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Analytic comparison of multibeam echo soundings

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Analytic comparison of multibeam echo soundings

A numeric and visual analytic comparison of bathymetry data collected with high density multibeam echo sounding.

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Master thesis, 30 credits, in Geographical Information Sciences

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Abstract

This study makes a numeric and visual comparison of two different multibeam echo sounding (MBES) surveys performed at the exact same location, in an effort to establish how reliable and comparable the vertical depth measurements are. The horizontal position uncertainty is not issued in this study.

The analysis was performed on data delivered by two survey contractors, The Norwegian Coastal Administration (NCA) and the Norwegian Mapping Authority Hydrographic Service (NMAHS). The area of interest is located north west of the Norwegian city of Ålesund, and contains a dredged channel making it safer to navigate the area. Several MBES surveys were performed both before and after the dredging of the area. The present study deals only with NCA, NMAHS survey data and own elaborated survey data.

Comparative analyses were set up, using both visual methods and practical empirical methods. The findings are presented in maps, raster images and tables, illustrating results from each analysis. Two of the analyses were evaluated against the *International Hydrographic Organization, IHO S-44 standard*, setting preferences for hydrographic measurements. The analysis indicates some artifacts at especially the NCA data produced before the dredging. The first analysis method in the present study compares the two operator's datasets before dredging within three test zones, and even though it is based on only a few test zones, the results still gives an indication that some differences occur. But perhaps just as important, two out of three measurements indicate a very good match. A second method makes a comparison between one of the datasets after dredging, and manually measured reference depths indicating an average uncertainty of 0.19m, well within the ±0.26m defined by the IHO S-44 standard for operating on depths of 10m. A third set of analysis were also performed on a cell by cell basis between the two surveys datasets collected before dredging, both as a visual analysis and a numeric analysis in tables. The visual comparison revealed that only a few number of cells had differences involving the values at the high end of the scale, as 3.5m to 5.3m. A pattern also emerged from the visual analysis, revealing what seemed to be artifacts along the heading direction of the survey. Later to be investigated in a hillshading analysis. The numeric analysis was set up to find the value of the highest appearance of difference, the frequency the differences appear at. The difference of -0.13m occurs 18771 times, as the one with the highest frequency illustrated in a difference graph (Appendix 3). A table shows the cells tested against IHO S-44 standard, giving an 89% with 364873 cells within the IHO S-44 standard of a total of 410055 cells tested (Tab.8). Analysis using hillshading reveals the appearance of artifacts with a *ridge*

pattern in the NCA data. The errors were described as an effect of incorrect velocity values through the water column on a multibeam swath. A second hillshade analysis performed on the NMAHS data revealed a missing HIB-West1, affecting the results of the analysis using weighted sounding line (WSL). The analysis also established that the NCA survey tends to measure the depths lower than the NMAHS survey. 91% of the cells are located lower than the NMAHS cell depth values. This could be a consequence from the fact that NCA calculates the middle value of the soundings as the valid cell value, while NMAHS selects the most shallow depth value indicating the minimum depth within the cell. Some artifacts also appeared as *holes* in the NMAHS dataset before dredging probably caused by variations of the vessels speed, mostly located at the north and south ends. The artifacts taken into account, the depth differences and the uncertainties generally still are within the IHO S-44 standard where this standard is applied. The NCA survey data before dredging did not cover the entire area of the dredged channel, and thereby fails in meeting the IHO S-44 criteria of a *Full Seafloor Search* for *Special order* surveys where under keel clearance is critical (IHO, 2008).The last analysis gave a 3D visual view of the area and a better understanding of the calculated differences.

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All pictures and tables used in the present study, if not self-elaborated, are permitted by the referred publisher.

List of tables

Key words

Words	Explanations
3D surfaces	A calculated interpretation of 3D data into a continuous surface
Artifact	Something observed in a scientific investigation or experiment that is not naturally present but occurs as a result of the preparative or investigative procedure.
Bathymetry	Study of underwater seafloor in oceans or lakes.
Depth soundings	The measured depth of a given point at the seafloor
Dredging	Removing sediments and rocks from the seafloor
Hillshading	A calculated shade effect of surface data to create a relief that makes the hills, heights and depths stand out.
Ping	A pulse of sound
Test zone	Digitized zone/rectangle where a mean depth value is calculated
Reclassification	The reclassification functions, reclassify or change cell values to alternative values using a variety of methods (ESRI, 2013)
Single beam echo sounder	Echo sounder using only one vertical beam
Sound velocity profile	A calculated profile of the sounds velocity versus depth
Source data	Data from the surveys, provided by the contractor
Survey	Systematical collection of data
Standard deviation	A statistical measure of the spread of values from their mean, calculated as the square root of the sum of the squared deviations from the mean value, divided by the number of elements minus one. The standard deviation for a distribution is the square root of the variance (ESRI, 2013)
Transducer	In this case equipment that transforms an electrical signal to sound waves, and transmits and receives the sound waves

Abbreviations

Abbreviations	Explanations
*.asc format	ASCII text file format, used to exchange data between software
DEM	Digital Elevation Model, a representation of continuous elevation values over a topographic surface by a regular array of z-values (ESRI, 2013)
HIB	High Speed Vessel Seamark with Indirect Light From Norwegian (Hurtigbåtmerke Indirekte Belysning)
LAT	Lowest Astronomical Tides. Lowest water level that can be considered under medium meteorological conditions and at all possible constellations between earth, moon and sun
MBES	Multibeam Echo Sounder
NCA	Norwegian Coastal Administration
NMAHS	The Norwegian Mapping Authority Hydrographic Service
NTNU Ålesund	Norwegian University of Science and Technology Ålesund
RMSE	Root Mean Square Error, a measure of the difference between locations that are known and locations that have been interpolated or digitized (ESRI, 2013)
WSL	Weighted Sounding Line, finding depth by lowering a weighted sounding line

1. INTRODUCTION

1.1 Research questions

Figure 1: Dredging and placing HIB
(Photo by: Olav Helge Matvik/Kystverket).

The NCA is responsible for services related to maritime safety and maritime infrastructures along the extensive Norwegian coast. NCA was established in 1974, and is engaged in operative activities at their seven operative units consisting of five regions, the shipping company and the head office located in the city of Ålesund at the west coast of Norway. The agency has around 50 operative units (Kystverket.no). As the contracting authority for this present study, NCA offered some interesting questions related to a shipping route in which they had commissioned dredging an area and professionally and with high precision positioned eight distinctively Norwegian seamarks, perhaps best described in English as a *High Speed Vessel Seamark with Indirect Lights* (HIB) (Fig.1).

- Are there any significant differences between measurements made by the two different survey operators in the exact same area, using MBES equipment from different suppliers?
- How accurate are they compared to manually measurements using WSL?

They found it interesting to compare their data in an area where they knew surveys recently were conducted by another operator, and made the surveys data available to this study. The surveys were conducted by the NCA itself and the Norwegian Mapping Authority Hydrographic Service (NMAHS). NMAHS was established in 1932 and has operated as a division of the Norwegian Mapping Authority since 1986. The division is based in the city of Stavanger, at the west coast of Norway. Both the NMAHS and NCA use Multibeam Echo Sounder (MBES) equipment to map the bathymetry along the Norwegian coast to provide safe source data for navigational maps, and to plan improvements related to safe passages.

1.2 Research aim

Faculty nautical specialists from The Norwegian University of Science and Technology Ålesund (NTNU Ålesund) and the professional staff at Norwegian Coastal Authority (NCA) find it interesting to establish a numerical and visual documentation, to illustrate the difference between the depths truth defined as data of higher accuracy of selected points at the seafloor from a weighted sounding line (WSL) survey compared to MBES measurements. It is essential to have knowledge about the data collected, and to learn more from how the performance of these surveys will affect the results given. Using different brands of software, the data is analyzed and compared to verify if any differences occurs and to obtain more knowledge about the uncertainty of the MBES surveys. The MBES systems are advanced, and as with any complicated technical systems many factors influences the results, e.g. changes in sea temperature, calibrations performed and equipment failures. It is important to obtain accurate measurements, mappings and calculations of the seafloor when dredging an area to correctly calculate the costs, and also to verify the correct depths for the traffic that will navigate through the passage that is dredged. Documenting the uncertainty could also give the NCA an occasion to strengthen their procedures and the reliability of the NCA surveys. The aims of the study were defined by the contracting authority NCA as to validate MBES surveys performed by two different operators in the exact same location, and confirm if there exist any differences in their results and how big the differences are. To achieve this, this study will make use of numeric analysis and 2D/3D visual analysis to compare the survey results for the purpose of documenting any differences between them, and also compare against what could be defined as *depth truth* or *higher accuracy validation data* from manually measurements using Weighted Sounding Line (WSL) in a survey performed during the study. The study is initiated in cooperation with NCA represented by Jan Erik Dyp and NTNU Ålesund represented by Professor Norvald Kjerstad. Norvald Kjerstad is the local supervisor in this study, and works within the fields of navigation and positioning systems, simulation technology, underwater acoustic, offshore operations and arctic navigation.

1.3 Data harvest

The standard S-57 has so far been the main standard used in navigational charts (IHO, 2010). These data consist largely from a mixture of very old data collected by manual methods for example using WSL and similar methods, to modern data harvest using MBES and high-tech equipment. MBES systems have become a widespread method for surveying the seafloor. The system is based on echo sounders with several beams using sound to measure and calculate the depths of the seafloor. MBES surveys gives us a higher density of data with a more correct view of the real shape of the seafloor, but it is easy to make the mistake of believing that these data almost perfectly mirror the bathymetry of an area and set the exact correct depths at each point registered. Uncertainty in measurements provided by MBES systems are important knowledge also related to the use of such data in e.g. electronic charts used for navigational purposes. Even though MBES systems are among the more expensive systems, it has become a popular system used in many scenarios, as survey of oceans, lakes and rivers, and also as an advanced system for locating fish in the modern fishing industry (Kjerstad, 2010). These advanced MBES systems can even provide a 360 degrees overview of the trawl input (Furuno Norge, n.d.). The MBES systems are typically mounted on the hull of a vessel.

2. BACKGROUND

2.1 Previous studies

This study deals with sea depth values in *.asc file format, but it would be natural to also associate with methods used to analyze height values on land. On land, heights often are presented in DEM (Digital Elevation Models) or DTED (Digital Terrain Elevation Data), as raster representation of the height data where each cell holds the elevation (Longley, et al., 2001). A number of analytical methods exist to evaluate raster images holding values representing heights or depths (USGS, 1998). It appears difficult to find studies that are directly comparable to this present study. There are studies available focusing on the differences between single beam and multibeam echo sounding systems, different modes and settings or other systems or techniques as in an article written by Lear (2008). Others focus entirely on different brands uncertainty up against the IHO S-44 standard, as in the study of Haga, Føhner and Nilsen (2003). The article of Ernstsen, et al. (2006) compares different surveys and measurements addressing both the vertical and horizontal accuracy using MBES systems and a high precision differential global position system (DGPS). The article also refers to a study made by Artilheiro and Pimentel, (2001 cited in Ernstsen, et al. 2006) evaluating high resolution MBES and vertical resolution, but the study relates to onshore, dry dock measurements and not offshore surveys as in the present study. A similar study of Eeg (1998 cited in Ernstsen, et al. 2006) examine the vertical resolution accuracy on two particular MBES systems offshore, the RESON SeaBat 9001 and the BCC (Elac's bottomchart compact shallow water) at 22m depth. This study also deals with the changes between the different beams of the multibeam swath. But nor this or any of the other mentioned studies relates to different survey operators offshore testing both hotspots and larger areas on a cell level as in the present study. Nevertheless all of the studies add insight to the subject, and especially Ernstsen, et al. (2006) on their work on vertical accuracy. At some point in the present study a decision had to me made to instead look to similar studies made in related fields. Since depth data are similar to height data, a measure of vertical distance between two points, studies comparing height differences onshore are also adjacent to the present study. Parts of the approaches used in analysis of Digital Elevation Model data (DEM) from radargrammetry are applied in this study, and also reliable approaches studied from Kyarizu, (2005) and Wechsler, (2003). The root mean square error (RMSE) analysis is often used evaluating DEM data. Wechsler, (2003) points out that the root mean square error (RMSE) analysis does not give an accurate valuation on how well each cell in the DEM represents the true elevation, but only presents an estimation of how well the DEM matches the data it was generated from, and that the impact of uncertainty on results from DEM analysis is difficult to quantify. RMSE can be calculated for a particular DEM if data of a higher accuracy are available, an approach adapted by the present study using the standard deviation (SD) tool in the ArcGIS software provided for the study. Kyarizu, (2005) notes that the approaches for evaluating DEM quality can be separated into three classes, empirical approach, analytical approach and visual approach, where the empirical approach is the practical one, mostly depending on validating datasets using a reference DEM or sample points to determine the statistical quality such as SD or RMSE. The analytical approach describes terrain relief by a stochastic model, using the correlation theory of random functions and applying error propagation to estimate the effect of the error introduced at a certain stage on the result of a given function. Qualitative validation can also be done through visualizing a DEM and DEM derivatives, as a tool for finding patterns, spatial distribution and causes of DEM errors. An article by Wechsler, (2003 cited in Kyarizu, 2005) refers to that in some studies the mean error and SD error are considered more meaningful statistics in assessing DEM accuracy than mentioning RMSE only. It was decided for the present study to use both the empirical and the visual approach, and that the SD tool would be relevant in analyzing how the spread of the differences data appear.

2.2 Depths

Normally, depths are specified in positive numbers related to Lowest Astronomical Tide (LAT) equal to the Norwegian vertical chart datum (Kjerstad, 2013). LAT is the reference point for the depths used in this study. The depths from the datasets applied in this study contain negative numbers due to the values registered in the *.asc files handed over from the contracting authority. This however is not important for these analyses since it does not matter if the number is negative or positive e.g. -4.5 or +4.5. The difference value will be 4.5, either it is negative or positive. Depths are measured in units of meters.

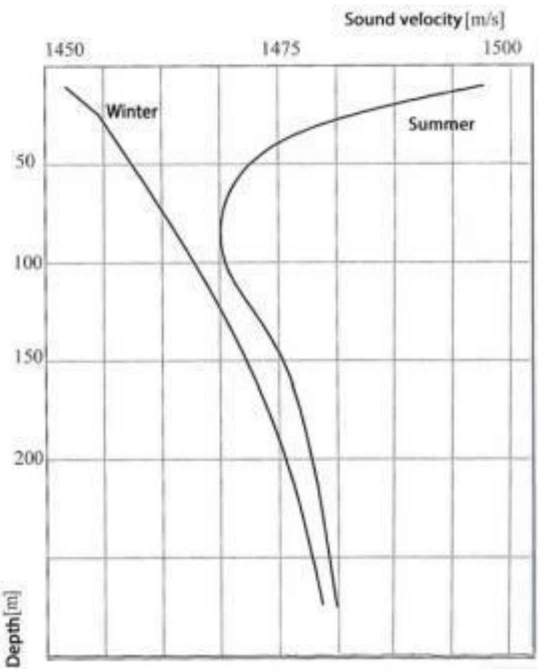


Figure 2: Typical sound velocity profile, summer and winter (Kjerstad, 2010).

2.3 Sound velocity

Even though the calibrations conducted by the operators are performed according to the equipment's user manuals and the IHO S-44 standard for surveys, it is unknown to this study how well it was followed through. But it is still important to know the principles of what could affect the survey results. Sound travels with a speed of approximately 1500 m/s in water, but the speed is influenced by temperature, pressure and salinity in the water. Temperature is the factor that has the highest influence on the sound speed. It is common to use a Sound Velocity Profiler (SVP) to register the sound velocity profile. The sound velocity is set up as a function of depth on a specific location, and provides the sound velocity profile (Kjerstad, 2010) (Fig.2). Velocity values through the water column are measured by e.g. a free falling sound velocity probe dropped down through the depths where the survey is taken place. The measurements are done repeatedly throughout the survey to catch changes in the velocity. The IHO Manual on Hydrography stresses the importance of precise calibrations, that all errors are eliminated, necessary corrections made, offsets and variable values such as velocity profiles set IHO, (2005, Cha.1, p.14). Figure 2 illustrates the differences that might appear in the sound velocity profile comparing winter and summer season and variations in depths (Kjerstad, 2010).

2.4 The IHO S-44 standard

The International Hydrographic Organization, IHO S-44 standard sets the preferences for hydrographic measurements, and is used to predict the accuracy or error of hydrographic surveys. In its preferences it aims to describe the orders of survey that are considered acceptable to allow hydrographic offices / organizations to produce navigational products that will allow the expected shipping to navigate safely across the areas surveyed (IHO, 2008).

To achieve this it defines 4 orders of surveys, under where the one suited for this study is named as the Special order. This is the most rigorous of the orders and its use is intended only for those areas where under-keel clearance is critical. Because under-keel clearance is critical a full seafloor search is required and the size of the features to be detected by this search is deliberately kept small. Since under-keel clearance is critical it is considered unlikely that Special Order surveys will be conducted in waters deeper than 40 meters. Examples of areas that may warrant Special Order surveys are: berthing areas, harbors and critical areas of shipping channels (IHO, 2008).

IHO has since 2008 in most cases replaced the word *accuracy* and *error* by *uncertainty* where differences exist between the measured value and the true depth value. Since the true value is never actual 100% known it follows that error itself cannot be known. *Uncertainty* is a statistical valuation of the likely extent of this error (IHO, 2008). The term uncertainty will therefore be used in this study to define depth errors. When the present study refers to other literature or studies, their use of terms will be kept, respectively accuracy or uncertainty.

Dealing with vertical uncertainty a survey should be carried out meeting the minimum standards of the IHO S-44. Failing to do so, must be considered to be a significant uncertainty or difference. At depths applicable for the present surveys, the *special order* of survey in IHO S-44 is defined in Table 1 as:

Minimum Standards for Hydrographic Surveys	
Order	Special
Description of areas	Areas where under-keel clearance is critical
Maximum allowable TVU 95% Confidence level	a = 0.25 meter, b = 0.0075 (Calculation factors used at this order)
Full Sea floor Search	Required
Feature Detection	Cubic features > 1 meter

Table 1: IHO S-44 Standard sets the preferences for calculating the minimum uncertainty.

The present newest IHO S-44 standard from 2008 gives a formula calculating the uncertainty expected.

$$\pm\sqrt{a^2 + (b \cdot d)^2}$$

Where:

a Represents that portion of the uncertainty that does not vary with depth.
b Is a coefficient which represents that portion of the uncertainty that varies with depth.
d Is the depth.
b x d Represents that portion of the uncertainty that varies with depth.

The *confidence level* is defined by the probability that the true depth value of a measurement will lie within the specified uncertainty from the measured value. The *special order* is a maximum allowed TVU (Total Vertical Uncertainty) of 95% for confidence level of areas where under-keel clearance is critical using the parameters of a=0.25m and a factor b=0.0075.

$$\pm\sqrt{0.25^2 + (0.0075 \cdot 10\text{m})^2} \approx 0.26\text{m}$$

The uncertainty for the survey depths about 10m used in this study should then become ±0.26m. The calculated differences between the datasets should be within this tolerance. It is useful to also study a specific brand and their systems for evaluating the predicted uncertainty. Kongsberg Maritimes Simrad MBES systems are widely used, and will serve as a representative example. The predicted system depth uncertainties for the Kongsberg MBES EM 2040 are in the order of 0.1% of the measured depth, and an uncertainty of 0.01m at 10m depths. The total measurement uncertainty will also depend upon the inherent errors of additional instruments as vessel motion sensors, heading sensors, positioning systems and the sensors used to measure the speed of sound at the transducer depth and through the water column. Also the quality of the installation will affect the total system uncertainty (Kongsberg Maritime, 2014). Figure 3 shows a standard deviation of 0.15% = 0.03m for a 20m depth, for a particular Kongsberg MBES EM 2040.

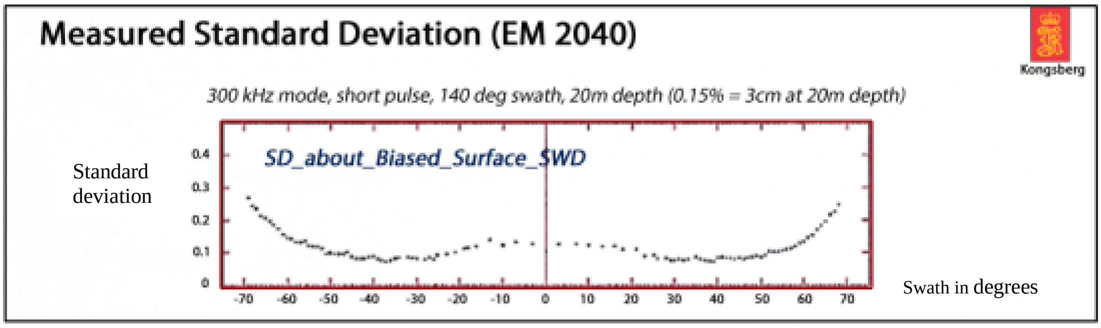


Figure 3: Accuracy of 0.15% at 20m depth for EM 2040 (Kongsberg Maritime, 2014, courtesy of NAVOCEANO and CHS).

3. MATERIAL AND METHODS

3.1 Presentations and restrictions

The analysis are mainly performed with ArcGIS v.10.2 software (ESRI, 2013), and the results are presented in tables, 2D/3D raster images and in maps, but also explained in text. The 3D visual comparison is made to better understand what the differences are about, as we often tend to understand contexts better using visual presentation of findings from number and analysis. The MBES data used are already collected by the two survey operators, and it would be nearly impossible in this study to refer back and verify the grade of uncertainty that the calibrations and surveys were performed with by the individual survey operators and the different brands of equipment they used. It is important to remember that these differences are between *datasets* from NCA, NMAHS and a WSL survey, and give no exact answer on the uncertainty against the actual real seafloor depths. Since the true value is never actual 100% known it follows that error itself cannot be known (IHO, 2008). The expected most accurate or reliable datasets are in this study referred to as the *higher accuracy validation data*, or *depth truth*. This study can only establish if differences exist between the datasets and if so, give some suggestions to what possible could cause such differences. Despite these restrictions, the analysis performed gives a good indication of the differences between the survey datasets. Early in the study, a decision was made to use just a few reference zones for the first analysis on the locations where the professional contractor had their focus on precise leveling of the seafloor for accurate positioning of the HIB basements.

To obtain a flow in the process of making the analysis, and to get the most out of the available data, several software brands were used to produce the analysis in this study.

<u>Global Mapper</u>

Global mapper (Blue Marble Geographics, 2012) is an affordable GIS software capable of importing/exporting most common known image and GIS formats, and a license is provided by NTNU Ålesund. The software offers a nice and quick interface to investigate the data even though its tools for running GIS analysis are rather limited.

<u>ArcGIS</u>

ArcGIS (ESRI, 2013) is a well-known marked leader in GIS analysis software package, and cover many disciplines with special developed tools. ArcMap, ArcCatalog and ArcScene are among the tools used from this software package. ArcGIS is also used by the contracting authority NCA, and regarded as well suited for this study. Geodata, as the Norwegian supplier of ArcGIS, generously provided 1 year free license and support.

<u>Microsoft Office Excel</u>

Microsoft Office Excel is a frequently used spreadsheet tool from Microsoft (Microsoft, 2010), suited to make calculations, graphs, analysis and storing data.

3.2 Available data

Source data derived from surveys performed by two different survey operators can be a challenge concerning differences in data quality and data formats. Both the NCA and the NMAHS collected their data using MBES systems mounted on a ship hull, in principle working the same way, but carried out at different years and seasons. The NCA data was collected in June 2011 using the RESON PDS2000 software (RESON, 2010) and to the author's knowledge a SeaBat MBES, and the NMAHS data was collected in September 2010 and 2012 using Kongsberg Maritime SIS software and their shallow water MBES EM3002 (Kjerstad, 2010, p.101). The difference in season between the collected data sources could affect the measurements since temperature and salinity along with pressure are the main factors influencing the sound speed in water (Kjerstad, 2010, p.13-14). These issues are however well known by professional operators, and should be taken into account in the planning of the surveys. Some data was delivered as source data in proprietary formats used by the survey equipment, and some data in more common formats derived from the survey data. Using the survey equipment proprietary source data would require tools from each system supplier, and would cause an unnecessary extra amount of work for the study since data already existed in *.asc format readable by most GIS tools. Therefore the source data in *.asc format, was selected for the analysis in the present study. The contracting authorities naming of the files in Norwegian was kept to maintain a continuity and recognition of the data throughout the study. In the planning of the study, it was expected that both survey operators would deliver survey data from both before and after the dredging. This would benefit the study, and give a broader comparison of the two operators. A preview of the data in Global Mapper however indicated

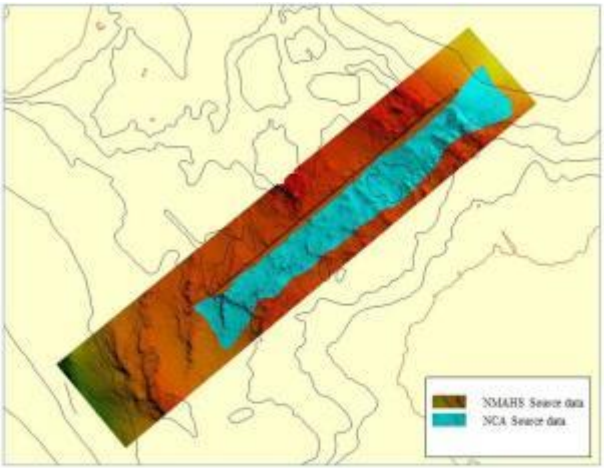


Figure 4: NCA data, not covering the entire dredged area.

that the NCA data had some issues e.g. in lack of presenting any data from after the dredging, and not covering the entire area in their before dredging survey (Fig.4). Clear artifacts appeared as ridges along the survey direction, and together with scattered spikes one could expect them to affect the analysis results. The data provided by NCA turned out to be defined as from a test survey, and not to be considered as data quite up to what they under normal circumstances would deliver. The NMAHS data sets appears to be of a higher quality in covering the entire area to be dredged, with fewer visible artifacts in the actual area and delivering data both before and after the dredging. Depth data was also collected in a self-elaborated WSL survey. Table 2 shows an overview of source data used in this study.

Survey operator	Dataset	Performed	Equipment	Date
NCA (Norwegian Coastal Administration)	*Lepsøyrevet med kor tidevann og lydhast 1 m oppl med målt tidevann lepsøyrevet.asc* *(Lepsøyreef with corrected tides and sound velocity 1m resolution with measured tides Lepsøyreef.asc)*	Before dredging	RESON PDS2000 software and SeaBat MBES system	27.06.2011
NCA (Norwegian Coastal Administration)	---- Not Existing ----	After dredging		
NMAHS (Norwegian Mapping Authority Hydrographic Service)	*Esri grid lepsøyrevet 1 m celler SKSD oppmåling.asc* *(Esri grid lepsøyreef 1 meter cells Government Mapping Sea Department measurement.asc)*	Before dredging	Kongsberg SIS software and EM3002 MBES systems	16.09.2010
NMAHS (Norwegian Mapping Authority Hydrographic Service)	*KSD etter utdypning 120831_Lepsøyrevet_Avsluttet_UTM32_1x1_copy.asc* *(Mapping Sea Department after dredging 120831_Lepsøyreef_ended_UTM32_1x1_copy.asc)*	After dredging	Kongsberg SIS software and EM3002 MBES systems	26.09.2012
Self-elaborated	*Depth measurement in Excel table*	After dredging	Pre measured rope and sinker	04.03.2015

Table 2: Initial source data overview.

3.3 Data alignment

Both the NCA and the NMAHS uses the spatial reference set to WGS 1984_UTM ZONE 32N for their surveys. Both defining a grid of 1m x 1m in UTM zone 32N, ensuring a perfect match within the cells where the sounding data are collected. Several pings are registered in each cell, but the cells are given only one valid depth value. The NCA calculates the average for the cell value, while NMAHS selects the most shallow depth value indicating the minimum depth within the cell.

3.4 The study area

The study area is located at the west coast of Norway, just outside the city of Ålesund at a narrow passage between the main land and an island (Fig.5). The passage is shallow with a depth between -5 and -9 meters containing a danger reef, and has throughout the years caused several marine incidents and accidents. The Norwegian authorities decided to dredge the area down to contour -11.0m below Lowest Astronomical Tide (LAT) equal to the Norwegian vertical chart datum. 470.000 m³ of hard seabed sediments was removed to provide safer navigation for especially larger ships. Eight HIBs (Fig.1) were set up to show passing ships where the dredged channel is and guide them safely through the channel (Fig.6). After the dredging, the navigational maps were updated displaying the locations of channel and the HIBs.

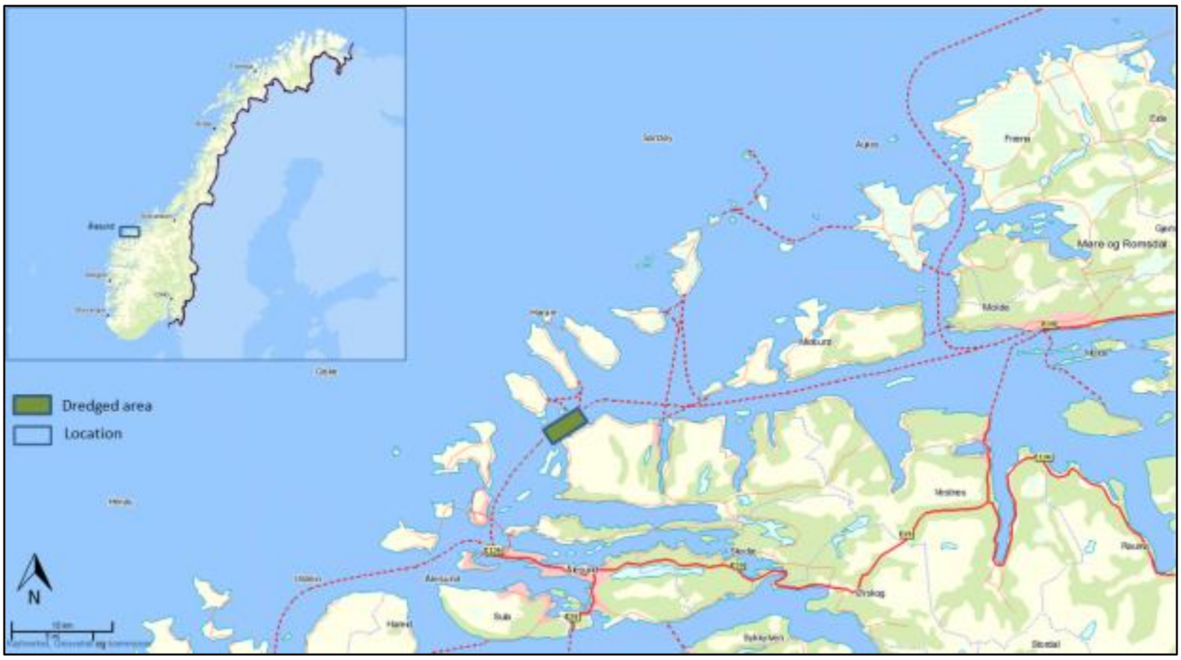


Figure 6: The location of the dredged area North West of Ålesund city, marked with a green rectangle (Kystverket.no).

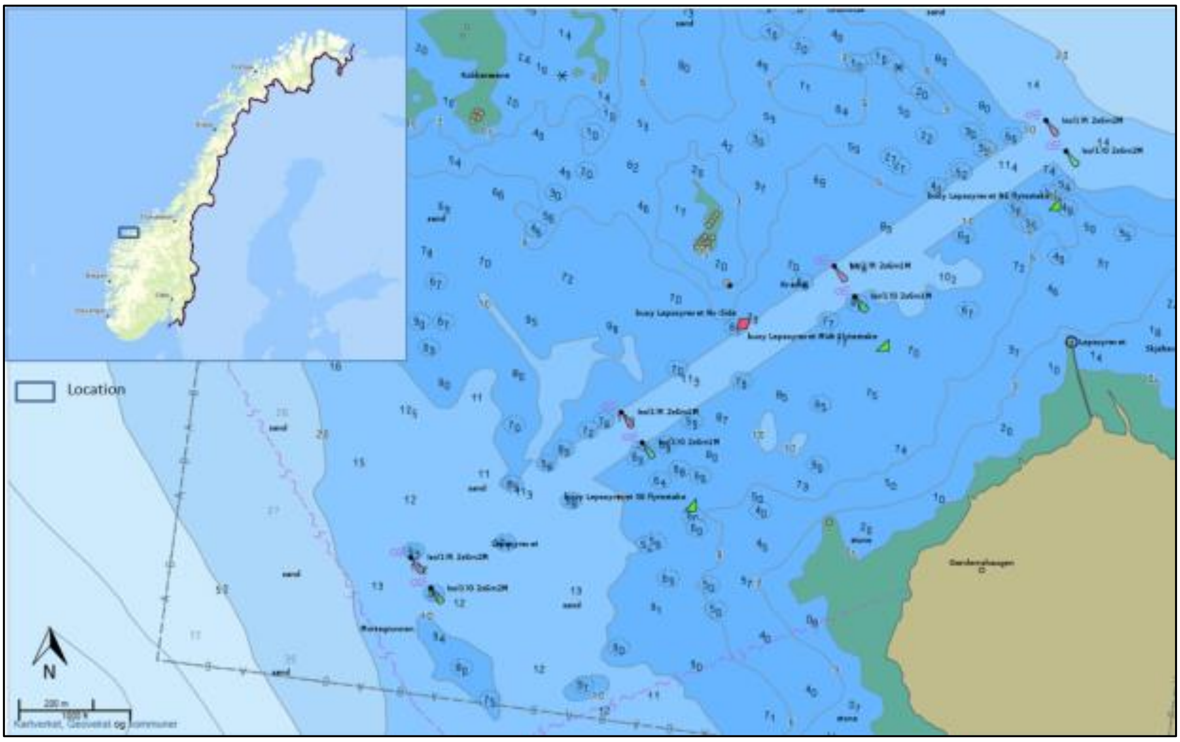


Figure 5: Dredged area, a channel with eight HIBs (kartverket.no/Kart/Sjokart/).

3.5 Multibeam echo soundings

The NCA uses equipment capable of measuring a resolution of 0.2m x 0.2m horizontal grid to map the seafloor, giving a higher density of depth information than using a 1m x1m grid. The datasets used in the present study have a resolution of 1m x1m since that is the only resolution provided to this study by both survey contractors. High density of data is often used in special areas of interest as in narrow sailing areas or harbors. However the uncertainty received from the measurements highly depends on how well calibrations and preparations are conducted. So even if the equipment is capable of measuring a grid of 0.2m x 0.2m resolution containing several depth values, many factors must be addressed before any reliable results are acquired. Tides, water temperature, waves and instrument calibration are among them. Ship hull mounted echo sounding systems measure the distances from transducer equipment mounted on a vessel down to the seafloor, by sending an acoustic pulse often referred to as a ping with a defined frequency, direction and opening angel through the water with the speed of sound (approx. 1500 m/sec). The sound bounces back from the seafloor, and is picked up by a hydrophone system at the equipment. The depth is then calculated from the sound travel time (Kongsberg Maritime, 2014).

Single beam

Early echo sounding systems are known as *single beam echo sounding systems*, and as the name indicates they use only one beam to calculate the depths. Compensations are made for sound velocity in the water column and heave (Kongsberg Maritime, 2014).

The depth is basically calculated by:

D_raw = Cmean · T/2 **Ds = D_raw - H** **D = Ds + Tp – Tc**	D_raw	= Depth before corrections
	D s	= Sounding depth (Depth from transducer to seafloor)
	C_mean	= Mean sound velocity in water column
	T	= Travel time
	H	= Heave – Ship vertically movement caused by waves
	Tp	= Transducer vertical position on vessel
	Tc	= Tidal correction
	D	= Depth

Multi beam

Today many modern surveys make use of MBES systems and therefore cover a wider swath on the seafloor at each run than the single beam system does. The range of today's equipment is capable of measuring depths from 0.5 to 11000 meters. The multi beam system is far more advanced, efficient in covering surfaces and capable of registering more details than using single beam systems. But it also increases the system costs and vulnerability to errors, and requires a high data capacity. They might operate with a swath of 200º of the measuring fan of beams, and as much as 800 beams. The basic differences between single and MBES systems are illustrated in Figure 7. With the MBES system, compensations must be made to heave, roll and pitch to adjust for the survey vessels movement in the sea, heading/gyro to control the direction, sound velocity to compensate for the variations of the speed of sound through the water column, position to set correct position in the coordinate system used, tide to make adjustments to the tide according to the time of day, and clock is used to timestamp the ping to ensure a correct geographic position for each ping. The survey speed influences the accuracy and the density of the data. This is all handled by the special survey software and hardware systems, an extremely complicated and advanced system. The MBES calculation for the depth is far more complicated than using single beam systems (Fig.8) (Kongsberg Maritime, 2014). A Vertical Reference Unit (VRU) or a Motion Reference Unit (MRU) compensate for the vessel heave, roll and pitch movements in the three axis referred to as the x, y horizontal orientation and z vertical orientation.

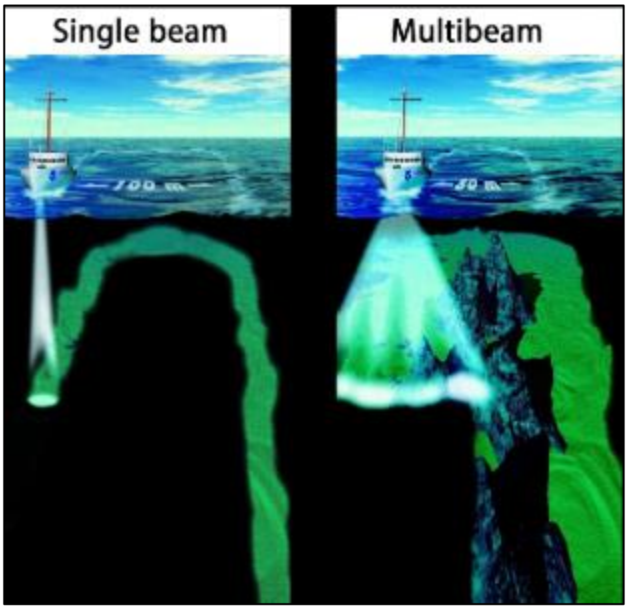


Figure 7: Multibeam vs single beam echo sounder, more beams capture more depth values than using single beam (http://www.nauticalcharts.noaa.gov/mcd/learnnc_surveytechniques.html).

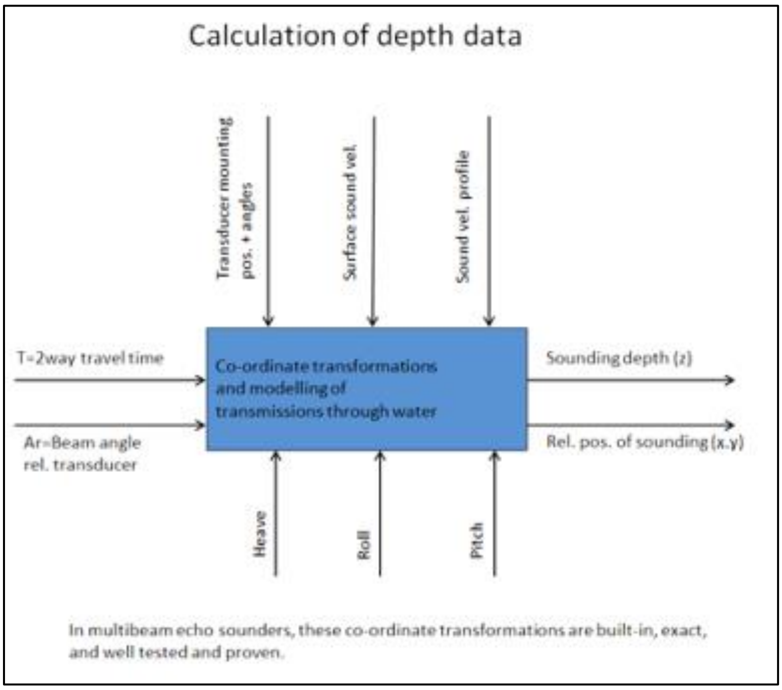


Figure 8: Multibeam depth calculation (Kongsberg Maritime, 2014).

Errors

The error sources are also more complex with MBES systems than with single beam systems. This will increase the possibility for deviations in the measured depths. Figure 9 gives an overview of the errors to take into consideration. Knowledge, good routines and practice is required to achieve the best results. The total system error will also depend upon the quality of the positioning system, vessel motion and sound velocity sensors (Kongsberg Maritime, 2014).

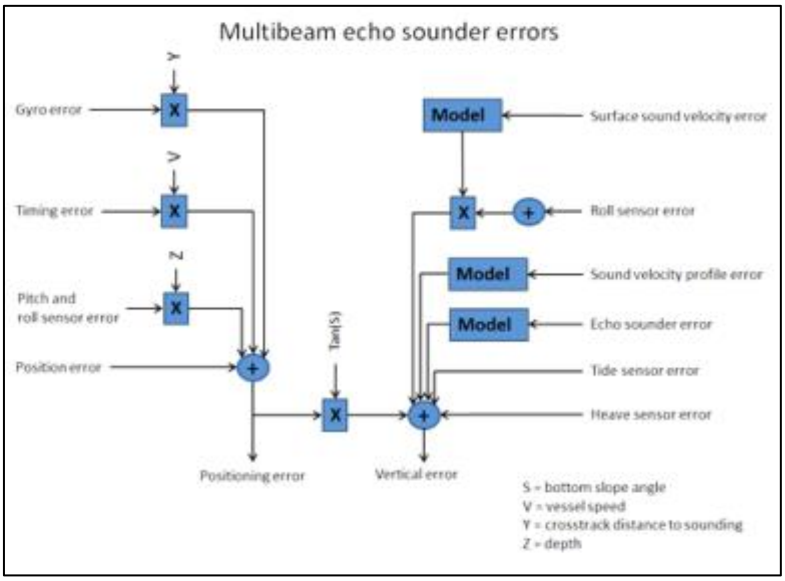


Figure 9: MBES errors (Kongsberg Maritime, 2014).

3.6 Analysis methods

Two aspects of the present studies source data to be particular aware of, is the quality and the differences between them. This study deals with the differences on the existing data, and barely touches the issue regarding the quality of them. It just points out that the datasets show some indication of carrying artifacts, suggests explanations for it, and in some analysis, tests the survey data up against the IHO S-44 standard. Several analysis methods are used to see if the results from the different analysis can add any knowledge about the survey results and the datasets.

Practical empirical methods

- **Method 1:** Before dredging. HIB – mean depth within three test zones of 7m x 7m. Comparisons between two datasets mean depth before dredging within a few selected test zones.
- **Method 2:** After dredging. HIB – mean depth within seven test zones and WSL. Relative comparison of a few manually accurate measured depths using WSL against NMAHS data after dredging, and WSL recognized as the higher accuracy data. Results are tested against the IHO S-44 standard for surveys.
- **Method 3a:** Before dredging. Full area cell by cell comparison – map in ArcMap. **Method 3b:** Before dredging. Full area cell by cell comparison – table in Excel spreadsheet. Cell by cell comparison between the two datasets. As an interesting

aspect, the NMAHS is recognized as the higher accuracy data for the IHO S-44 standard for surveys.

Visual analysis methods

- **Method 4:** Hillshading.
  Visualization of the survey surfaces with hillshading.
- **Method 5:** 3D surfaces.
  Visualization of the survey surfaces in 3D.

Method 1: Before dredging. HIB – mean depth within test zones.

The NMAHS dataset cover all HIB locations as illustrated in Figure 10. A digitized square in ArcMap of 7m x 7m within the HIB basement of 10m x 10m on the seafloor is used as test zones for the depths. Only three of the HIB pillars located east of the dredged area are within a shared overlapping area of both survey datasets (Fig.11), and can be directly compared.
Using a few selected test zones, this first practical empirical method compare the two datasets

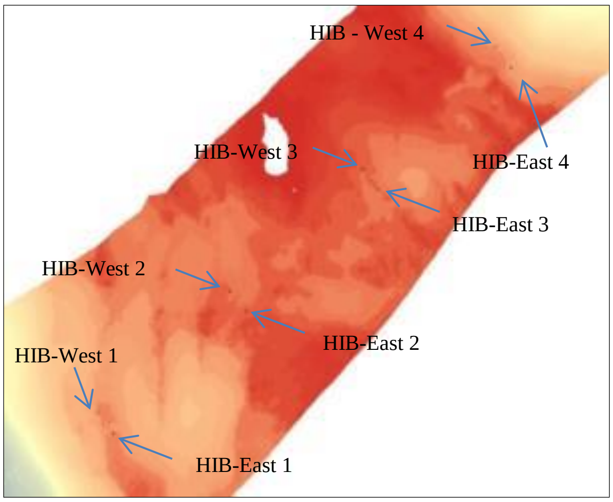


Figure 11: NMAHS - HIB zonal coverage.

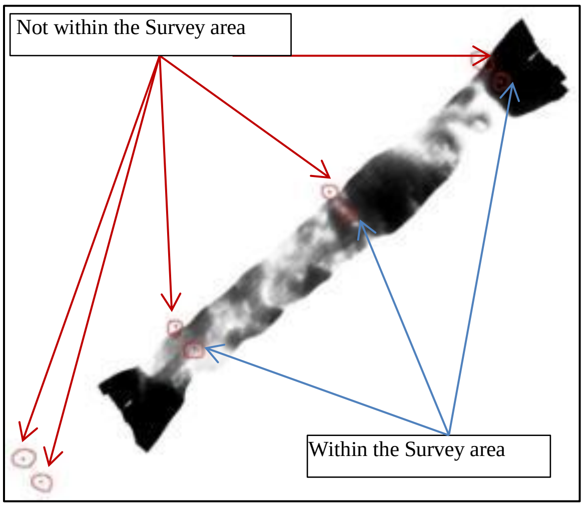


Figure 10: NCA - HIB zonal coverage.

before dredging from NCA and NMAHS, in the limited three HIB test zones that are within the survey area from both surveys. All eight HIB test zones were digitized and named.
The mean depth within each of the three test zones was calculated for both the NCA and the NMAHS datasets, using the zonal statistic as table tool in ArcGIS. The two resulting tables were compared to find any differences.

Method 2: After dredging. HIB – mean depth within test zones and WSL.

These WSL measured depths (Fig.12) serves as reference data recognized as the higher accuracy data, against the NMAHS survey data and all eight calculated mean depths within the HIBs rectangle test zones, derived after the dredging. The eight test zones used were the same zones as those defined in the previous analysis, Method 1. They were not used against any NCA survey data, as there are no data from NCA after the dredging. In this study it was decided to use this manual WSL procedure in one of the analysis, to at least give a solid clue if the multibeam measurements are within reasonable values. The line used was a 1.5cm diameter nylon rope with a sinker tied to the end. With this method there are no sound profile errors to consider, nearly no calibration errors or installation errors, hardly any risk of operator errors, or any errors due to technical failure. One could issue that temperature and current could affect the measurements, but on a depth of 10m with an excepted accuracy of centimeters, it would hardly have any affect, and temperatures in the sea in these waters are fairly stable, with small differences over time.

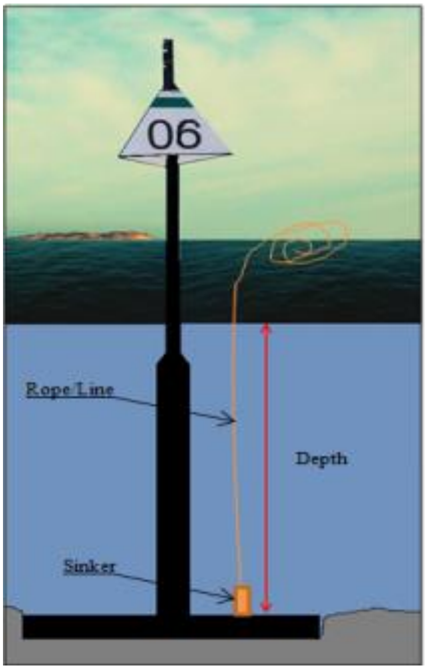


Figure 12: Finding reference depth using weighted sounding line.

Middle temperature between 1976 and 2005 for this area at 1m depth in March is measured to 4.8 ˚C (Institute of marine research, 2016). The survey was performed during tide at its highest between 9 and 11 AM in March 4, 2015, ensuring lowest possible influence of currents, and a measured temperature of 5.9 ˚C at a depth of 1m. For this method to be as correct as possible it is also important to make the measurements in as calm seas as possible. The survey were setup in association with the local supervisor and former hydrographic surveyor Professor Norvald Kjerstad at NTNU Ålesund, and depths at all eight HIBs measured manually using WSL to best establish a higher accuracy data at these eight points. The base foot of the HIBs consists of a 10m x 10m large concrete solid platform (Fig.12), a compact foundation for measuring the depths. The depth was measured by lowering the weighted line, marked for each meter around the expected depths. The date and time for each measurement was noted, and the result adjusted to the LAT (Lowest astronomical Tide) for this location according to a public table of observed water levels delivered by The Norwegian Mapping Authority from

Wednesday, 04. March 2015	
Time	**Observed water level**
09:20	179 cm
09:30	182 cm
09:40	184 cm
09:50	187 cm
10:00	189 cm
10:10	190 cm
10:20	190 cm

Table 3: Tide levels from The Norwegian Mapping Authority

their internet services (Tab.3) (Kartverket, n.d.). From 1 January 2000, the LAT was defined as equal to the Norwegian vertical chart datum at this location of Norway (Kjerstad, 2013). The end result from the measurements was set up in an Excel table and analyzed against the NMAHS data after dredging, but this time with eight qualified reference depths recognized as the higher accuracy data from the WSL survey. The results were tested against the IHO S-44 standard for surveys.

Method 3a and 3b: Before dredging. Full area cell by cell comparison

Method 3a produces a map illustrating the differences, while method 3b uses Microsoft Excel tables to calculate and reveal the differences. This is a comparison between two datasets, and there are no higher accuracy data points representing the depth truth valid as reference as used in Method 2. Still, it would be interesting to see how the uncertainty would unfold when selecting the NMAHS survey appearing to be the better of the two surveys, to be recognized as the higher accuracy data, and anyway test the uncertainty of the surveys up against the IHO S-44 standard for surveys. This will reflect the uncertainty between the two datasets, and if they at least between themselves are within the IHO S-44 standard. It is perhaps not considered to be a complete valid test against IHO S-44, but serves in this study as an interesting aspect. The two datasets from NCA and NMAHS before dredging with perfectly aligned cells were compared cell by cell finding the differences in the cell values (Fig.13). This was performed by two approaches. The first one referred to as Method 3a, using raster images compared cell by cell producing a resulting new visual raster image, and the second one referred to as Method 3b, using raster values in the attribute tables producing results in a new table. The first approach using visual raster image comparison cell by cell was performed in ArcMap to get the differences between each cell directly from the raster images. The NMAHS data extent was clipped to match the NCA extent. Graphs were made analyzing and illustrating the results. Comparing the survey raster's cell by cell gives an overview of the differences, and an insight at what range and values we will find the majority of the differences. Defined as the frequency that the differences occur at, or how often a specific difference does occur.

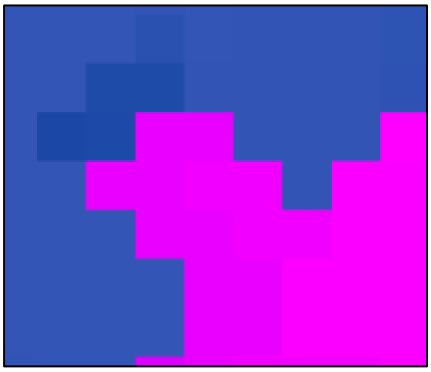


Figure 13: Perfectly overlapping and aligned cells, NCA blue cells NMAHS pink cells.

Method 4: Hillshading

Using hillshading on the surfaces provides a good visual view over the context and shape of the seafloor. This analysis is rather easy to run simply by using the *hillshade* tool in ArcGIS ArcToolbox. Different settings for the hillshading can be altered, but for this study the default settings provide sufficient effect to analyze the surfaces. The light angle (Azimuth) is defined by north as 0 degrees running clockwise to 360 degrees, and at default set to 315 degrees. The altitude of the light is defined by 0 degrees at the horizon and 90 degrees directly overhead, and at default set to 45 degrees. The illumination source is considered to be infinity. Hillshade is best viewed and analyzed when one can use them in an interactive tool giving the possibility to pan, zoom in and out, viewing the data at different distances and resolutions. In this written study one will have to settle with selected images to illustrate findings revealed by hillshade analyzed data. The study however also provides a self-developed software handed in with the thesis report, providing an interactive view of the hillshaded data.

Method 5: 3D Surfaces

In ArcGIS ArcScene, the NMAHS hillshaded data both before and after dredging were set up reflecting the depths in 3D. The 3D analysis gives a better visual comprehension of the differences appearing between the two surveys. The 3D analysis also simulates the surface of the seafloor, and a flyby animation supports the understanding of the seafloor shape. The 3D views also illustrative revealed some of the abnormal readings from the surveys. In 3D scenes, Z values representing heights or depths are often exaggerated to better illustrate the surfaces. Since the depths and differences between the two surveys from NMAHS and NCA before dredging are rather small, using exaggerations provides a better 3D visual view over the differences. 3D analysis were produced, comparing the before and after dredging datasets from NMAHS. This provides an impression of the dredged channel area before and after dredging, and reveals the changes made to the seafloor.

4. RESULTS

4.1 Analysis

Method 1: Before dredging. HIB – mean depth within three test zones.

In Appendix 1, a map shows the compared datasets and the results from the Method 1 analysis. The locations for the HIB test zones are visualized and show the lack of overlap between the datasets and the HIB locations. This analysis compares the depth differences between the NCA and NMAHS survey before dredging in three specific known locations within both datasets overlapping area in a table. The results from the two tables are compared, showing any differences between the two MBES surveys. Since only HIB-East 2, 3 and 4 are within both datasets, these three HIB test zones are the only valuable results compared at this stage (Tab.4).

<u>Observations</u>

The result in Table 4 indicates differences between the two MBES surveys. The largest difference is at HIB-East2 with 0.18m. The results serve as an indication on existing differences, and as a foundation for the next analysis comparing against WSL.

HIB test zone name	NCA mean test zone depth	NMAHS mean test zone depth	Differences in meters
HIB-East1		10.64m	
HIB-East2	8.75m	8.58m	0.18m
HIB-East3	9.03m	9.01m	0.02m
HIB-East4	11.42m	11.40m	0.02m
HIB-West1		11.61m	
HIB-West2		9.01m	
HIB-West3		8.82m	
HIB-West4		11.48m	

Table 4: Differences within test zones between NCA and NMAHS data before dredging. No reference to the actual physical seafloor depths.

Method 2: After dredging. HIB – mean depth within seven test zones and WSL.

This analysis is aimed to find the depth differences between the NMAHS after dredging data and a new WSL survey locating eight manually measured depths within the HIB zones. The depth at all eight HIB concrete basements were manually measured using WSL in a survey as referred to in the description of analysis Method 2. The WSL measurements are recognized as the higher accuracy data, and the results are held up against the IHO S-44 minimum standard for surveys, giving a maximum uncertainty of ±0.26m on depths of 10m.

In ArcMap, calculating mean zonal depth after dredging

The mean zonal depth is calculated in ArcMap for the NMAHS data after dredging, within the 7m x 7m test zone on the 10m x 10m concrete basement of the HIB pillars. The NMAHS data clearly shows the dredged area as a channel with the basements for the HIB pillars lined up along both edges of the channel (Fig.14). The calculated mean depth of the test zones is shown in the *HIB mean test zone depths* column of Table 5.

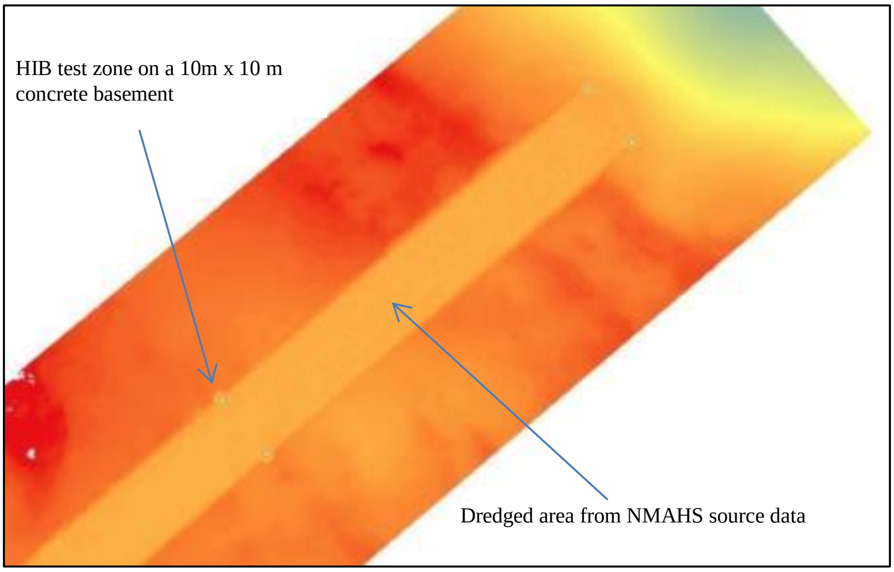


Figure 14: NMAHS - After dredging source data, 10 x10 m concrete base.

In a Excel table, measurement from WSL survey

LAT corrections are made in Excel to the WSL measured depths, from observed water levels at the exact time of the survey. The differences between the WSL measurements and the NMAHS survey after dredging are calculated in meters shown in the column *Difference in meters* in Table 5.

Date of WSL survey: 04.03.2015			LAT observed water level		NMAHS	Results
HIB test zone name	**Time (UTC+01:00)**	**WSL depths**	**Observed water levels**	**Tide adjusted WSL depths**	**HIB mean test zone depths**	**Difference in meters**
HIB - East 1	10:08	13.50m	1.89m	11.61m	11.30m	0.31m
HIB - East 2	10:02	13.50m	1.89m	11.61m	11.37m	0.24m
HIB - East 3	09:38	13.30m	1.84m	11.46m	11.52m	-0.06m
HIB - East 4	09:24	13.60m	1.79m	11.81m	11.42m	0.39m
HIB - West 1	10:13	13.50m	1.90m	11.60m	12.72m	-1.12m
HIB - West 2	09:57	13.50m	1.89m	11.61m	11.53m	0.08m
HIB - West 3	09:48	13.30m	1.87m	11.43m	11.41m	0.02m
HIB - West 4	09:29	13.60m	1.82m	11.78m	11.55m	0.23m

Table 5: HIB mean depth within test zones and tide adjusted weighted sounding line (WSL) differences, on data after dredging.

Observations

The first calculated result indicated that the highest difference is at the missing HIB-West1, with a difference of 1.12m. A new calculation taking the missing HIB-Wedt1 into consideration, gives a more reasonable result with an average difference of 0.19m in the remaining seven test areas. Some false cell depth values is however recorded from the rising HIB pillars within the 7m x 7m test zones, slightly affecting the mean values from the test zones. The influence is presumed to be small, and will not be further considered in this study.

HIB names	**Average depth difference all HIB test zones in meters**	**Average depth difference without HIB 1 west in meters**
HIB - East 1	0.31m	0.31m
HIB - East 2	0.24m	0.24m
HIB - East 3	-0.06m	-0.06m
HIB - East 4	0.39m	0.39m
HIB - West 1	*-1.12m*	-
HIB - West 2	0.08m	0.08m
HIB - West 3	0.02m	0.02m
HIB - West 4	0.23m	0.23m
Average depth	**0.31m**	**0.19m**

Table 6: Average depth differences improve to average 0.19m without HIB 1 west data.

Method 3a and 3b: Before dredging. Full area cell by cell comparison

The full area cell by cell comparison is performed by two methods. A visual method producing a map illustrating the overall differences, and a table related method producing graphs illustrating at which depth the highest appearance of differences are located.

Datasets used in this analysis are the NCA and NMAHS before dredging (Tab.2). Both datasets need some preparations to be better suited for the cell by cell analysis. Some positive signed values exist in the NMAHS dataset, indicating land and not sea depth values. They could be a result of small deviations in the measurements during the survey. This will marginally affect the analysis result since it applies only to three cells, so these values are just ignored. Some fault readings of the data causes spikes, often caused by errors in the equipment's readings of the multibeam, or soft variations in the sediments causing the sound to penetrate deeper than the actual bottom.

Method 3a: Visual raster image comparison cell by cell - ArcMap

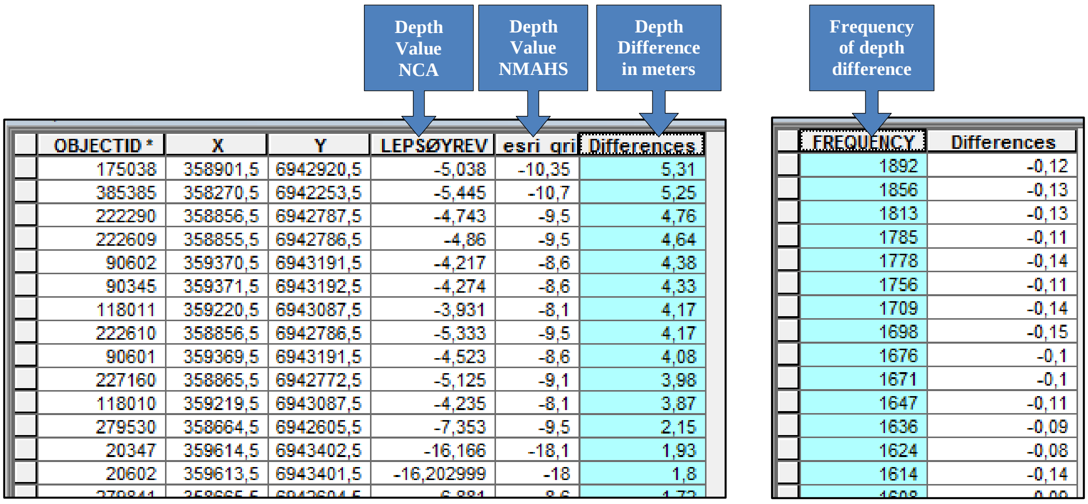
The visual analysis is aimed to find the overall depth differences between the NMAHS and the NCA surveys before dredging. The datasets were setup in ArcMap. The same cell size and spatial reference system used on both dataset preserved that their cell locations have a perfect match. A new visual raster with cell values representing the differences was prepared. A *differences* map (Appendix 2) was made to visualize these results with classification and symbology divided into eight ranges of depths. The highest differences calculated are 3.5m and -5.3m. These are high values in relation to a depth of 11 – 14m seafloor, but it applies only to a few numbers of cells. One cell between 3.0m to 3.5m, and 10 cells between -3.9m to -5.3m of a total of 412576 calls. Visual studies of the differences map (Appendix 2) shows that the majority of cell differences are registered between -0.2m and 2.0m, also the depth differences seem to follow a *pattern* in line with the direction of the survey. Analysis using hillshade looks closer into this indication.

<u>Method 3b: Raster values in attribute tables - Excel</u>

This numerical table analysis is aimed to find the frequency of the depth differences cell by cell. The method uses the exact same two surveys source data as used in method 3a. In this analysis the cell depth values and coordinates are set up in tables, and compared cell by cell according to their locations. Graphs are made in ArcMap to illustrate the differences. The first steps are straight forward in ArcMap, which make out the foundation for the rest of this analysis. As mentioned in the methods paragraph, the NMAHS survey appearing to be the better of the two surveys, were recognized as the higher accuracy data. In that context, using the IHO S-44 standard will reflect the uncertainty between the two datasets, and if they between themselves are within the IHO S-44 standard. It is not a fully qualified test up against more proven accurate measured data as one normally would use by means of the IHO S-44 standard, but serves as an interesting aspect.

<u>ArcMap</u>

Figure 15 shows the depth values from the NCA dataset and the NMAHS dataset in a joined table calculated in ArcMap, where the new field *differences* hold the calculated depth differences. Just as information, one also might be aware of the total cells count of 412576 cells in this operation, limited to the NCA survey data extent as the smallest dataset. Figure 15 also shows a table with the calculated frequency the depth differences occur at. These values are the foundation for the calculations of statistic standard deviation and mean of the depth differences and their frequency shown in the following graphs in Figure 16-18.



OBJECTID *	X	Y	LEPSØYREV	esri_gri	Differences
175038	358901,5	6942920,5	-5,038	-10,35	5,31
385385	358270,5	6942253,5	-5,445	-10,7	5,25
222290	358856,5	6942787,5	-4,743	-9,5	4,76
222609	358855,5	6942786,5	-4,86	-9,5	4,64
90602	359370,5	6943191,5	-4,217	-8,6	4,38
90345	359371,5	6943192,5	-4,274	-8,6	4,33
118011	359220,5	6943087,5	-3,931	-8,1	4,17
222610	358856,5	6942786,5	-5,333	-9,5	4,17
90601	359369,5	6943191,5	-4,523	-8,6	4,08
227160	358865,5	6942772,5	-5,125	-9,1	3,98
118010	359219,5	6943087,5	-4,235	-8,1	3,87
279530	358664,5	6942605,5	-7,353	-9,5	2,15
20347	359614,5	6943402,5	-16,166	-18,1	1,93
20602	359613,5	6943401,5	-16,202999	-18	1,8

FREQUENCY	Differences
1892	-0,12
1856	-0,13
1813	-0,13
1785	-0,11
1778	-0,14
1756	-0,11
1709	-0,14
1698	-0,15
1676	-0,1
1671	-0,1
1647	-0,11
1636	-0,09
1624	-0,08
1614	-0,14

Figure 15: NCA and NMAHS depth differences in meters, and the frequency the depth differences occur at.

<u>ArcMap graphs</u>

The first statistic calculation is performed in ArcMap. All 412576 raster cells from the study area are used. The first graph shows an overview of the depth differences (Fig.16). The graph indicates that the majority of variations are somewhere between 0.5m and -1m. Relative few scattered cells contain larger differences.

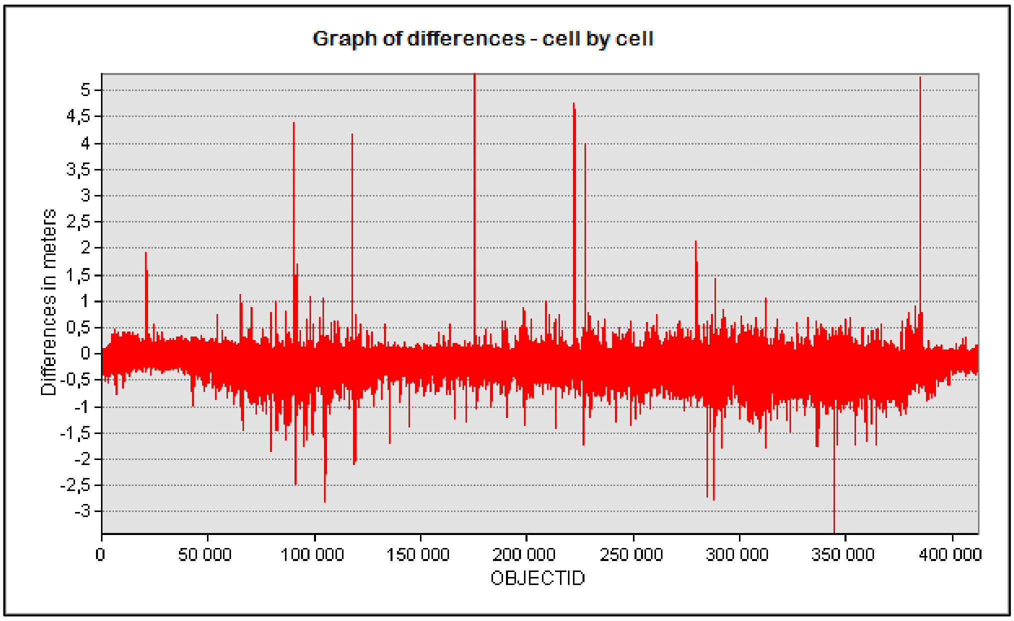


Figure 16: NCA and NMAHS differences in meters cell by cell.

A second graph visualizes and further clarifies the depth differences (Fig.17). It shows the number off cells within the depth differences in meters. A closer look at the graph indicates that somewhere between -0.335m to 0.105m difference is where the highest number of cells is located. Statistic mean for the differences is -0.138m, and a standard deviation of 0.137m reveals that the majority of depth differences tend to be close to the mean value of -0.138m. The majority of differences are gathered around mean, and the graph indicates that the differences between the NCA and the NMAHS data are rather small but that the values are slightly biased towards negative values, as one could expect knowing that the two operators approach to calculate the cell values differs. The NMAHS uses a conservative approach selecting the shallowest value as the valid cell value, while the NCA calculates the mean of the cells.

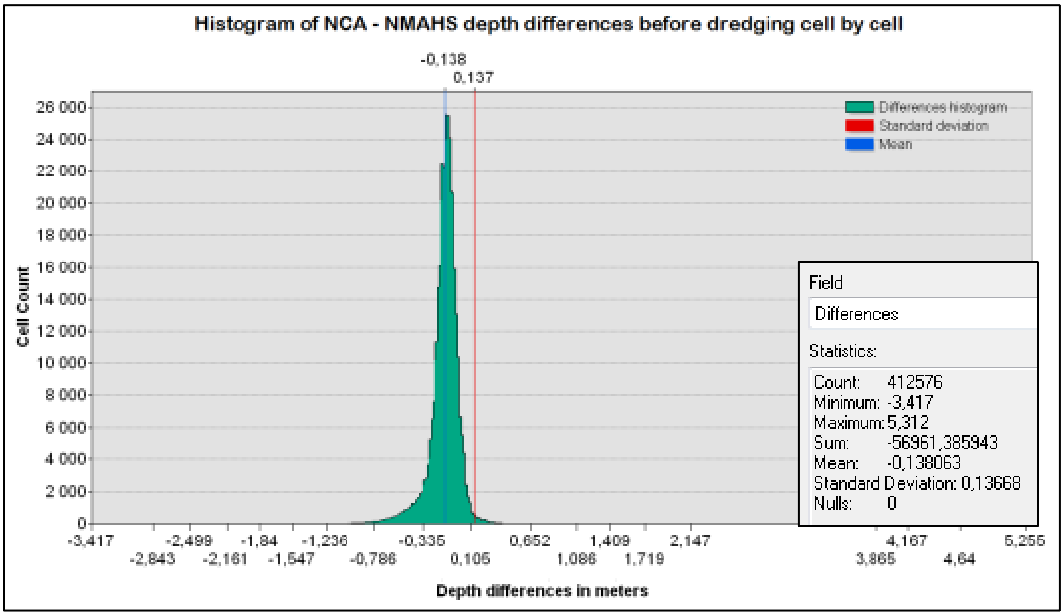


Figure 17: Statistics histogram, standard deviation and mean of depth differences in meters.

The next graph (Fig.18) presents the frequency the depth differences occur at. It shows how

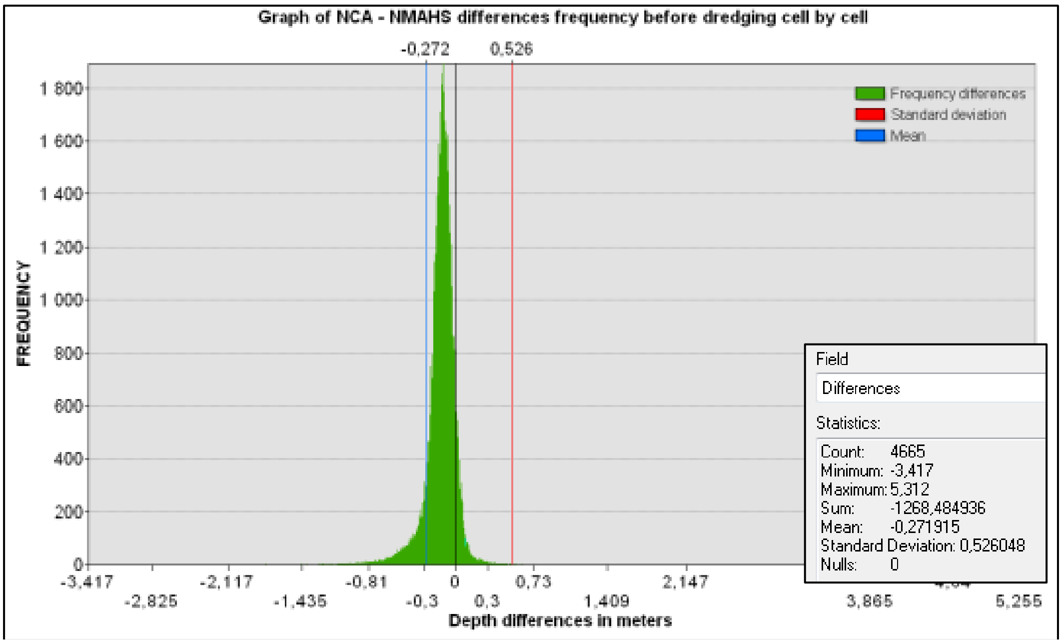


Figure 18: Statistic graph, standard deviation and mean of differences frequency.

often each depth difference value occurs. Statistic mean for the difference frequency is -0.272m and a standard deviation of 0.526m indicate that the majority of the differences frequencies deviate from the mean value of -0.272m, confirmed by the fact that most depth difference values are located between 0m and the mean value of -0.272m. The graphs indicate that there is a good match between the NCA and the NMAHS datasets.

Excel

Microsoft Excel spreadsheet was used in a further investigation of the depth difference values that occur most times, *the highest frequencies for all existing differences within each category of differences*. The differences were sorted in groups of only two decimals e.g. 0.12, avoiding one for 0.12345, one for 0.12658 since there were no use for accuracy higher than two decimals. The differences were categorized gathering all that applies to 0.12, all that applies to 0.13 and so on. For all differences that apply to 0.12 the frequency of their appearance will be summarized. Table 7 shows that the NCA survey results tend to measure the depths as lower than the NMAHS measurements.

Percent cells where NCA measures the lowest values	Cells with 0 value	Cells with negative value where NCA measures the lowest depth value	Cells with positive value where NMAHS measures the lowest depth value	Total number of cells
91%	635	375763	36178	412576

Table 7: NCA - NMAHS cell values indicates that NCA tend to measure the lowest values, and their result is registering a lower seafloor than the NMAHS measurements.

Observations

A resulting graph shows that we have the highest appearance of differences around -0.13m (Appendix 3). So this is where we find the majority of differences between the two surveys. In reference to Figure 15, the negative values that we see dominating the difference column also dominates the resulting graph on Figure 18, from the fact that the NCA dataset has the highest frequency of the deepest depth values. The positive values, is where NMAHS has the deepest depth values. Parts of the Excel table are shown in Appendix 4. A few values in the highest range are the most interesting values, at a frequency from 1000 an upward, and the only ones selected for the graphs. Further calculations in Excel revealed the number of cells meeting the IHO S-44 standard for depths at 10m. A test against IHO S-44 standard, gives 89% cells counting 364873 cells within the S-44 standard (Tab.8).

Percent cells within IHO S-44	Number of cells within IHO S-44	Number of cells not within IHO S-44	Total number of cells. Minus values lower than 2 digits after comma.
89 %	364873	45182	410055

Table 8: NCA – NMAHS depth differences related to IHO S-44 standard, where NMAHS is recognized as the higher accuracy data.

Method 4: Hillshading

This analysis takes a closer look at the artifacts discovered using hillshading in the initial preview of the data sources.

<u>NCA before dredging</u>

The hillshaded raster image in Figure 20, side by side with the plain surface source data before running this tool in Figure 19, clearly illustrates some of the benefits of using hillshading in a study of the surface data.

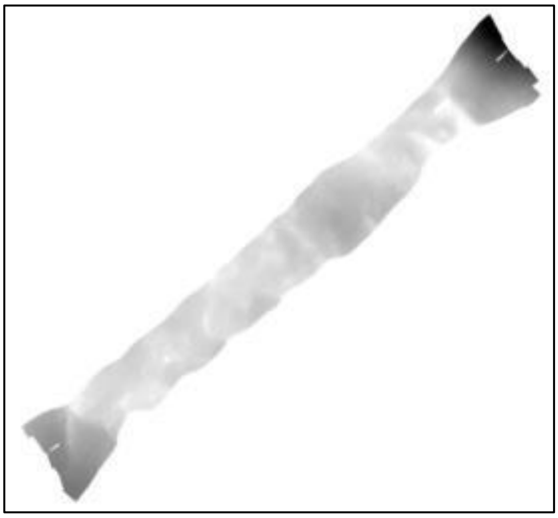


Figure 19: Illustration of NCA Source data without hillshading.

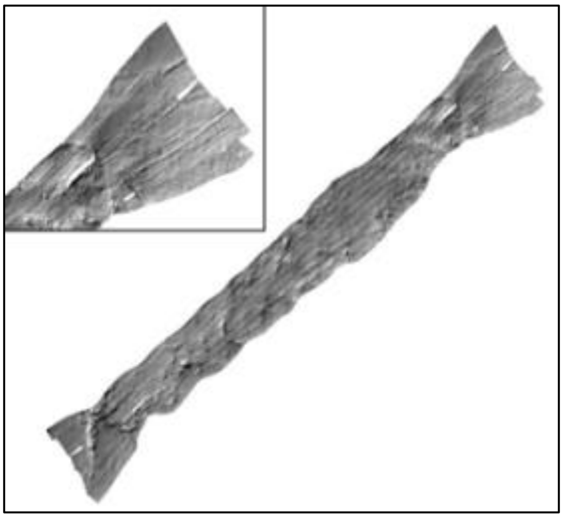


Figure 20: Illustration of NCA data hillshaded.

As discovered in the preview of the NCA dataset and the full area cell by cell comparison analysis, artifacts appear all over this dataset. The final map in the Appendix 5 contains more detailed view of the distinct artifacts running along the full length of the dataset equal to the direction of the survey spreading out in a fan shape at both the south and north ends.

MBES operator course material from Kongsberg Maritime deals with errors that might happen during MBES surveys. Figure 21 shows a picture from these lectures where a similar *pattern* occurs. This visible error is described as "*an effect of incorrect velocity values through the water column on a multibeam swath*" (Kongsberg Maritime, 2014). For verification, contact was established with Torunn Haugland, working as a course instructor of underwater mapping at Kongsberg Maritime. She agrees with the conclusion that something seems wrong in the

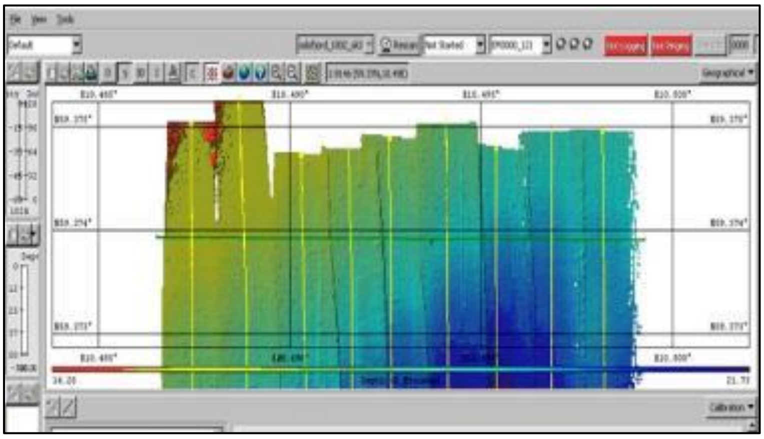


Figure 21: Kongsberg Maritime, incorrect velocity values through water column (Kongsberg Maritime, 2014).

NCA survey data, probably caused by errors in the sound profile, *an effect of incorrect velocity values*, but it could also be caused by calibration errors. Without knowing exactly how or how well the calibration procedures were followed by NCA before and during the survey, it will be very difficult if not impossible to verify an absolute reason for these errors. But we can establish that an error has led to some of the largest depth differences appearing in the *Full area cell by cell differences map* made under the visual raster image comparison cell by cell analysis in method 3a. The NCA survey data before dredging did not cover the entire area of the dredged channel, and fails in meeting the IHO S-44 criteria of a *Full Seafloor Search* for *Special order* surveys where under keel clearance is critical (IHO, 2008).

<u>NMAHS before and after dredging</u>

The first NMAHS hillshade analysis deals with the NMAHS after dredging dataset and the result from the WSL analysis, revealing a probably missing basement. On the final map in Appendix 7, it is undoubtedly visible that HIB-West1 base appears different from the other basements. The actual cement foundation seems to be missing at HIB-West1, as seen in Figure 22. It is likely that HIB-1 West have been removed before the survey took place. At NCA's internet site, a map is available showing registered maritime accidents, and yes a maritime accident is registered at this HIB as shown in Figure 23 (Kystverket.no).

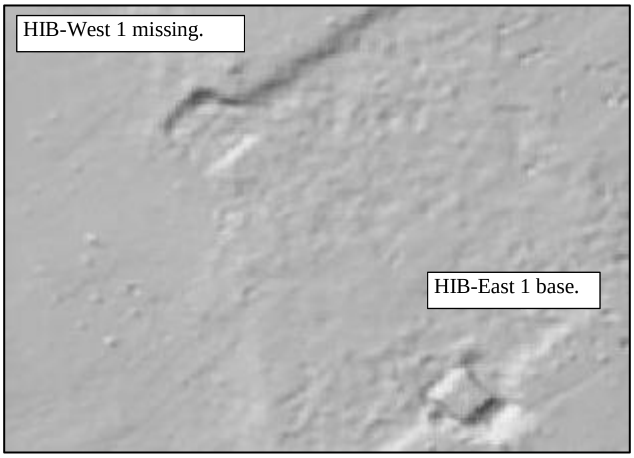


Figure 22: Missing basement of HIB-West1 after accident.

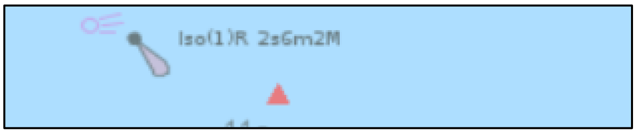


Figure 23: Maritime accident at HIB-West1, marked by red triangle. HIB run down by ship.

A request to NCA main office confirms the suspicions. Ruling out the measurements for HIB-West1was a correct decision and the average depth differences somewhat improves.

In the second NMAHS hillshade analysis using the collected data before dredging, holes appear especially in the south west as shown in Figure 24. Holes in the collected data often occurs at the end of a survey run, caused by a vessels speed increase as it prepares to turn direction for another survey run. Also one can discern artifact lines along the survey direction (Fig.25), but since it is hardly noticeable in the dredged area it will not be considered further in this study. Appendix 6 shows a full hillshaded map visualizing this dataset.

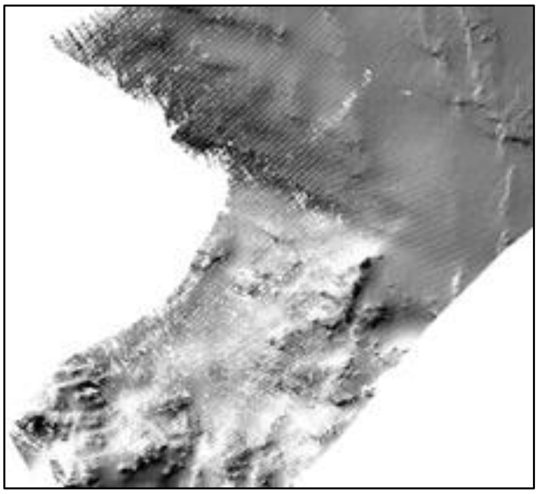


Figure 24: NMAHS south before dredging – line and hole artifacts.

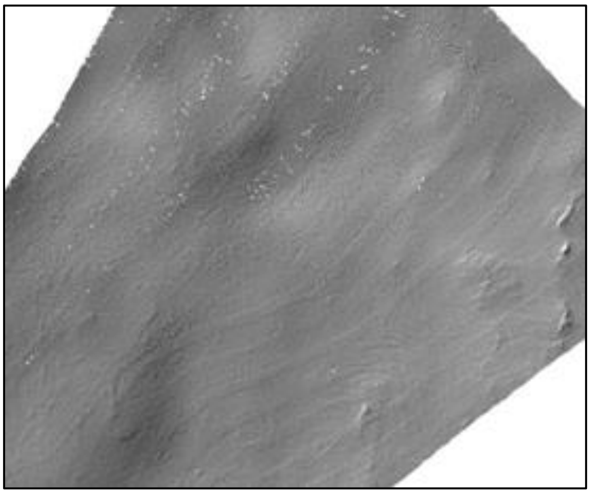


Figure 25: NMAHS north before dredging - line and hole artifacts.

Method 5: 3D surfaces

NMAHS survey before and after dredging.

The 3D Surface's analysis also deals at a cell level in visualizing every cell in the NMAHS before and after dredging datasets. Using a vertical exaggeration factor of 5 for the z values (depth/height) improves the visual understanding of the data presented in the 3D scene, but it will also increase the recorded errors. Errors recorded during the surveys, are often caused by soft sediments, and are visible as *spikes* peaking up or down from the surface in the 3D scene (Fig.26). Better calibration of the software would remove most spikes already at the data collection during the survey (Kongsberg Maritime, 2013). It is likely to believe that even though they are few and most often appear between 0.10m and 0.5m, the highest difference values derived from the previous analysis, are considered to be spikes showing values up to several meters. To visualize the surfaces before and after dredging, an animation was set up running through the scene.

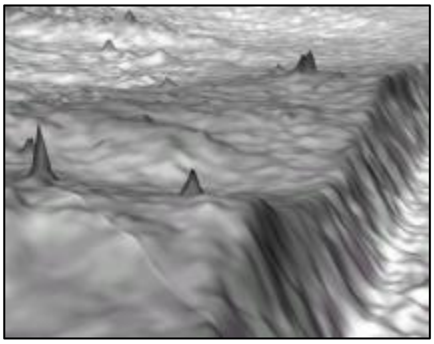


Figure 26: Spikes recorded during the surveys, are often caused by soft sediments.

Observation

The animation gives an overview of the area, and a better understanding of some of the issues unfolded in this study related to the NMAHS surveys before and after dredging. Besides giving information about the seafloor, HIB positions, characteristics and visual form of the channel, the animation illustrates how the dredged channel is cut into the seabed and how the new seabed compares to the seabed situation before the dredging. The exaggeration of the depths amplifies the interesting factors from the data, and gives an understanding of the HIB basement seafloor locations and their relation to the dredging. These 3D pictures (Fig.27) from the scene serve as an impression of the animation. The actual movie are presented as an *.avi file handed in with the thesis report.

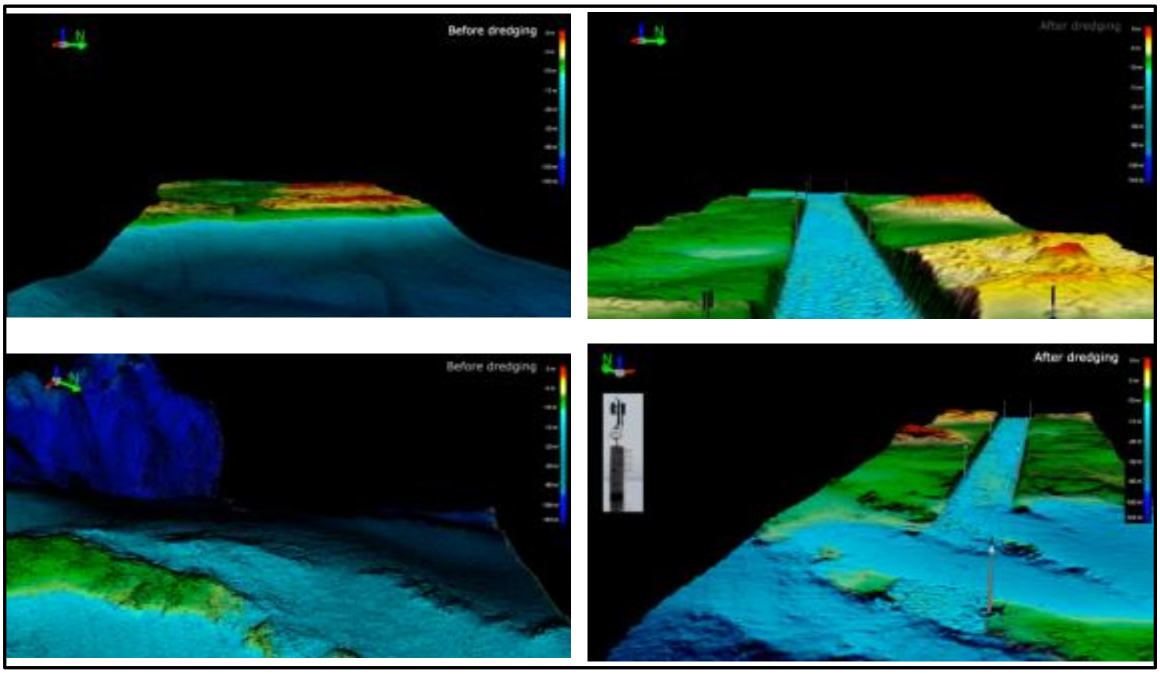


Figure 27: Animation – screen dumps from NMAHS after -before dredging.

<u>NMAHS and NCA before dredging</u>

The before dredging datasets from NMAHS and NCA are set up in ArcScene. A subtraction is performed on the datasets to extract the depth differences on a cell by cell level as performed in method 2. A vertical exaggeration of 50 is set on the scene to better visualize the depth differences. Figure 28 illustrates the depth differences, and where on the surface they appear. A 3D illustration is attached as Appendix 9. This analysis emphasizes the findings in the previous analysis making them easier to recognize, as most of us probably benefits from viewing geographical related information in 3D.

<u>Observation</u>

This 3D analysis shows all the depth differences displayed in one scene between the two surveys. In 3D the depth differences become very visual, and the artifacts running along the survey direction are making out the majority of the depth differences. But the most spectacular spikes probably come as results of errors in the equipment's readings of the multibeam, e.g. the previous explained variations in sediments.

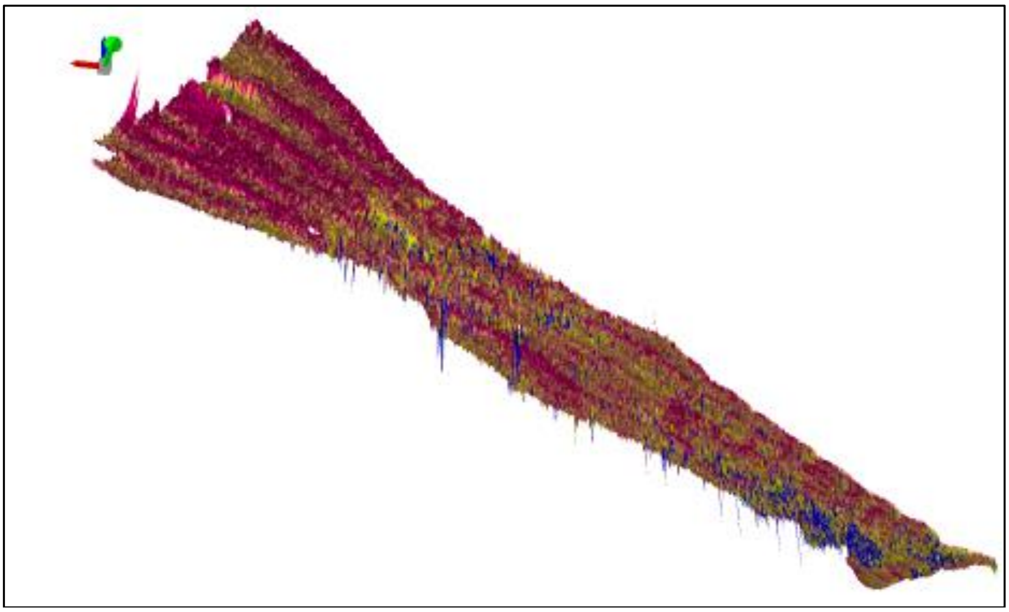


Figure 28: NMAHS-NCA depth differences exaggeration factor of 50. No depth differences would give a flat area.

Analysis results overview

Table 9 shows an overview of all methods and analysis results from the present study. This overview sums up the study.

	Practical empirical methods			**Visual analysis methods**	
	Method 1 HIB - mean zonal depth NCA/NMAHS before dredging	**Method 2 HIB – mean zonal depth WSL/ NMAHS after dredging**	**Method 3 Full area cell by cell NCA/NMAHS before dredging**	**Method 4 Hillshade**	**Method 5 3D surface**
Test zones/cells tested	3 HIB test zones	7 HIB test zones	410055 cells		
HIB-East1 Mean dif. meter		0.31			
HIB-East2 Mean dif.	0.18m	0.25			
HIB-East3 Mean dif.	0.02m	-0.06			
HIB-East4 Mean dif.	0.02m	0.39			
~~HIB-West1~~ Mean dif.		-			
HIB-West2 Mean dif.		0.09			
HIB-West3 Mean dif.		0.02		Appendix 5,6 and 7	Appendix 9
HIB-West4 Mean dif.		0.23			
Mean dif. meter	0.073 m	0.19 m			
Cells = IHO S-44 ± 0.26m at 10m			364873 cells		
Cells ≠ IHO S-44 ± 0.26m at 10m			45182 cells		
% Cells = IHO S-44 ± 0.26m at 10m			89%		
IHO S-44 ± 0.26m fulfilled	Not applicable	Yes	Yes		
Comments	Few test zones	WSL = weighted sounding line	Biased to negative values.		Closer visual view of the dredged area, and the artifacts
Results	No significant differences	Three differences to be aware of, but no significant differences	Some *spikes* to be aware of, but overall no significant differences. 91% cells where NCA measures the lowest/deepest values	Noticeable artifacts. Probably causing the majority of differences	Gives an extended understanding of the dredged area, and the artifacts.

Table 9: Overview of all methods and results from the present study.

5. DISCUSSIONS

The aim of this study was, as set up earlier: "*To validate MBES surveys performed by two different operators in the exact same location, to confirm if there exist differences in their results and how big the differences are. To achieve this, the study would use numeric analysis and 2D/3D visual analysis to compare the two surveys results for the purpose of documenting any differences between the survey results, and "depth truth" from manual measurements using weighted sounding line".* The technical goals are performed as described, even though the study had to be limited in relation to the initial plans. Differences are documented, as well as artifacts in the survey datasets.

The present study was dealing with issues of comparing and verifying real MBES survey data, using data from different survey operators offshore, testing both hotspots and larger areas on a cell by cell level. Several soundings are registered within each cell of 1m x 1m resolution, but the cells are given only one valid depth value. Estimating the costs of dredging an area, the NCA have chosen to calculate the average for the cell value. NMAHS due to their focus on production of nautical charts and safe navigation has a more conservative approach, and selects the most shallow depth value indicating the minimum depth within the cell. Their different approach in calculating the cell value, affects the results they achieve. One can predict that the NCA survey data could give a lower depth value than the NMAHS survey data, if they otherwise have performed equal surveys.

An extensive search for related literature on internet and available libraries returned very limited results. Requesting information from the NCA and Kongsberg Maritime as a manufacturer of MBES systems returned no knowledge of similar studies. It is expected that similar studies exists, but also local survey professionals related to NTNU Ålesund had no knowledge of such similar work. At some point in the present study a decision had to me made to instead look to similar studies made in related fields. The approach selected for the analysis came from onshore related land based studies using DEM data and approaches studied from Kyarizu, (2005) and Wechsler, (2003), but without using (RMSE) statistic to specify accuracy or uncertainty. Instead the statistical calculation in ArcMap was used, providing Standard Deviation (SD) analysis. Previous studies on the subject using MBES equipment had too much dissimilarity for this present study. An article of Ernstsen, et al. (2006) compares different surveys and measurements addressing both the vertical and horizontal accuracy using MBES systems and a high precision differential global position system (DGPS). They also address the fact that decreased accuracy could come as a result of dismounting the system between annual surveys, rougher sea conditions during one survey and small number of annual surveys (thin collection of data). They differ though compared to the present study that uses two different surveys, operators and contractors, by running several measurements in only one single survey. Operating at depths of 10–13m, they found a vertical precision of ±2 cm at a 95% confidence level. Comparing between several surveys the accuracy decreased to a vertical precision of ±8 cm at a 95% confidence level. This was probably the study most alike the present one, but they also found it difficult to locate any related studies. An article made by Artilheiro and Pimentel, (2001 cited in Ernstsen, et al. 2006) refers to a study evaluating high resolution MBES and vertical resolution, but the study relates to onshore, dry dock measurements and not offshore surveys as in the present study. It is more related to calibrating the equipment. A study of Eeg (1998 cited in Ernstsen, et al. 2006) also examine the vertical resolution accuracy on two particular MBES systems offshore, the RESON SeaBat 9001 and the BCC (Elac's bottomchart compact shallow water) at 22m depth, respectively finding a vertical precision of ±9.3 cm and ±8.7 cm, but focusing on a single stone in the measured field for depth truth. This study also deals with the changes between the different beams of the multibeam swath. Their results match the findings in the present study, meeting the IHO S-44 standard. The study in Eeg (1998 cited in Ernstsen, et al. 2006), uses however just one reference point, while three HIB bases serves as depth truth in the present study. If both contractors had provided data covering the entire area of interest causing all HIBs locations to be present in both datasets, the present study could at its best have used all eight HIBs in its analysis. Beside the field stone, the Eeg (1998) study also concentrate on using a flat area as possible for its statistical modeled calculations. The surveys are set up for this task, while the present study uses actual contractor’s survey data from NCA and NMAHS. Nevertheless all of the studies mentioned add insight to the subject, and especially the studies of Ernstsen, et al. (2006) on their work on vertical accuracy.

The present study indicates that modern MBES systems have no problem in meeting the IHO S-44 standard in vertical precision and the equipment accuracy specifications even goes far beyond the IHO S-44 standard (Kongsberg Maritime, 2014). Studies by Wells and Monahan (2002) and Heaps (2004) cited in Ernstsen, et al. (2006) regarding horizontal accuracy, questions the suitability of the IHO S-44 standard as a quality control standard for modern MBES systems. Modern surveys using state-of the-art MBES high resolution systems have no problem meeting the IHO S-44 Special order standards (IHO, 1998), raising an issue of questioning the usefulness of the IHO S-44 as an appropriate quality control standard (Wells and Monahan (2002) and Heaps (2004) cited in Ernstsen, et al. (2006)). The IHO S-44 standard sets minimum standards for the MBES surveys, and is regularly renewed. It is likely to believe that the standard will be more up to the challenge of matching the modern range of MBES equipment after its next edition.

Early in the study, a decision was made to use just a few reference zones for the first analysis on the locations where the contractor had their focus on precise leveling of the seafloor for accurate positioning the HIB basements. It is important to remember that this is not a difference compared to the actual seafloor, but a direct comparison between datasets. All eight HIB test zones were digitized in ArcMap as rectangles of 7m x 7m within the 10m x 10m HIB basement location, and named after their location e.g. HIB-East1, being the first HIB located east. This based on the location given by the MBES survey performed after dredging, showing the solid basements of the HIB pillars. The ideal difference would be close to 0, giving an almost identical result between the two surveys in method 1. That is however practical impossible to achieve, and differences are to be expected. A *mean* value of the seafloor within the 7m x 7m HIB test zones was calculated on the data before dredging available from both the NMAHS and NCA, and the results was compared in a table. The results of 0.02m difference from the first analysis are by any means to be considered as a very good result for HIB–East 3 and HIB–East 4 test zones.

The analysis in method 2 uses WSL manually measured values compared against MBES collected data from NMAHS. One could ask oneself, what does an old method such as using weighted sounding line (WSL) possible add to a modern survey using MBES systems? The question is highly reasonably, but even though this is an old method, under proper conditions it is for this study the best method for comparison to what the actual depth is at the point measured. Carried out correctly it should under the best conditions give an accurate depth within centimeters, and is actually still used to calibrate modern sounding equipment (IHO, 2005) or to measure depths especially in shallow waters where modern equipment sometimes cannot be set up appropriate due to e.g. physical limitations (Kjerstad, 2010, p.101). As one of the earliest tools used for depth measurement, it is still valid and remains in use to this day (International Hydrographic Organization, IHO, Cha.3, p.186, 2005). Depths in many navigational maps today still contain some data collected by this method, or even just by local guide's knowledge (Kartverket, 2010). The challenge is not necessarily the accuracy of the depth measured by WSL in shallow waters, but rather inaccuracy in position and the lack of sounding density, making the profile of the seafloor surface unknown between the points of collected data. Multibeam sounding data gives a high density of data, replacing and filling the gaps from the old data. At the analysis in method 2 using WSL, HIB- East4 has the highest calculated difference between the NMAHS survey data and the reference values from the WSL survey. HIB-West3 has the lowest calculated difference of 0.02m difference. These differences are remarkably close to the result in the previous analysis, even though this is a comparison of the data recognized as the higher accuracy data from WSL, while the previous was comparing two MBES datasets. The average uncertainty of 0.19m for the survey depths is well within the IHO S - 44 standard ±0.26m. Although HIB-East1with 0.31m and HIB-East4 with 0.39m don't quit meet the standard, and indicates that perhaps a closer look at the setup or calibrations could be recommended. Some of the differences could be caused by sediments resettling over the dredged area the last three years since the dredging took place, caused by tidal currents in the channel. One could perhaps expect the resettling of sediments to be minimal due to the fact that they appeared hard during the beginning of the dredging, but that is yet to be investigated by the NCA, running new surveys to analyze changes in the sediments. Another issue to be aware of is that the depths calculated from the NMAHS data, will be slightly affected by the HIB pillars rising up from the HIB basements. In the 3D analysis, one can slightly see the peaks rising from the HIB basements. To avoid the values from the pillars to affect the results one could have digitized the test zones so they avoided the pillars. Despite this, using mean values reduces the impact this will have on the results of the analysis. In a future improvement of this method 2 analysis, it would serve the analysis better to calculate a mean from the 10m x 10m basements using a method to rule out the data cells of the basement where the rising of the pillars are recorded. Also one could have statistically calculated the dredged channel to find how successfully the dredging has been in flattening the new bottom, and a future analysis should address this issue.

The map in appendix 2 from the third cell by cell analysis reveals that the high extent in difference in meters in itself is not an important issue, since it applies only to a few numbers of cells. E.g. 3.0m to 3.5m apply only to one cell, and -5.3m to -3.9m apply only to ten cells of a total of 412576 cells. This could be caused by artifacts spikes, picked up by faulty readings of the survey equipment. Visual studies of the differences map (Appendix 2) shows that the majority of cell differences are registered between -0.2m and 2.0m. Also the depth differences seem to follow a pattern along with the heading of the survey lines, most likely caused by errors in the sound profile at the water column (Kongsberg Maritime, 2014, Torunn Haugland). The highest depth difference among the values that are represented over 1000 times is the depth of -0.45m with a count of 1009 cells, and the depth value that occur the most is -0.13m (Appendix 3).

The 3D analysis adds valuable understanding to some of the issues related to this study. Not all issues are necessarily well suited for presentation in 3D, but 3D often contributes to the readers/viewers understanding of more or less complicated issues. The animation strengthens the knowledge of the NMAHS survey data, and gives a clear view of NMAHS's two surveys before and after the dredging of the area.

There will always be room for improvements in studies like this, and a number of approaches to implement the analysis. The issue is however often tied up to time and costs as well as the quality of the data available. It would be interesting to improve the analysis applied in this study using a better second set of data provided by a complete new survey from NCA with results also from after the dredging, without uncertainty related to sound profile, calibration or tidal adjustments and also covering more of the same area as the NMAHS survey data. With more time spent, one could make use of core source data from the initial surveys, setting up information about the vessels and their setup of equipment and calibrations. Digging deeper into the material should also include information of the calibration quality from both survey operators, and ensure that they meet the standards described in the IHO S-44 standard. This would make a better foundation for the comparison of the surveys. If a decision was made to use RMSE analysis, as often used with onshore DEM data, a minimum of 28 reference points are needed for statistical testing. 8 edge points and 20 interior points (USGS, 1998). Also it could be interesting to compare data from surveys carried out in deeper waters, to see if the differences increased or decreased. Even though the data used in this analysis has a resolution of 1m x 1m, NCA also provided a dataset of 0.2m x 0.2m resolution from their data before the dredging (Appendix 8). In a feature analysis a new comparison could be performed using two 0.2m resolution survey after the dredging. It is likely to believe that future surveys will be conducted in this dredged area, to observe any changes of the sediments. Perhaps the findings from this study could serve as a reminder of things to take into consideration. Related to IHO S-44 standard, the uncertainty of the measurements indicates that the area can be regarded as safe for marine traffic.

6. CONCLUSION

This thesis is restricted to the study of the data products delivered by two MBES survey operators, and one self-elaborated WSL survey. Several important factors are limiting the study, such as the lack of knowledge about the preparations and calibrations of the MBES surveys. Another issue not covered in this study is the influence of time of the year, water temperature, salinity, pressure and weather conditions during the surveys, and the effect they could have on the results. Sound velocity is an important part of any MBES survey, and as part of the calibration procedure it should be frequently measured during a survey (Kongsberg Maritime, 2014).

The study aimed to answer these questions.

- Are there any significant differences between measurements made by the two different survey operators in the exact same area, using MBES equipment from different suppliers?
- How accurate are they compared to manually measurements using WSL?

The answer on the first question will have to be that there are no significant differences between the depth measurements made by the two different survey operators from the surveys that were compared in method 1, method 3a and method 3b. The two surveys give comparable results even though artifacts appear on the NCA dataset, mainly within some smaller values. The NCA dataset is biased towards negative values probably due to the fact that they calculate the average value of each cell, while the NMAHS calculate the shallowest value. Using the same approach of calculating the cell value, the differences between the surveys would probably even be less. Also at the north and south ends of the NMAHS dataset before dredging artifacts appeared, but the differences in general still are within the IHO S-44 standard. It should however be noticed that the NCA data failed to meet the IHO S-44 minimum standard of *full seafloor sea*rch applicable for depths of 10m. For the second question, the depths registered by the NMAHS survey in 2012 also show reasonable results held up against the IHO S-44 and the self-elaborated WSL survey in the method 2 analysis, meeting the minimum standards of the IHO S-44 of ±0.26m at depths of 10m. An average difference of 0.19m from the seven test zones, are not considered to be a critical uncertainty related to safe navigation in this area. To the author’s knowledge the depth data in electronic charts are correspondingly updated by the collected depths from the NMAHS surveys, and it is reasonable to expect their data to be the most reliable. Even though the surveys are meeting the IHO S-44 standard, the resulting differences are significant relate to the equipment's expected accuracy. The predicted system depth uncertainties for the Kongsberg MBES EM 2040 are in the order of 0.1% of the measured depth, and an uncertainty of 0.01m at 10m depths. Perhaps the present study could serve as an inspiration to future studies conducted in relation to the NCA in following the development for this dredged area.

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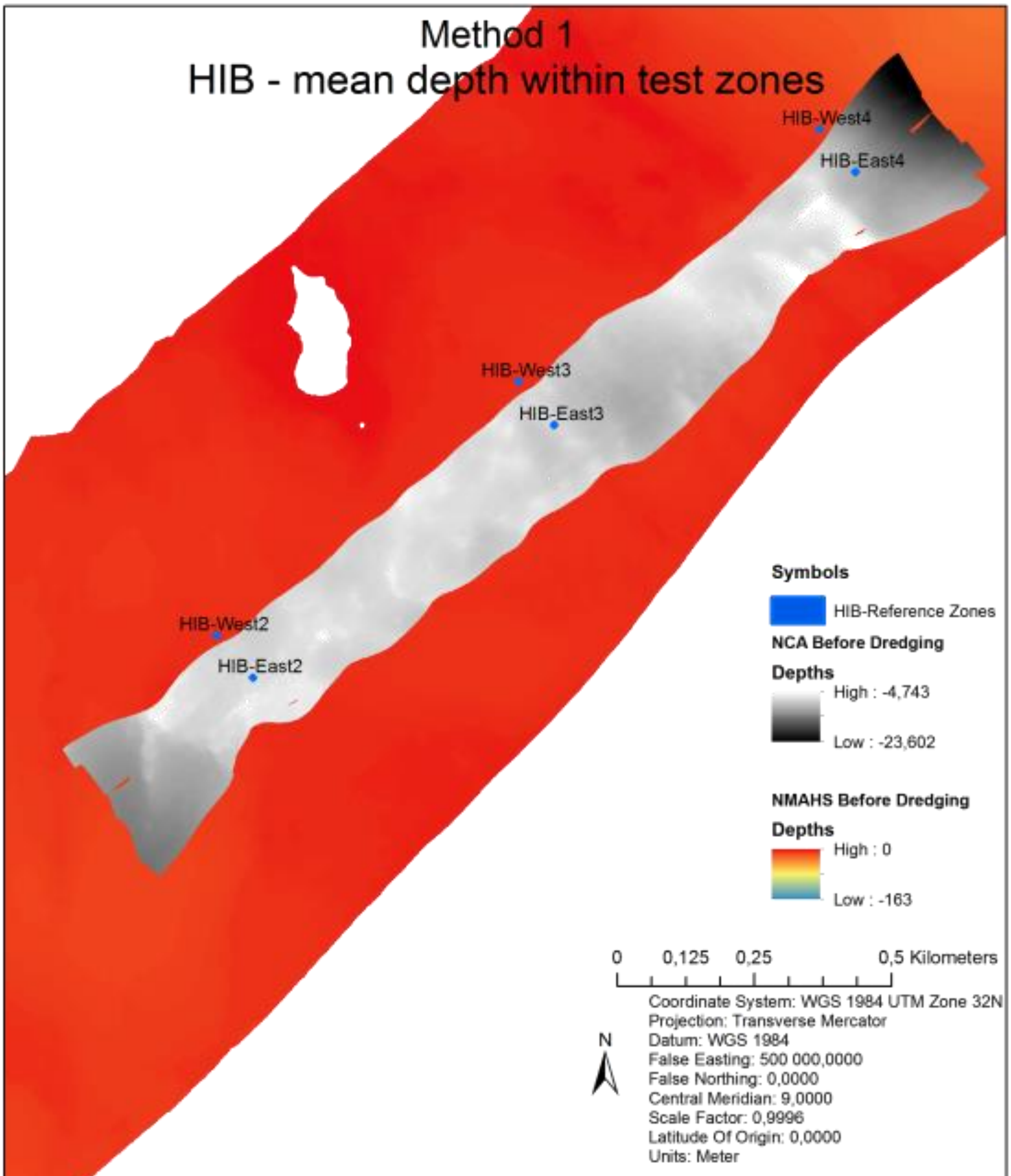
APPENDICES

1. HIB - mean depth within test zones



HIB Test zone name	NCA mean Test zone depth	NMAHS mean Test zone depth	Differences in meters
HIB-East1		10.64m	
HIB-East2	8.75m	8.58m	0.18m
HIB-East3	9.03m	9.01m	0.02m
HIB-East4	11.42m	11.40m	0.02m
HIB-West1		11.61m	
HIB-West2		9.01m	
HIB-West3		8.82m	
HIB-West4		11.48m	

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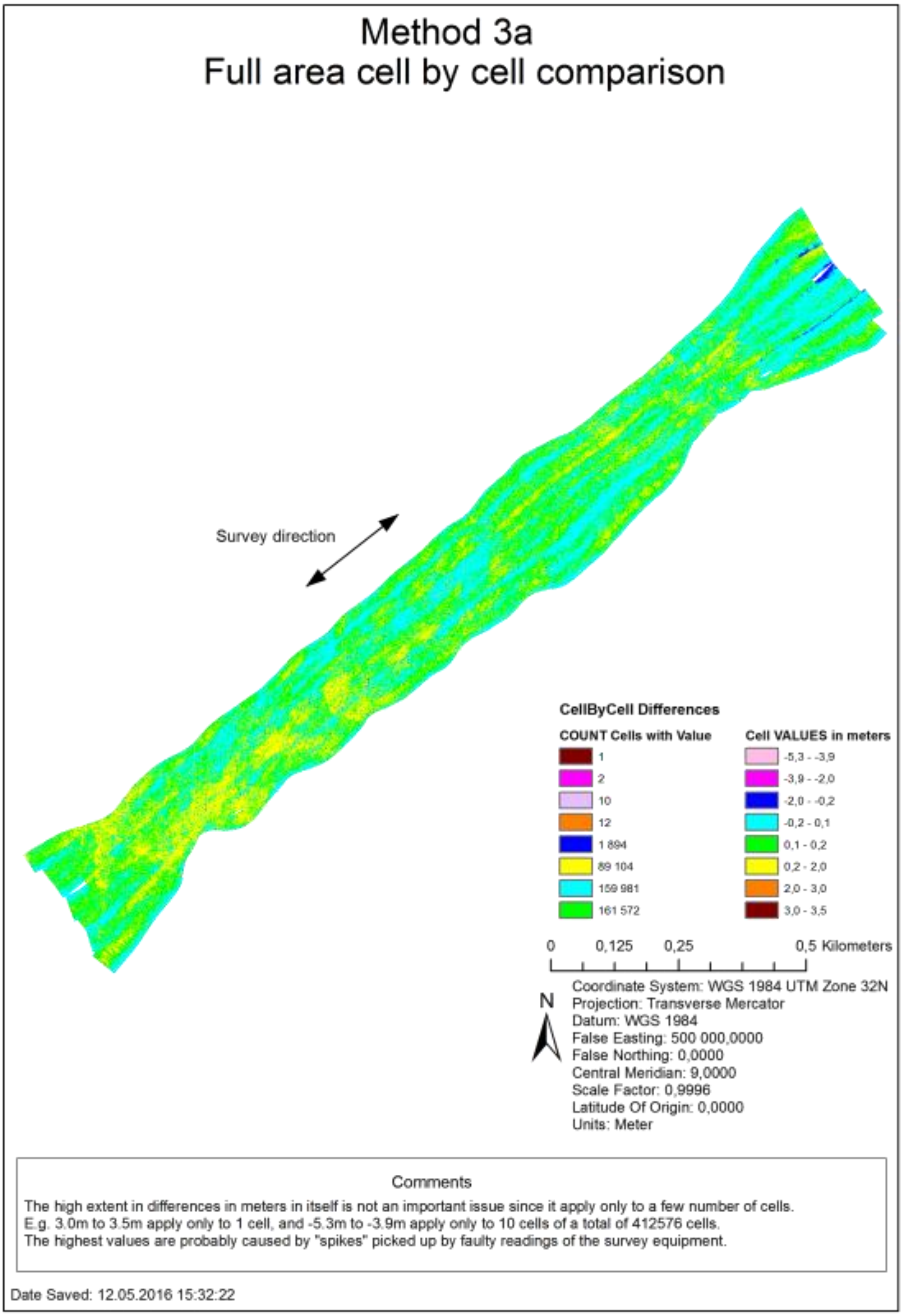
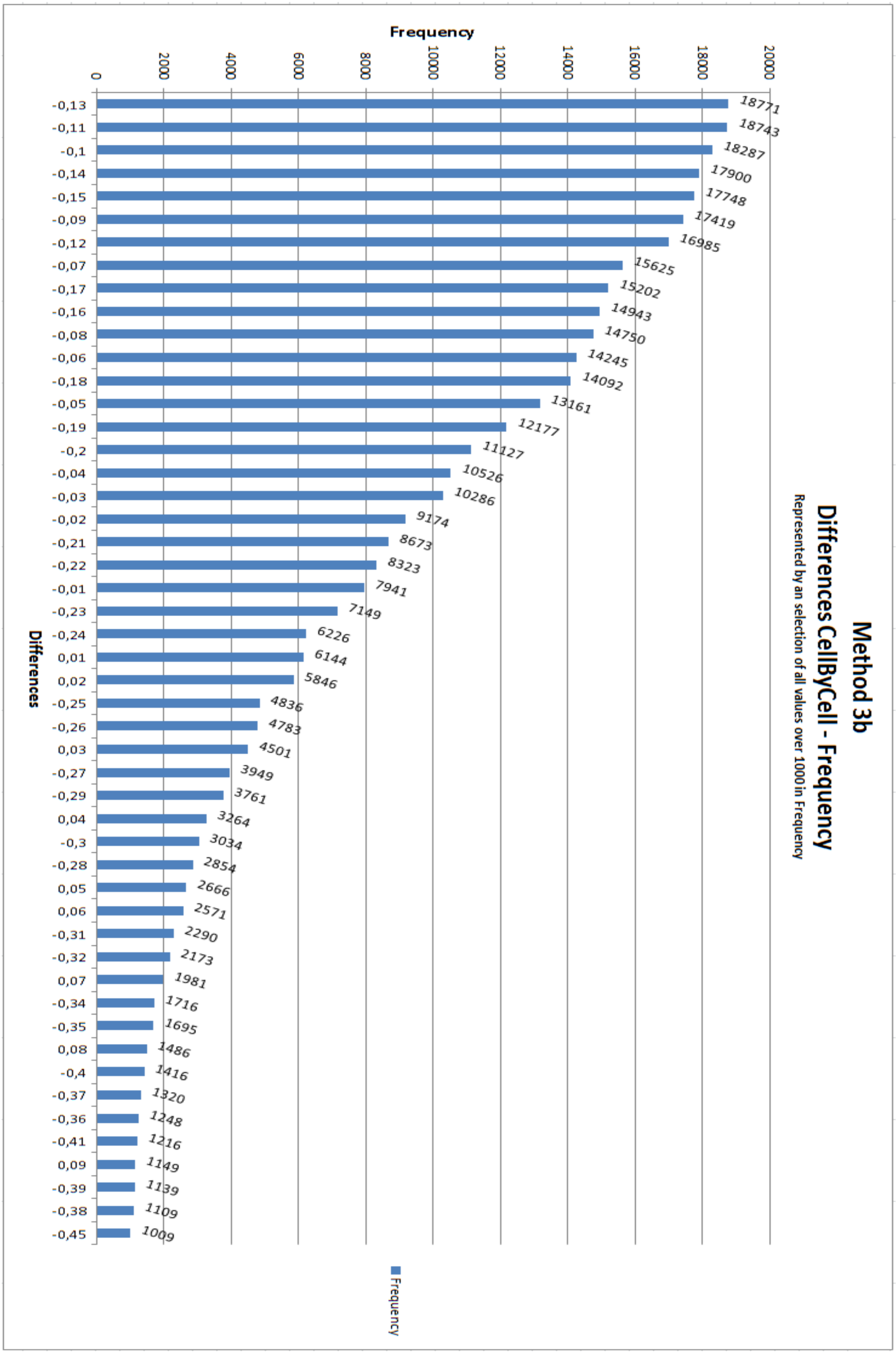
2. Multibeam echo sounding NCA and NMAHS before dredging differences



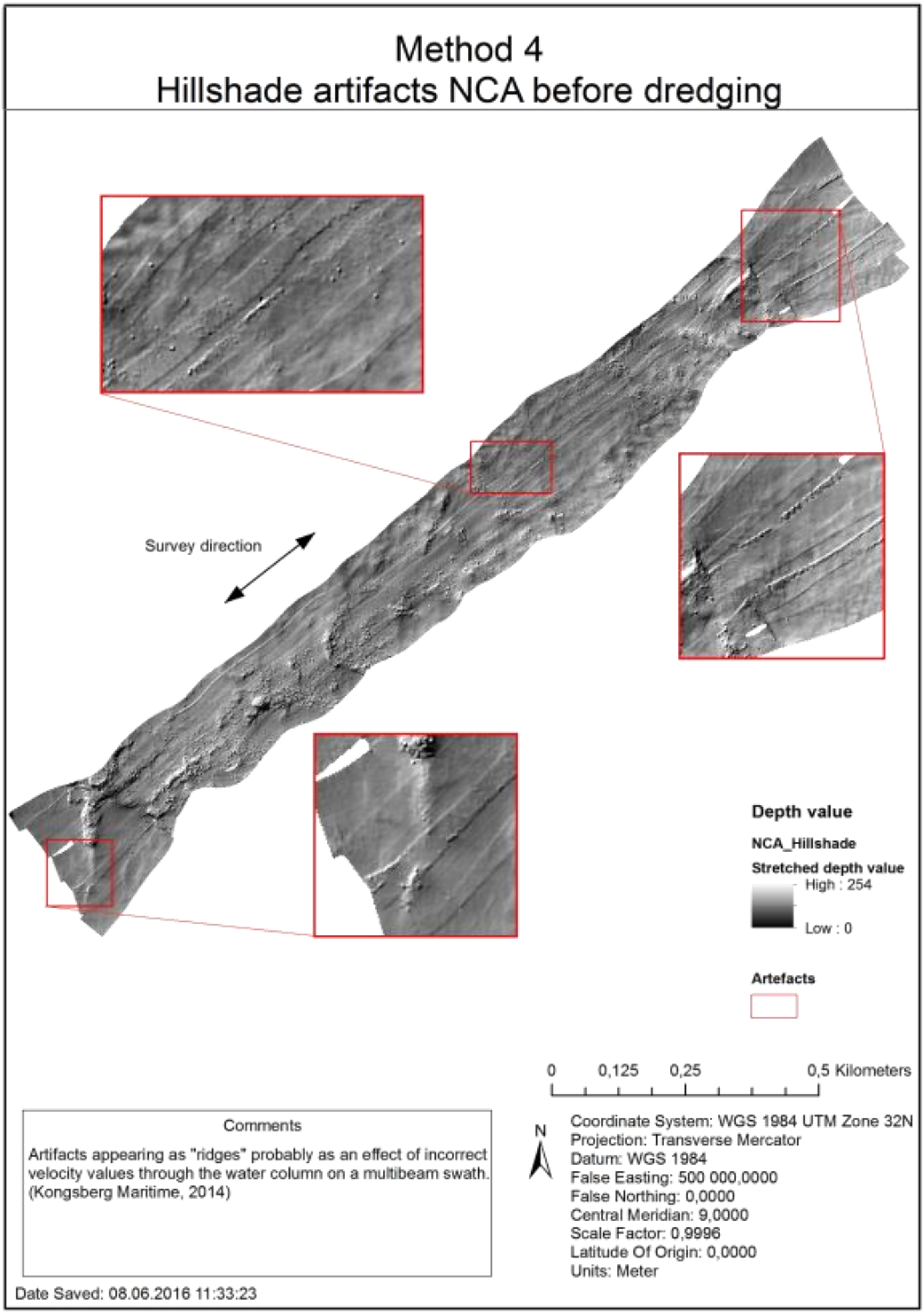
3. Differences graph – cell by cell – frequency



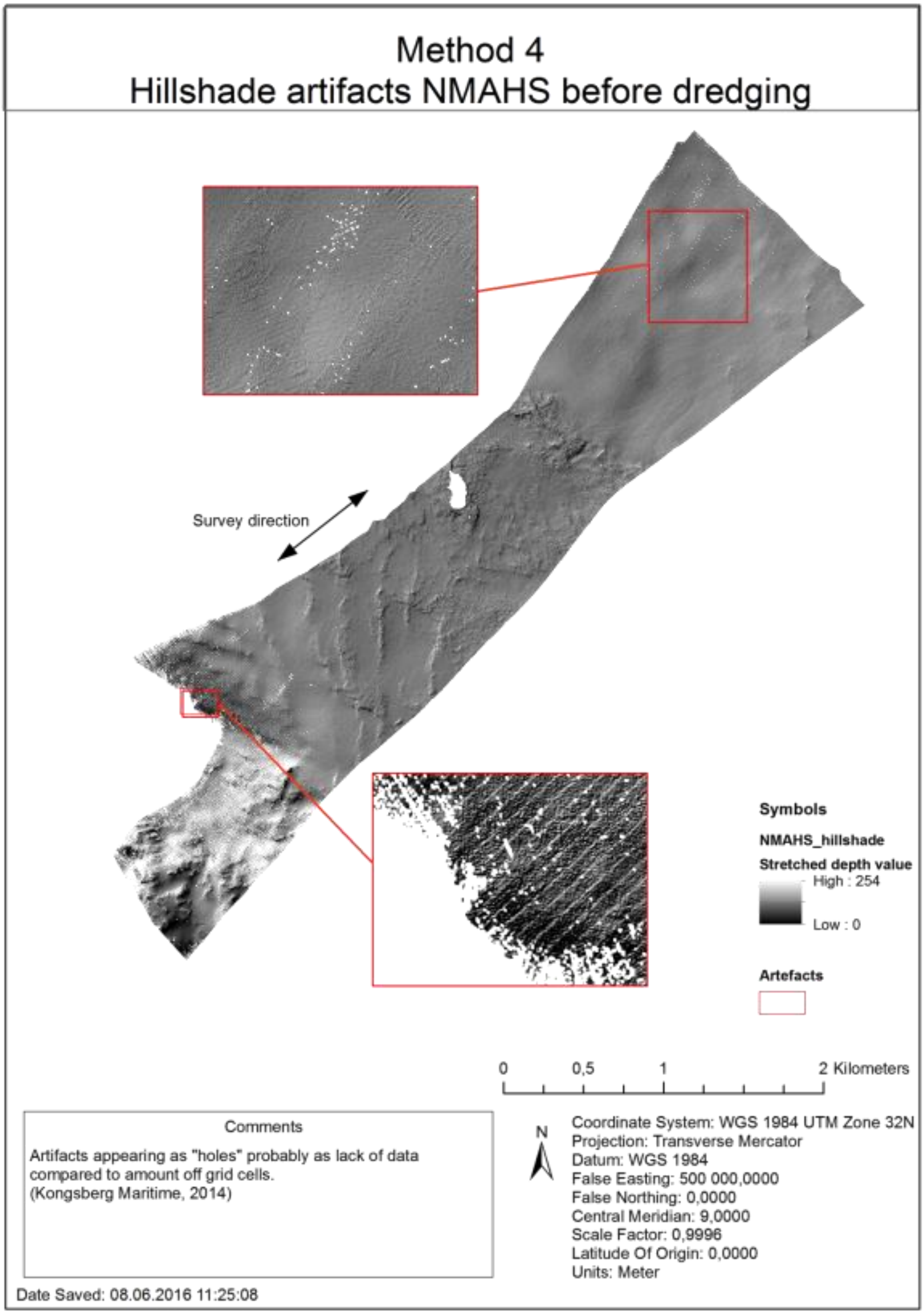
4. Excel table of differences – cell by cell – frequency

OBJECTID	FREQUENCY	Sample_NCA_Differences
2837	1892	-0.12
2810	1856	-0.13
2784	1813	-0.13
2866	1785	-0.11
2764	1778	-0.14
2858	1756	-0.11
2757	1709	-0.14
2728	1698	-0.15
2893	1676	-0.10
2913	1671	-0.10
2886	1647	-0.11
2938	1636	-0.09
2984	1624	-0.08
2735	1614	-0.14
2964	1608	-0.09
2680	1591	-0.16
3009	1562	-0.07
2708	1550	-0.15
2823	1524	-0.12
2879	1507	-0.11
2851	1492	-0.11
3036	1483	-0.07
2633	1464	-0.17
2804	1458	-0.13
2932	1458	-0.09
2654	1457	-0.17
2906	1456	-0.10
2798	1434	-0.13
2771	1431	-0.14
2990	1431	-0.08
2830	1417	-0.12
2791	1416	-0.13
2873	1413	-0.11
2845	1412	-0.12
2924	1406	-0.10
2626	1396	-0.17
2604	1395	-0.18
2777	1386	-0.13

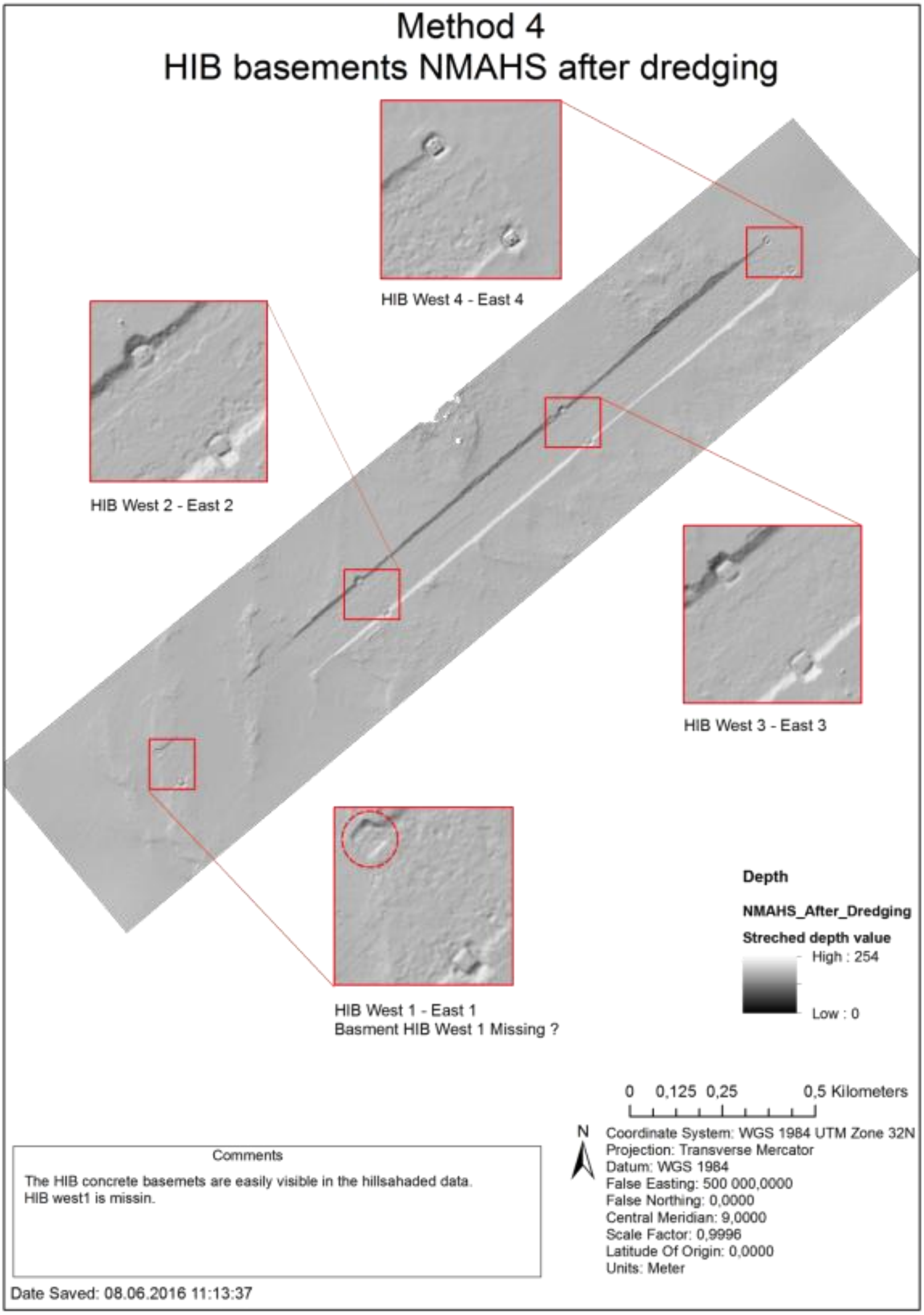
5. Hillshade artifacts NCA before dredging



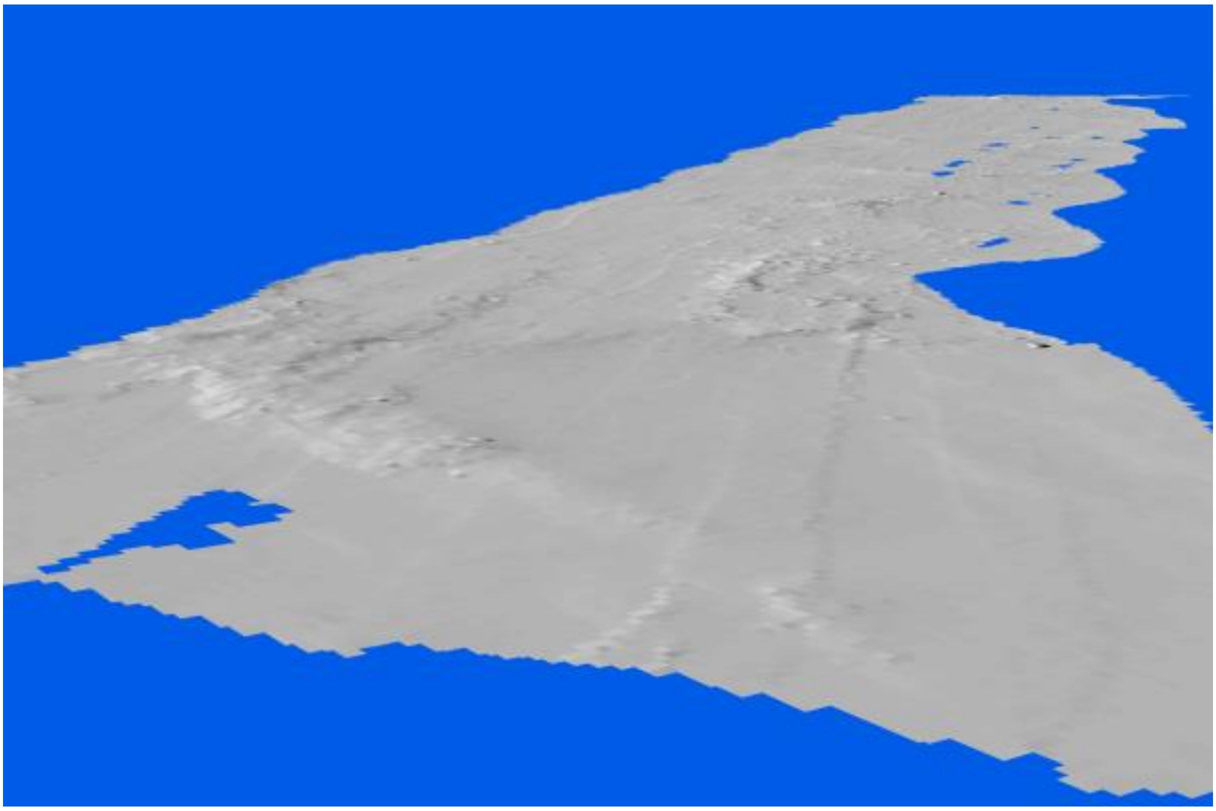
6. **Hillshade artifacts NMAHS before dredging**



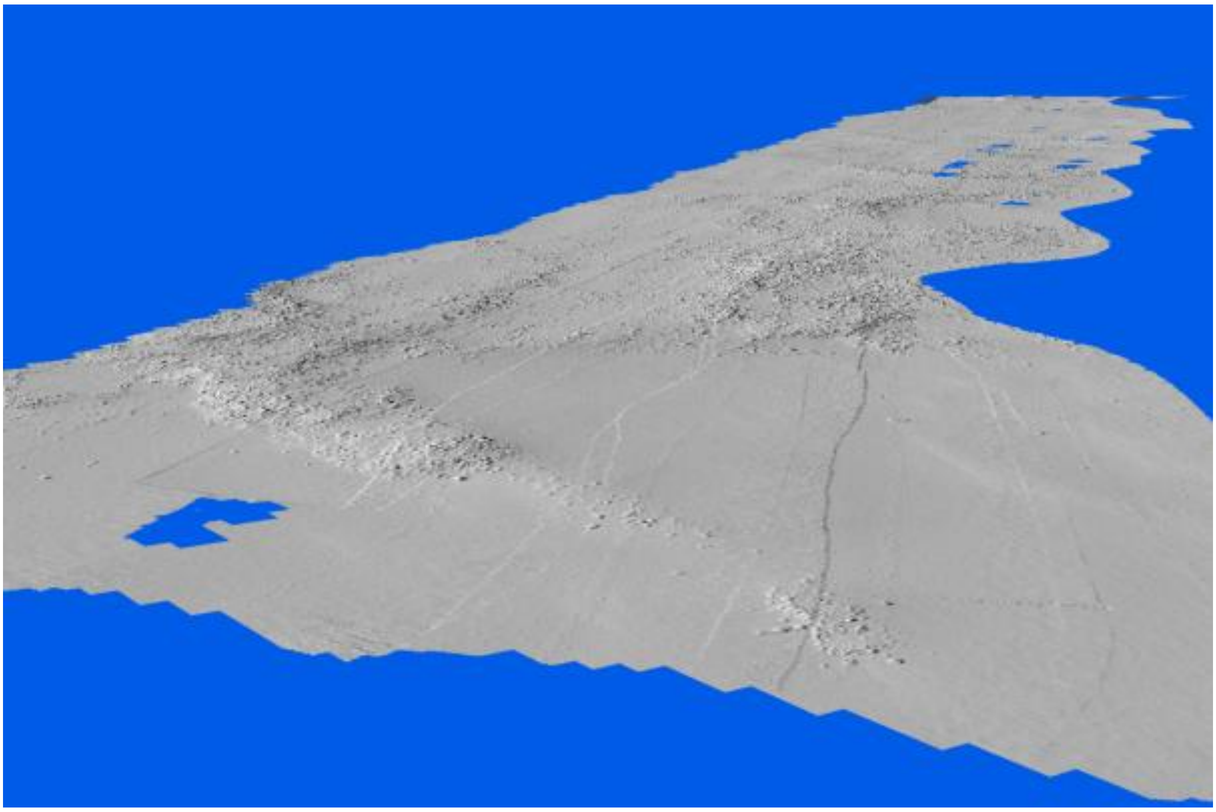
7. **HIB basements NMAHS after dredging**



8. 3D compared resolutions of NCA data before dredging



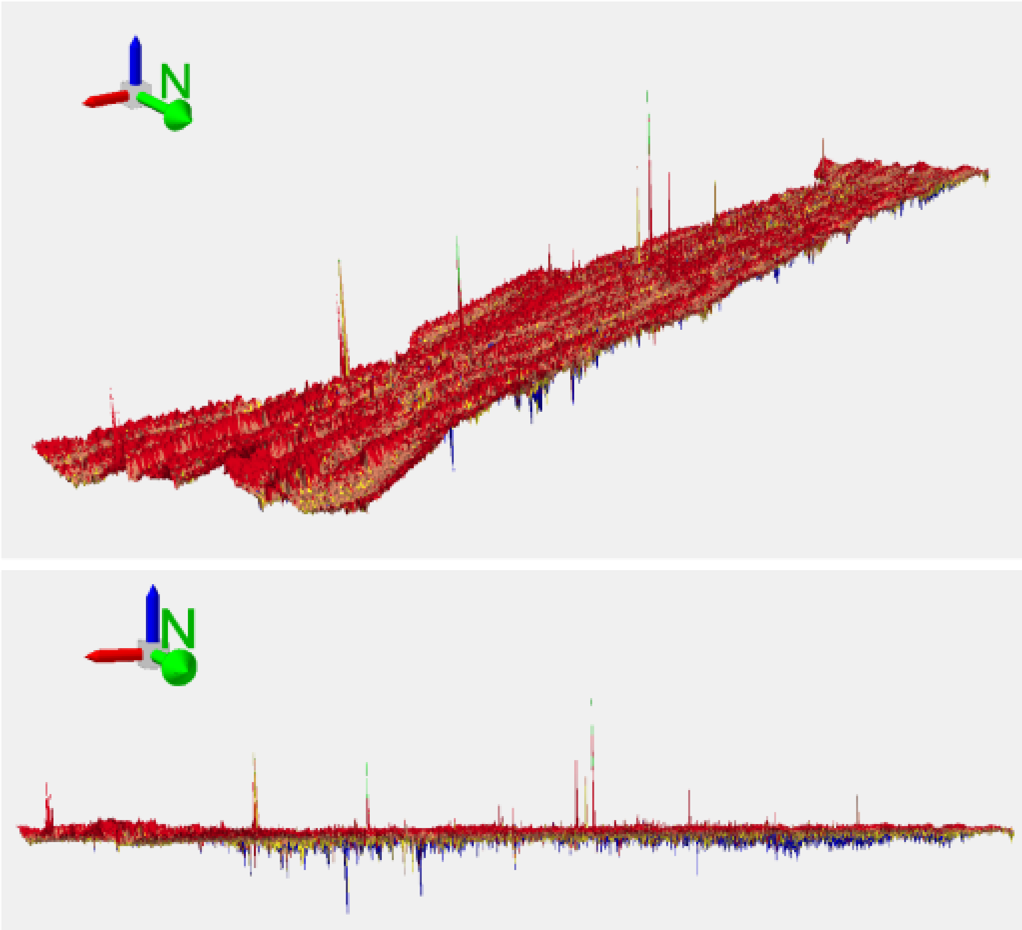
NCA 1x1 meters resolution.



NCA 0.2x0.2 meters resolution.

9. 3D surfaces – differences between NMAHS and NCA before dredging

Method 5
NMAHS NCA differences displayed in 3D



Subtracted depth values with a visual exaggeration factor of 50

Coordinate System: WGS 1984 UTM Zone 32N
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500 000,0000
False Northing: 0,0000
Central Meridian: 9,0000
Scale Factor: 0,9996
Latitude Of Origin: 0,0000
Units: Meter

NMAHS - NCA compared
Differences in meters
-3,42- -0,47
-0,47 - -0,23
-0,23 - -0,09
-0,09- 2,16
2,16 - 5,31

Comments

Datasets from Norwegian Mapping Authority Hydrographic Service (NMAHS) and The Norwegian Coastal Administration (NCA) before dredging analyzed by subtracting the depth values and displaying the differences in a 3D visual analysis using colored depth ranges. The most spectacular"spikes" probably come as result of error in the readings of the multibeam due to sediments variations (Kongsberg Maritme, 2014).
Most of the differences are located where the artifacts are found. Displayed as "ridges" along the survey direction.

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