and the necessary dredging is limited to the (not navigable) solid mud.

Start, finish and quantities of the dredging campaign will be determined correctly using an accurate sounding method. This has considerable beneficial effects upon:

- The safety and fluency of shipping traffic
- The planning of the dredging campaigns
- The quantities to be dredged
- The production and efficiency of the individual dredgers
- The budget of the maintenance dredging works

The introduction of the Rheocable sounding method, measuring directly and accurately the interface between fluid and consolidated mud, will provide the competent authorities with an adequate tool to support their decisions and will significantly improve cost savings and safety for shipping traffic.

References


Biographie of the Authors

ir. Marc Druyts has been a part of the Belgian dredging company Decloedt, later called DEME NV, for years.

He achieved an engineering diploma for naval architecture at the State University of Gent, and started working at the company Decloedt in Zeebrugge in 1985, where he initially led the technical department. Between 1991 and 2001, he led the dredging operations on the Belgian coast in the function of Executive Director of the TV (temporary company) Noordzee & Kust. This TV is still performing dredging operations on the Belgian coast to this day.

Since May 2001 he is a self-employed consultant through his company MDCE bvba. (http://mdce.be)

Dr. ir. Peteralv Brabers has done geo-technical surveys for years with his own company all over the world, mainly on water but also on land, primarily for dredging companies, but also for harbour authorities and management boards. His unique specialty is the execution and processing of resistivity measurements, a geophysical method capable of accurately defining the seabed geology.

P. Brabers is CEO of his company DEMCO nv. (http://www.demco-surveys.com)

Marc and Peteralv founded THV Nautic as a partnership, to give a home to their combined activities related to sounding the nautical bottom.
HYDROGRAPHIC CONFERENCES - SOME OBSERVATIONS
Ian W. HALLS
IHR Editor

Abstract
In my capacity as the IHR Editor, I am fortunate to have been invited to two international hydrographic conferences in 2011. The first was hosted by The Hydrographic Society of America (THSOA) and was held in Tampa, Florida USA in April. The second conference was hosted by the Australasian Hydrographic Society (AHS) and was held in Fremantle, Western Australia in November. My last attendance at an international hydrographic conference was in 2003 at the AHS-hosted conference in Christchurch, New Zealand – so it has been a few years between visits. This paper describes my observations about the two conferences and in particular notes the similarities and the differences between the two conferences and hopefully may provide some ideas for future conference organising committees.

Background
Usually each conference will have its own theme directed at the current issues at hand. The underlying purpose is to provide a forum for education, cooperation, networking, professional development and catching up with friends who usually work in far flung, remote environments. Such conferences provide many in the profession with the single opportunity each year or couple of years to meet up and share their journey.

In Australia, the Australasian Hydrographic Society (AHS) organises through the International Federation of Hydrographic Societies (IFHS) to host a conference in the Australasian region every 4 years. Often this is the only time when hydrographers who work on either side of the continent or overseas are able to meet with one other and renew friendships. The importance of these events in Australasia cannot be underestimated.

Hydrographic Conference Schedule
The schedule of hydrographic conferences from 2010 to the end of 2012 are listed at Table 1.

<table>
<thead>
<tr>
<th>Date</th>
<th>Conference</th>
<th>Place</th>
<th>Host</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 2010</td>
<td>Canadian Hydrographic</td>
<td>Quebec, Canada</td>
<td>Canadian Hydrographic Association (CHA) – held every 2 years</td>
</tr>
<tr>
<td></td>
<td>Conference</td>
<td></td>
<td></td>
</tr>
<tr>
<td>November 2010</td>
<td>HYDRO 2010</td>
<td>Rostock, Germany</td>
<td>German Hydrographic Society for IFHS</td>
</tr>
<tr>
<td>April 2011</td>
<td>US HYDRO 11</td>
<td>Tampa, USA</td>
<td>The Hydrographic Society of America (THSOA) – held every 2 years</td>
</tr>
<tr>
<td>November 2011</td>
<td>Hydro 2011: Down Under</td>
<td>Fremantle, Australia</td>
<td>The Australasian Hydrographic Society for IFHS</td>
</tr>
<tr>
<td>February 2012</td>
<td>Shallow Survey 2012</td>
<td>Wellington, New Zealand</td>
<td>Held every 4 years</td>
</tr>
<tr>
<td>April 2012</td>
<td>IHO International Hydrographic Conference</td>
<td>Monaco</td>
<td>International Hydrographic Bureau (IHB) – held every 5 years</td>
</tr>
<tr>
<td>May 2012</td>
<td>Canadian Hydrographic</td>
<td>Niagara Falls, Canada</td>
<td>Canadian Hydrographic Association (CHA)</td>
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<td></td>
<td>Conference</td>
<td></td>
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</tr>
<tr>
<td>November 2012</td>
<td>Hydro12</td>
<td>Rotterdam, The Netherlands</td>
<td>Hydrographic Society Benelux for IFHS</td>
</tr>
</tbody>
</table>

Table 1. List of major international hydrographic conferences 2010 - 2012
The above table shows that major conferences are conducted annually by the IFHS within Europe and Australasia (every 4 years) along with annual conferences in the North America region. This provides a good balance of opportunity for hydrographers to meet regularly within their own region. Within Australia, this is not so predominant but we need to operate in a global economy and the importance of the events usually means that members of the profession will attend overseas events as needs and opportunities dictate.

Scattered amongst these major conferences are also regular technology supplier user or training conferences e.g. CARIS, ESRI, HYPAC. These are becoming large conferences in their own right.

**US Hydro 2011 and AHS Hydro 2011 – Observations**

Comparing the two conferences, there were many similarities:

Both conferences were very well attended with full exhibition spaces, good venues, on-the-water demonstration capabilities, and a full program of presentations. Presentations covered a range of topics to ensure that all aspects of the profession were covered and both conferences provided specific workshops that were well attended. Whilst presentations were predominantly from local authors and organisations, overseas presentations provide opportunities to share and learn about important survey and R&D activities in those regions.

The US and Australasian regions are quite different in terms of the numbers in the profession, academic support, R&D opportunities and the size of the industry as a whole. Some of the noticeable differences were:

- Attendee age
- Student attendance
- Female involvement
- Role of Academia

**Age of Attendees**

At the Australasian conference, the average age of attendees was markedly higher than that attending the US conference. The age issue was commented on during an open session at the AHS conference and is an ongoing concern within the Australasian region. Encouraging younger people into the profession is an issue facing our industry. The younger average age of participants at the US conference can probably be attributed to the THSOA Student Outreach Program.

**THSOA Student Outreach Program**

THSOA has a magnificent Student Outreach Program. The program commenced in 2003 with three students. In 2011, this had grown to 27 students representing 18 colleges and universities. The purpose of the Student Outreach Program is to introduce the field of hydrography and associated education and employment opportunities to undergraduate students. I had the pleasure of meeting several of the students and they were all energetic about the conference opportunity. Several had never been exposed to hydrographic surveying. The students had their own program and attended the conference functions with the rest of the delegates. I cannot speak more highly of this initiative and recommend to all Societies and organising committees to consider adopting a similar model. This program will capture the imaginations of our young geospatial students and foster a mentoring role to maintain a healthy profession.

In comparison, there were only a very small number of students in attendance at the Australian conference. It is not known why this was the case. November is probably not a good time of year due to being at the end of the university year and could clash with final exams. Another reason could be related to the overall poor state of surveying, geomatic and hydrographic education within Australian universities. Refer to O’Connell (2006) for further discussion on opportunities for attracting young people into the profession.
Females in the Profession

This is always going to be a difficult area to discuss. The nature of the work and the operating environment makes this a more difficult profession for women to be actively and/or desirable to be involved. The issue of encouraging more females into the profession is a global challenge. There were markedly more women at the US conference, aided by the 30% of students being females.

Involvement of Academia

This was an area more dominant in the US than Australia, primarily due to the larger number of universities and dedicated research groups in the US. At this time, there is no major institution teaching postgraduate hydrography in the Australasian region (hopefully to be remedied soon). The US conference has always been noted for the quality of the presentations made from academia.

Some of the key Australian universities that have previously provided excellent surveying courses have altered the course to be predominantly engineering-based. Further, with no dedicated post-graduate and research schools in hydrography, the academic R&D within the region is extremely poor. Hopefully, some new education initiatives will address some of these issues.

Hydrographic conferences are an important aspect of our profession. They provide opportunities for improving education, allowing current and future professionals to meet with one another, industry to showcase its technology and an open sharing environment for the profession to come together. Our profession is not on its own with issues around an aging workforce, small number of females, attracting youth to the profession, the impact this has on academic support and diminishing travel budgets. Running a conference is hard work and requires a dedicated team on the organising committee. The end result though is worth it.

In comparing the two conferences, what stood out was the Student Outreach Programme developed by THSOA. Supporting such a programme locally within the jurisdiction of each Society has added benefits to potentially increase the support of academia and include more females into the profession.

Acknowledgements

I would like to sincerely acknowledge my thanks to the THSOA organising committee who funded my attendance to the US Hydro 2011 conference in Tampa. My last US Hydro conference was in 1992 in Baltimore which ran back-to-back with the first ECDIS conference. It has been a long time between visits and both were very beneficial. I also need to thank the Hydrographer of Australia, CDRE Rod Nairn, RAN AM who sponsored my attendance to the recent Australasian Hydrographic Conference in Fremantle.

References

A REPORT ON HYDROGRAPHIC ACTIVITIES FOLLOWING THE GREAT EAST JAPAN EARTHQUAKE

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Abstract

The Great East Japan Earthquake (Mw=9.0) on 11 March 2011 accompanied with a huge tsunami of more than 10 meters in height devastated many cities and ports along the Pacific coast of northeastern Japan, and claimed nearly 20,000 lives with many of them still missing. This report reviews actions taken by the Japan Hydrographic and Oceanographic Department (JHOD) after this unprecedented disaster.

Immediately after the earthquake, the JHOD carried out hydrographic surveys for the urgent need to help clear the passage in ports due to sunken debris swept away by the tsunami. These surveys have enabled the vessels with relief supplies on board for the affected areas to enter the ports.

The JHOD revisited the affected ports for the next stage of hydrographic surveys. These surveys will contribute to revised nautical charts based on new data collected after the earthquake, and includes the ongoing restoration and reconstruction work of quays and port facilities. This stage includes the re-determination of the datum level of the affected ports, which is necessary because of large subsidence being reported in the areas.

All of these efforts by the JHOD clearly demonstrate the significance of the hydrographic activities in case of the post-quake emergency situation, not only for the safety of navigation but also for economic recovery.

1. Introduction

An unprecedented huge earthquake (Mw=9.0) occurred on 11 March 2011, with the hypocenter located under the Pacific Ocean seafloor off the coast of eastern Japan. This resulted in a huge tsunami of more than 10 meters in height slamming into the Pacific coast along northeastern Japan. The earthquake and tsunami devastated many coastal cities and ports, and claimed nearly 20,000 lives with many, sadly still missing.

Immediately after the earthquake and tsunami, the Japan Hydrographic and Oceanographic Department (JHOD) of the Japan Coast Guard (JCG) dispatched all five survey vessels belonging to the JHOD to the affected areas, as part of emergency actions taken by the government of Japan (Sengoku and Saegusa, 2011). We carried out hydrographic surveys to help clear the passage in ports with sunken debris. These surveys have enabled the vessels with relief supplies on board for the affected areas to enter the ports. Our prompt dispatch of hydrographic survey vessels has been highly appreciated by local communities and pilots associations.
Significant subsidence of ground level caused by the earthquake was reported in the ports around the east coast of Japan. The tsunami surge was so powerful that water depth in the ports were changed. The JHOD has been revisiting the affected ports to carry out hydrographic surveys, including the observation of the datum level of the affected ports. The surveys identify progress of restoration and reconstruction work of quays and port facilities, and will enable new editions of nautical charts to be published. The JHOD has also made GPS/Acoustics seafloor geodetic observations near the hypocentral region.

This report describes work undertaken by the JHOD in response to the Great East Japan Earthquake. We hope that knowledge of our experience will be useful for other hydrographic offices to study and prepare for similar natural disasters in the future.

2. The Great East Japan Earthquake and Subsequent Tsunami

2.1 The Earthquake and Tsunami

The massive earthquake occurred at around 14:46 on 11 March 2011 (Japan Standard Time), with the hypocenter under the seafloor off the Pacific coast of Tohoku region of Japan. The magnitude of the earthquake (Mw) is estimated to be 9.0, which is the most powerful earthquake ever to hit Japan. This earthquake is typical of a plate boundary earthquake, which occurred on the upper boundary of the Pacific Plate subducting beneath northeastern Japan. Aftershocks followed subsequently. The hypocenters of these aftershocks have spread across a huge area with a length of 500 km and a width of 200 km (Figure 1).

Shortly after the main shock, a massive tsunami of more than 10 meters in height hit the Pacific coast of northeastern Japan. A second and third tsunami hit the coast, causing further devastation.

2.2 Damage due to the Earthquake and Tsunami

The earthquake and tsunami have claimed nearly 20,000 lives. Significant damage was experienced at logistically important ports such as the Port of Hachinohe, Port of Sendai-Shiogama, Port of Onahama, etc., and some of the largest fishing ports in Japan, such as the Port of Kesennuma, along the Pacific coast of eastern Japan (Figure 1). The tsunami not only damaged the facilities of these ports, but also mercilessly swept away parts of towns, the residential areas and factories.

The breakwaters protecting these ports, quays, and aids to navigation were destroyed. Cars, containers, port facilities and debris of destroyed houses were swept into ports and coastal areas, and the debris tore fishing equipment and nets in the bay into pieces. Obstructions, which are dangerous for navigation, were scattered on the seafloor, drifting underwater or on the surface in some ports and coastal areas. The earthquake caused significant change in ground level in several coastal areas of northeastern Japan. Some places saw the ground subside by more than 1m. The tsunami largely scraped away the coastline and seafloor in some areas, and conversely deposited a large amount of sand, mud and debris in other areas. Grave accidents occurred at the Fukushima Daiichi Nuclear Power Plant.
3. Emergency Action Taken by the JHOD

3.1 Dispatch of All Survey Vessels

When the earthquake occurred on the Friday afternoon, most of our JHOD staff members were on duty. We set up the task force immediately both in the JCG Headquarters in Tokyo and in the second Regional Coast Guard Headquarters, which is in charge of the Tohoku Region, located in Shiohama City of Miyagi Prefecture and started to plan necessary emergency measures. After receiving information on the unprecedented magnitude of the disaster caused by the earthquake and tsunami, the JHOD issued an order to dispatch all five survey vessels belonging to the JHOD (Figure 2) to the affected areas. It is the first time in history since World War II that the JHOD issued the dispatch order for all of its survey vessels to the same region at the same time.

The survey vessel KAIYO had just arrived at the base close to the headquarters in Tokyo in the morning on the day of the earthquake after a 30-day voyage. It left the base on the following day on the emergency dispatch order, with supply of fuel, water, etc. The survey vessels SHOYO and TAKUYO were on other assignments in the Okinawa region, more than 1,500km southwesterly away from the affected areas. Both vessels immediately suspended their surveys and headed for the affected areas. In a couple of days, all five vessels arrived off the affected ports.

All the survey vessels carried out the surveys of passage obstructions in the ports as soon as they had arrived at the affected areas, as described in section 3.3. After the first phase, the survey vessel MEIYO proceeded to conduct GPS/Acoustic seafloor geodetic observations where a large crustal deformation caused by the earthquake was expected. MEIYO and KAIYO also collected seawater to monitor the radioactivity.

3.2 Issuing Navigational Warnings

Immediately after the earthquake, the JHOD issued navigational warnings on the earthquake occurrence and tsunami to ships in and around the region by NAVTEX and SafetyNet. The first warning was issued 15 minutes after the earthquake.

We continually issued navigational warnings on various subjects, e.g., extinction of lights, dislocation of buoys, and floating debris and ships. As of Feb. 6, we had issued 730 warnings.

The number of warnings had greatly increased as compared with normal periods because of the magnitude of the damage. At users’ requests, the JHOD posted a navigational warning map related to the Great East Japan Earthquake (Figure 3) on 17 March on its website, and have been posting it every day since then. The map contains all the NAVTEX navigational warnings related to the earthquake in one diagram which has been highly appreciated by the users, including the Japanese Ship-owners’ Association.

We conveyed news of the emergency events such as the serious accident at Fukushima Daiichi nuclear power plant to the vessels at sea by issuing navigational warnings. When we received the instruction from the government to take shelter inside or to avoid navigating in the cautionary zone due to the released radioactive materials from the nuclear power plant, we also conveyed the same information to the vessels at sea.
### Figure 2 Specifications of the dispatched survey vessels.

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Year Completed</th>
<th>Gross Tonnage</th>
<th>Length, Beam, Depth</th>
<th>Echo Sounder</th>
<th>Side Scan Sonar</th>
<th>Survey Assigned</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shoyo</strong></td>
<td>1998</td>
<td>3,000 t</td>
<td>98.0m x 15.2m x 7.8m</td>
<td>SEABEAM 2112 (mother vessel)</td>
<td>SYSTEM 3000, SYSTEM 3900</td>
<td>Hachinohe, Kuji, Ofunato, etc.</td>
</tr>
<tr>
<td><strong>Takuyo</strong></td>
<td>1983</td>
<td>2,400 t</td>
<td>96.0m x 14.2m x 7.3m</td>
<td>EM 122, EM 710S (mother vessel)</td>
<td>SYSTEM 3900</td>
<td>Kesennuma, Shiogama, etc.</td>
</tr>
<tr>
<td><strong>Meiyo</strong></td>
<td>1990</td>
<td>550 t</td>
<td>60.0m x 10.5m x 5.0m</td>
<td>EM 302 (mother vessel)</td>
<td>SYSTEM 3000, C3D</td>
<td>Sendai, Onahama, etc.</td>
</tr>
<tr>
<td><strong>Tenyo</strong></td>
<td>1986</td>
<td>430 t</td>
<td>56.0m x 9.8m x 4.8m</td>
<td>SEABEAM 1180, SEABAT 8125, PDR-601 (onboard craft)</td>
<td>SYSTEM 3900</td>
<td>Miyako, Ishinomaki, Soma, etc.</td>
</tr>
<tr>
<td><strong>Kaiyo</strong></td>
<td>1993</td>
<td>550 t</td>
<td>60.0m x 10.5m x 5.0m</td>
<td>EM 302 (mother vessel)</td>
<td>CM2</td>
<td>Kamaishi, Sendai, etc.</td>
</tr>
</tbody>
</table>
3.3 Sea-bottom Obstruction Surveys Performed by Survey Vessels

After the earthquake and tsunami, delivering necessary relief supplies to the affected areas was required to support the afflicted people. The number of evacuees, who had lost their houses or been evacuated and stayed at schools or public facilities, exceeded 400,000. It was necessary to enable emergency transport vessels with relief supplies on board to enter the affected ports as well as to restore the damaged roads connected to the affected areas. More than 15 ports suffered damage due to the earthquake and tsunami.

At the initial stage, we deployed the five survey vessels at the ports with top priority that had urgent need of supplies, and started obstruction surveys to secure the safe passages to the berths so that the emergency transport vessels could come alongside. The task force in the JHOD determined the priority of ports to be cleared and issued appropriate orders to each survey vessel. The task force also received detailed updates of survey status and survey results from each vessel.

We identified passage obstructions on the seafloor using echo sounders and side scan sonars on survey vessels or onboard survey craft (Figures 4a and 4b). The most annoying obstacle during these surveys was nets and ropes drifting in the seawater. The survey vessels were repeatedly tangled up in these nets and ropes. These problems interrupted our surveys several times a day. At some ports, however, a diving unit of the Japan Maritime Self-Defense Force assigned to the areas supported our work by watching for obstructions around our survey vessels and craft with their rubber boats, or by removing tangled nets and ropes. This support helped us carry out the surveys without trouble. The port authorities removed the spotted large obstructions that could impede safe navigation of the vessels.
The joint effort by the JHOD that performed obstruction surveys by the survey vessel Kaiyo and port authorities that removed the obstructions cleared the passage to the usable quays in the Port of Kamaishi on 15 March, four days after the earthquake and tsunami (Figure 5). Joint efforts also cleared the passages in the affected Ports of Miyako on 17 March and Sendai-Shiogama on 18 March.
These surveys enabled transport vessels to enter the ports full of relief supplies onboard. The long-awaited relief supplies were finally delivered to the evacuees. We continued the sea-bottom obstruction surveys for about a month until most affected ports were re-opened.

The JHOD has learnt that from the experience of past disasters such as the 1993 Southwest-off Hokkaido Earthquake and the Great Hanshin Earthquake in 1995, what we had to do immediately after the earthquake or tsunami was to conduct hydrographic surveys that would help transport vessels enter the affected ports. In these hydrographic surveys, we decided to dispatch all available resources as quickly as possible, considering the damage of affected ports. These experiences facilitated our prompt action this time.

The captains of the survey vessels, when they returned to the base in Tokyo, told us that their crews immediately recognized the magnitude of the damage after having seen the devastated towns and undertook their assignments eagerly in the severe environment where dangerous obstructions were drifting. We have received gratitude from the mayors of local municipalities and pilots engaged in port entry for our contribution. Our dispatched survey vessels cleared the passages one after another through the sea-bottom obstruction surveys.

3.4 Details of the Sea-bottom Obstruction Surveys

Five survey vessels and their respective 10m-type onboard survey craft carried out the passage obstruction surveys in the affected ports. The onboard survey craft carried out surveys mainly inside the ports whilst the mother survey ships conducted surveys outside of the ports.

Obstruction surveys were carried out using 4-channel single beam echo sounders together with side scan sonars. These survey instruments were urgently transported from many other regional headquarters all around Japan except those in the affected area. Only the survey craft of the survey vessel "Tenyo" had a multibeam echo sounder for shallow waters. In addition, we deployed an interferometric sonar that we had introduced and tested. These swath-type sonars turned out to be quite powerful and efficient in survey operations. Missions would have been completed in shorter times if all the vessels had been equipped with such modern instruments. Following is a list of survey instruments deployed for the initial stage of the obstruction surveys.

List of the survey instruments and the software deployed

- **Single Beam Echo Sounders**
  - PDR-601 (SENBON DENKI)

- **Multibeam Echo Sounders**
  - SEABAT8125 (RESON)
  - SEABAT9001 (RESON)
  - EM302 (KONGSBERG)
  - SEABEAM1180 (L-3 ELAC Nautik)

- **Side Scan Sonars**
  - SYSTEM-3900 (L-3 KLEIN)
  - SYSTEM-3000 (L-3 KLEIN)
  - CM2 (C-MAX)

- **Interferometric Sonar**
  - C3D-LPM (Teledyne BENTHOS)

- **Software**
  - HYPACK (HYPACK)
  - Bathy Pro (Triton Elics International)
  - SonarPro (L-3 KLEIN)
  - SIS (KONGSBERG)
  - TNTmips (Microimages)
The task force drew up a data processing flow to ensure access to the survey results as quickly as possible. Survey data was processed on board and summarized results such as the position and the size of the obstacles were reported to the task force. Subsequently the task force produced charts (Figure 6) to show the obstruction survey results in an illustrated manner. The established data flow enabled prompt notifications to the port authorities within the day of each survey, which contributed to the quick reopening of the ports.

The multibeam/singlebeam echo sounders and side scan sonars had an indispensable function to visualize the collected data immediately on site. This provided convincing information to the port authorities, who were then able to remove the detected obstructions. We realized that the onboard survey instruments to be used after the disaster must have a function of fast data processing speed as well as effective survey capacity. Figures 7a and 7b show sample records of a sunken ship on the seafloor and Figure 8 shows a fallen crane from a quay.
**Figure 7a and 7b** The record of a sunken pleasure boat on the seafloor measured by multibeam echo sounder (left panel) and the picture when it was salvaged (right panel).

**Figure 8** The multibeam echo sounder record of a fallen crane from a quay.
3.5 Seafloor Geodetic Observation

The JHOD has been developing precise seafloor positioning systems using the GPS/acoustic combination technique (*Figure 9*) and carrying out campaign observations along the major trenches on the side of the Pacific Ocean. The primary purpose of these observations is to detect and monitor the crustal movements caused by the subduction of the oceanic plate near the plate boundary where huge earthquakes have repeatedly occurred. In this observation, two different techniques are combined using a survey vessel. One is kinematic GPS to determine the position of the on-board GPS antenna. The other is acoustic ranging to measure the round-trip travel time between the on-board transducer and the acoustic mirror-type transponder installed on the seafloor. By combining these techniques, we get the position of the seafloor reference point with centimeters precision. From past observations, we have succeeded in detecting intraplate crustal movements and co-seismic movements at seafloor reference points with centimeter resolution.

![Figure 9](image)

*Figure 9* The GPS/acoustic combined method of seafloor geodetic observation

We have five seafloor reference points in the focal region of the 2011 Great East Japan earthquake with campaign observations carried out three times a year on average. After the earthquake, we conducted observations at these sites for the period from 28 March to 5 April.

Comparison between before and after the event, yielded co-seismic displacements of 5 to 24m toward ESE and −0.8 to 3m upward (*Figure 10*, Sato *et al.*, 2011). In particular, at the reference point near the epicenter, we detected a huge co-seismic displacement of about 24m toward ESE and about 3m upward. The horizontal displacement is more than four times larger than that detected on land. These displacements detected on the seafloor indicate that a huge slip generated on the plate boundary near the trench.
Observed seafloor displacements by seafloor geodesy have contributed to the estimation of the coseismic slip distribution on the plate boundary by combining crustal movements revealed from on-land GPS stations. While the slip estimated using only on-land GPS data was about 30 m at the maximum, the one estimated using both on-land and seafloor data was 50-60 m at the maximum and the location of the peak moved toward the trench (Geospatial Information Authority of Japan, 2011). This result shows that a huge slip occurred near the trench axis, and it provides valuable information to understand the mechanism of the huge tsunamis caused by the earthquake.

3.6 Airborne LIDAR Bathymetry of Coastal Region

The JHOD has been carrying out airborne LIDAR bathymetry in order to measure the depth of shallow waters, natural coastline and coral reefs, safely and efficiently.

After the earthquake, the Water and Disaster Management Bureau (WDMB) of the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT) requested the JHOD obtain bathymetric data in the very-shallow coastal water regions as soon as possible in order to support local governments to carry out the precise tsunami simulations needed for the future re-design of ravaged towns.

The JHOD, in collaboration with the WDMB, urgently carried out the airborne LIDAR bathymetry (Figure 11) along natural coastlines in June 2011.

Figure 10 Horizontal (upper panel) and vertical (lower panel) displacement at the seafloor reference points and the GPS station, associated with the earthquake. Red squares and blue dots show locations of seafloor reference points and the GPS station respectively.

Figure 11 The principle of airborne LIDAR bathymetry.
We had fine weather during the surveys. The transparency of seawater, which decreased just after the earthquake, had improved. We successfully obtained the data up to about 10m deep in the neighboring coast of Sendai, and about 15m deep in Miyako Bay, which helped us to have clear bathymetric detail (Figure 12).

With airborne LIDAR bathymetry, we were able to observe the disturbed seafloor topography in shallow waters due to the earthquake and tsunami. Characteristic depression features considered to be caused by the tsunami flow were recognized on the seafloor running parallel to the disturbed beaches and windbreaks. These results were already identified in the nautical charts and will be used for future restoration projects and disaster control in the relevant areas.

4. Effort to Publish New Editions of the Affected Charts

4.1 Policy of Hydrographic Surveys and Chart Updating for the Affected Ports

After the earthquake and tsunami, the JHOD provided chartlets and preliminary notices to mariners for the 27 affected harbor-charts containing the following warnings:

“CAUTION: As a consequence of earthquake and tsunami which occurred on 11 March 2011, depths, coastlines etc. may have changed, wrecks and obstructions may have been displaced, and new obstructions may exist. Mariners should expect considerable change.”

Figure 12 The seafloor topography near the estuary of the Natori River, south of Sendai. The result of airborne LIDAR bathymetry (upper panel) and aerial photographs taken before (lower left panel) and after (lower right panel) the Great East Japan Earthquake.
Since late April, the JHOD had started hydrographic surveys to provide new editions of the affected charts (Figure 13). By that time, main shipping routes of the affected ports had been cleared of hazardous obstructions enabling cargo vessels loaded with relief supplies on board to enter those ports. These vessels were however using out-of-date charts using pre-quake information. Such vessels requested us to update charts of the ports urgently.

![Flowchart](image)

*Figure 13  The flowchart of work for new edition nautical charts.*

We expected that it would take an enormous amount of time to accomplish updating the whole chart of every affected port and that the hydrographic information of the ports would change in the future according to the progress of restoration and reconstruction of the ports. Therefore, we planned to take a step-by-step approach to surveying and updating the charts in the order of priority. The Regional Development Bureau, which is a local branch of the MLIT, is expected to carry out hydrographic surveys each time restoration or reconstruction work is done. We apply those survey results to the charts as soon as we receive the survey data.

To update the affected charts quickly and efficiently, we set priority to ports and areas within those ports in which we would carry out hydrographic surveys and updating charts. We determined the order of priority of ports, considering economical importance, restoration status, and progress situation of obstruction removal in shipping routes of the ports. In that consideration, we collaborated with port authorities on the latest information of situation of the ports. As a first step, we planned to survey and update charts in front of available major quays, and within main shipping routes and anchorage areas. Then, we expand the coverage of surveyed and updated areas of charts step-by-step in the order of priority.
To provide users with the latest information as soon as possible, we offer fair sheets of the surveys as information diagrams before we start to compile nautical charts using the fair sheets. We published the sailing directions (Japanese version) covering the affected areas just on the day of the earthquake, and an additional correction (special post-earthquake edition) summarizing the situation after the earthquake on 30 September 2011.

4.2 Setting the Work Schedule

To publish a new edition of the affected charts, we needed to systematically carry out:

1) a determination of the chart datum,
2) hydrographic surveys,
3) processing of survey data, and
4) compiling charts.

In order to publish new edition charts quickly, the JHOD drew up a schedule of these works, considering our available capacity for hydrographic survey and chart compilation.

The top priority was the port of Sendai-Shiogama. We determined the chart datum and completed hydrographic surveys in the main shipping routes in the port by early June. Then we completed the processing of the survey data by the end of July, provided the seafloor information maps, compiled the charts of the port of Sendai-Shiogama and published new editions of the charts on 9 September 2011.

We are undertaking the same sequences of work for major affected ports in parallel, and we will have provided new edition charts or chartlets for the 11 major affected ports by March 2012.

We are undertaking these works as swiftly as possible to help restore and reconstruct the affected ports. However, the coverage reflecting new information obtained from the surveys after the earthquake is expected to be only 15% of the whole areas of the affected charts as of March 2012. The JHOD will continue updating charts for several years, considering the progress of restoration and reconstruction works in affected ports.

4.3 Determination of Datum Level

After the earthquake, large subsidence of ground level was observed along the coast of Pacific Ocean in Tohoku region. The Geospatial Information Authority of Japan reported the subsidence in some areas amounted to more than 1m from GPS observation. A number of quays and tidal stations were destroyed in ports, and most of the benchmarks necessary to define a datum level have significantly subsided or been lost. Re-determination of datum level at these ports was urgently required because datum level is used for not only depth sounding for nautical charts but also construction work in ports.

The JHOD, collaborating with port authorities and local municipalities, has been working to determine a datum level since mid-March 2011 by carrying out tidal observations at these affected ports. We determined datum levels at the Ports of Onahama and Hachinohe on 18 May 2011 (Figure 14), and 16 other ports by early July 2011.

4.4 Hydrographic Surveys

We carried out sea-bottom obstruction surveys to enable vessels to enter ports immediately after the earthquake. These survey results could not be used for updating nautical charts because the datum level was unclear and tidal corrections could not been made.

Figure 14 Land subsidence found in determination of a datum level at Ports of Onahama (right panel) and Hachinohe (left panel).
Therefore, we need to carry out additional hydrographic surveys at each port after the datum level determination. Since the extent of damage varied port by port and the port reconstruction works such as dredging and the construction of breakwaters were scheduled differently at each port, we had to carefully determine the necessary survey areas, collecting all the information available to avoid rescheduling. Although drifting debris decreased as compared with the time just after the earthquake, there is still a large amount of debris left off the main passages. In case clearing operations of sunken debris is underway, we need to postpone the surveys in these areas.

4.5 Providing the Seafloor Information Maps

It usually takes a couple of months after hydrographic surveys to process the measured data and to compile the nautical charts. However, considering the urgent needs of seafarers, we decided to provide users with the smooth fairsheets that we make upon completion of the measured data analysis as “seafloor information map” for users’ reference. We provided two maps for Sendai Section and Shiogama Section of Port of Sendai-Shiogama. These were the first of these maps and were issued in early August 2011 (Figure 15).

From survey data analysis of the Port of Sendai-Shiogama, the following changes to water depth were found:

1. The water depth deepened by 0.5 to 1m throughout the passages, which is probably due to the subsidence caused by the earthquake.
2. We observed small foul bottoms in many parts of the passages. The shallowest water depth with these obstructions were revealed.
3. The narrow part in the middle of the passage in Shiogama section deepened by about 2m, which would be due to erosion caused by the tsunami back-and-forth motion.

Figure 15  Land subsidence found in determination of a datum level at Ports of Onahama (right panel) and Hachinohe (left panel).
4. We found a partly shallow area next to the main passage. This was possibly due to sedimentation of sand and mud caused by the tsunami.

4.6 Compiling of Nautical Charts

When updating the nautical charts, we decided to specify the range of surveys after the earthquake using the following two methods. The first method is a Zone Of Confidence (ZOC) diagram newly introduced to the nautical charts, which indicates the newly surveyed areas (Figure 16). The second method is a magenta dotted line shown on the nautical charts to indicate the range of the newly surveyed areas after the earthquake. The latter method is not listed in the IHO Publication INT 1 – Symbols, Abbreviations and Terms Used on Charts. We decided to create it with explanations in charts, after hearing opinions of users, such as pilot organizations and captain organizations, which supported the method.

![Figure 16](image)

Figure 16  The Zone of Confidence (ZOC) diagram newly introduced in a new edition nautical chart of Shiogama Section.

Figure 17 shows the present status of hydrographic surveys and nautical chart updates. As of 6 Feb. 2012, we have published six new edition nautical charts and one chartlet of the damaged ports. Six more new edition charts will be published up to the end of next March. Our estimation shows it will take another three to five years to update all the hydrographic information in the nautical charts of damaged ports. We intend to continue the work in order to support the local community until the reconstruction of damaged ports is finished.
5. Conclusions

One of the most important lessons we have learnt is that hydrographic activities play an indispensable role after natural disasters by providing hydrographic information necessary to ensure safety of navigation. In order to transport relief supplies for refugees, we need to identify obstructions in the passages to open ports as quick as possible. In order to support recovery of the local economy, new editions of nautical charts need to be published quickly. It is the responsibility of national hydrographic offices to quickly respond to the urgent needs of the local community as well as of seafarers.

Immediately after the earthquake, we received letters, emails and phone calls from the President and staff of the IHB, and many hydrographic offices of member states of the IHO including the East Asia Hydrographic Commission. They expressed sympathy for us and kindly offered us support. All the JHOD staff members have been greatly encouraged and have sincerely appreciated these messages.

It has been almost eleven months since the Great East Japan Earthquake occurred, which was the postwar largest natural disaster in Japan. About 3,600 people are still missing, and the struggle with the Fukushima nuclear disaster continues. The JHOD will continue to undertake the necessary actions to provide information for navigational safety at sea through nautical charts, sailing directions and navigational warnings.

We do hope that the newly revised nautical chart information based on the survey data after the earthquake that the JHOD has provided will help improve safety of navigation, be useful for restoring the community and economy of affected areas, and aid in the reconstruction of port facilities, logistic centers, fisheries facilities and coastal factories.
References:


