A PRACTICAL APPROACH TO QUALITY CONTROL AND QUALITY ANALYSIS OF DEPTH DATA

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ABSTRACT

Quality analysis of a collected depth dataset is important in order to find the statistic accuracy and variance of the depth data. Any systematic errors have to be identified and if possible minimised. It is also important to establish if the data fulfils the accuracy standard stated in the survey specification.
The accuracy of collected depth data depends on several parameters such as the accuracy of the sensors in the survey system, the accuracy of the sensor calibration and the accuracy of any additional reductions to the dataset.
After a proper calibration of the sensors, the survey system may be tested against a ground truth object on the seafloor to verify the horizontal and vertical accuracy. Ground thruthing can also be used in order to determine the object detection capabilities of the survey system.

Online control has to ensure that sensors and collected depths are within acceptable limits. Additional reductions like tide or geoidal models etc. have to be analysed to ensure acceptable accuracy.
The quality analysis of the resulting depth data may include ensuring sufficient data density for object detection and standard deviation calculation, data gaps, outlier detection, standard deviation and variation, crosscheck analysis, surface comparison, etc.

This paper discusses some practical methods of establishing the theoretical accuracy of the survey system, to perform online control during data collection and to perform quality analysis on the resulting depth data.

INTRODUCTION

There are several papers describing theoretical accuracy in a multi beam system [Hughes Clarke, 2003] and quality analysis of multi beam data [Hare et al. 2004].
There is also a need for describing the practical application of the quality control and quality analysis in the field. The surveyor must have procedures and guidelines to be able to perform online monitoring and to perform analysis of collected data in an efficient and cost effective way.
The use of RTK GPS gives not only a precise 3D position but also numerous ways to exercise quality control of different sensors and other data (e.g. gyro and tide).
Individual sensor analysis will give the surveyor awareness of that specific sensor and also support in the elimination process of errors in the resulting depth data.
As a consequence of the development of new sensors with improved accuracy followed by the increased knowledge of the end user, there is a need to statistically prove that a survey fulfils the accuracy specification.
The need for procedures and guidelines are obvious in order to describe the quality work within the organisation as well as in the education of new surveyors. The field work has also a tendency to expand including more post processing and quality analysis, hence producing a more complete end product. The following is an attempt to methodically summarise the practical quality procedures in the field and are a part of the Swedish Maritime Administration (SMA) quality management system, ISO 9001 certified.
It should be noted that SMA at the moment only uses multibeam echosounder and barsweeping for bottom charting hence this paper will only discuss those methods. Single beam will only be discussed as a redundancy method for quality assurance. Full bottom search is always required for new surveys conducted by SMA.

GROUND TRUTH TESTING OF THE MULTIBEAM SYSTEM

Before the actual survey, the calibration of a multibeam system is a more or less standard procedure including individual sensor calibration followed by a patch test [Hughes Clarke, 2003].
The object of the calibration is to reduce the systematic errors to a minimum.
To estimate the statistical accuracy of the multibeam system, an error budget must be calculated where all the random errors from individual sensors and other contributions such as tide, draught, etc. are estimated. The remaining systematic errors in the system should also be estimated and included in the calculation. The resulting error, divided into horizontal and vertical, gives a total horizontal error (THE) and a total vertical error (TVE).
To determine if the THE and the TVE is realistic and corresponds to a true value, a man made or distinct object on the seabed could be used as ground truth. The object should preferably be geodetically measured with centimetre accuracy of the horizontal and vertical coordinates.
The result from a detailed investigation, i.e. crossing lines with narrow line spacing, of such an object gives a good estimation of the survey system’s depth and horizontal accuracy. Conducting this detailed investigation of the object on a regular basis also gives the positional variation for a specific multibeam system as well as comparison between different systems. For horizontal positioning RTK must be used to achieve optimal comparison of the object’s horizontal extent.
If using the object for repeated surveys, it must be fixed to the seabed in such a way that any movements of the object are negligible. A tide gauge must be available near the object to minimize any tide error and to control and verify the RTK height if used. It is important that the

sound speed profiles are correct to minimize any ray tracing error. The profile should be taken close to the object and in as short a time as possible before and after the survey.
Following the S44 accuracy standards [IHO, 1998], analysis shows that the critical variation is in the vertical extent. The horizontal accuracy is normally well within the accuracy limit if using RTK GPS provided a limited swath of 130 degrees is used.
Comparing the result to the error budget, the difference can be analysed and individual error contributions temporarily changed so that the budget agrees with the investigation result. It must be noted that the conditions at the investigation may be close to the ideal and therefore not representative in a real survey. Hence the error budget should not be changed unless it is greatly overestimated.
As an alternative, if the result gives a larger variation than the error budget, an additional error in the budget could be introduced. This additional error consists of systematic error residuals from the patch test and wrong estimations of the random errors. Knowing that some of these errors are depth dependent, this additional error could be divided in depth dependent (i.e. angles, sound speed) and not depth dependent errors (i.e. Heave, RTK height).
Comparing different systems gives valuable information about their performance and limitations and will assist in selecting the survey system for different survey areas.
It should be noted that the resulting depth and horizontal variation is based on the specific bottom characteristics of the object and will differ with other bottom characteristics e.g. soft muddy bottom.

Object detection
The manmade object on the seabed could be constructed in such a way that the capability of the system object detection could be tested. The size and extent of the object may be as specified in S44 or it could be divided into several types and shapes of which some could be smaller for testing the limit of object detection capability.
The multibeam should be set in all available modes (i.e. equidistance, equiangle, high density) that will be used in a real survey to find the optimum settings for object detection.

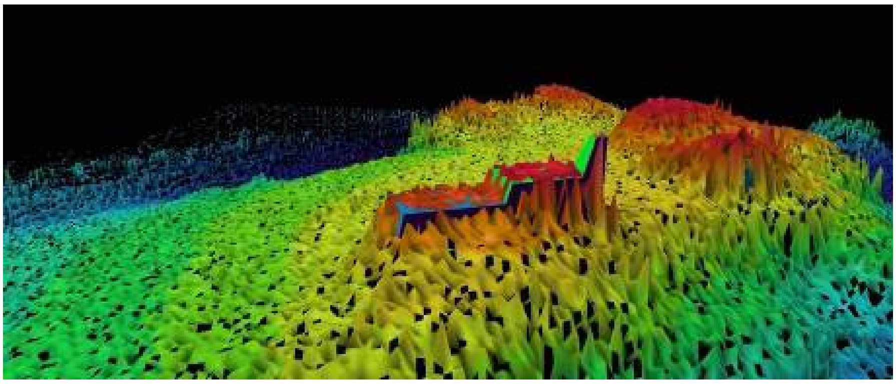

Fig.1 Object made of concrete on ~19 meter depth east of “Vinga” on the west coast of Sweden.
Two levels 2.5x4 meter and one top level 0.3x0.3 meter.

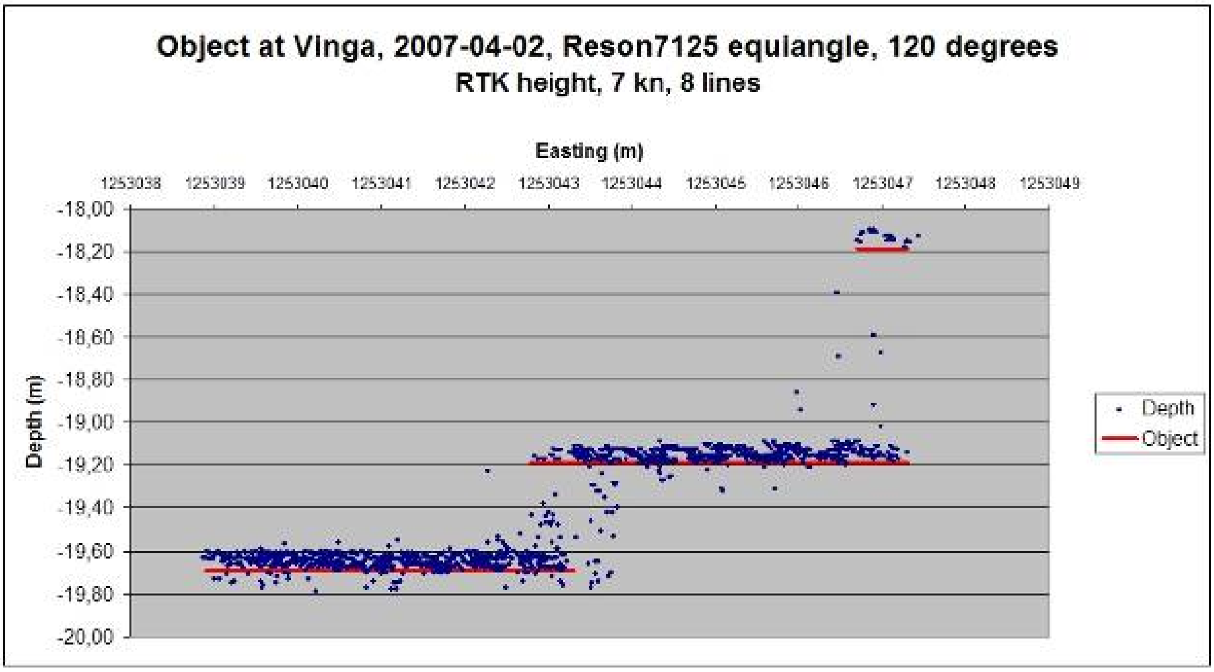

Fig.2 Reson 7125 1*0.5 degree beam. Lowest level depth difference 4 cm, depth range at 95% 14 cm. Middle level depth difference 4 cm, depth range at 95% 11 cm. Highest level depth difference 5 cm, depth range at 95% 7 cm.

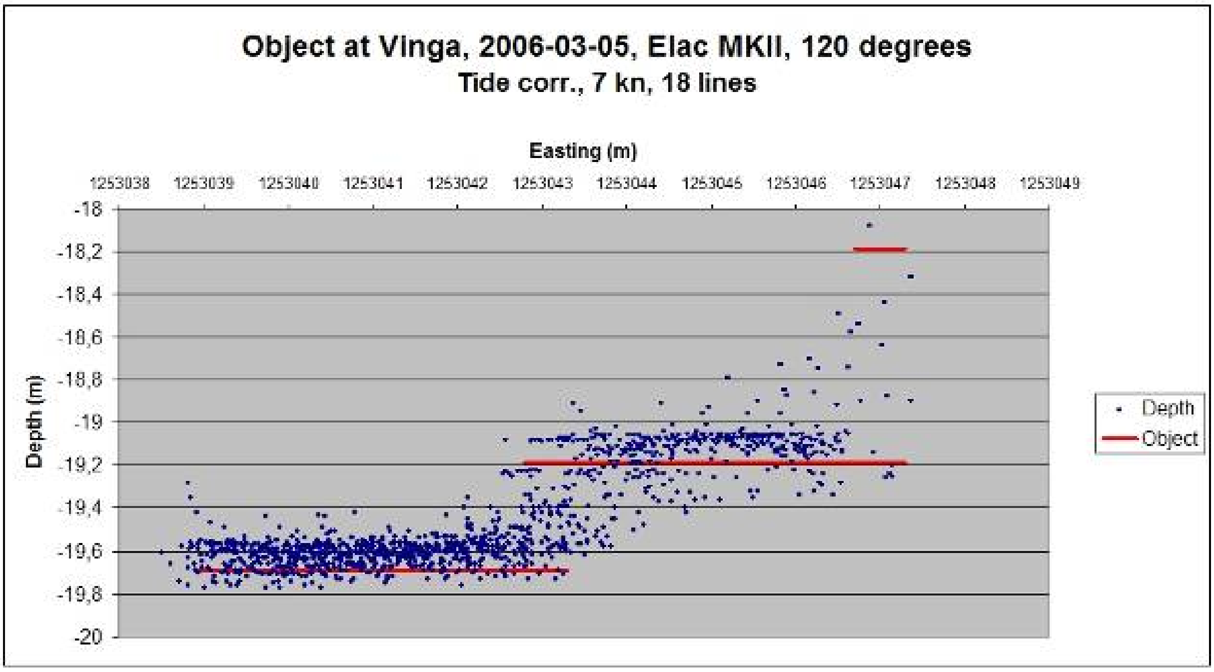

Fig.3 Elac MKII 1.5*1.5 degree beam. Lowest level depth difference 7 cm, depth range at 95% 25 cm. Middle level depth difference 8 cm, depth range at 95% 44 cm. Highest level not detected with certainty.

DATA COLLECTION ONLINE CONTROL

To minimize resurvey, it is important to perform online control during data collection.
If any sensor or values are outside acceptable limits, it could be more cost efficient to temporarily stop the survey and rectify the failing sensor or value.
Data collecting software normally has a number of values to display from sensors and calculated results. To be able to have control of the collected survey data, it is important for the operator to have the possibility to set alarm limits on the presented values. Hence the operators can respond quickly in the case of any malfunction or occurrence of bad data.
To identify and quantify errors in the online coverage, some pre-post-processing may be needed unless it is possible to process directly in the software.
It must be noted that it is not only the sensors that can fail and cause errors in the collected data but also failure in the computer software or hardware including setup and configuration.
If redundant sensor data are not recorded within the raw depth data file, it must be recorded separately.

Crosscheck lines

A crosscheck line should preferably be surveyed as the first line in a survey area [Wells, D. 2003]. This gives the possibility to analyse the overlap of any crossing survey line in the online coverage.
Any depth differences are visualized in the colour coding of the online coverage or the overlap could be pre post processed. Hence the depth difference in the centre to centre beams, centre to outer beams and outer to outer beams can be compared between the perpendicular lines.

Cross sections

To identify and quantify depth difference between the overlap in adjacent survey lines, a cross section of the lines can be investigated. A convenient way of doing this is if the software provides the possibility to draw a cross line in the online coverage and present the cross section in a two dimensional diagram (Simrad SIS data collecting software). By adjusting the scale in the diagram, the different survey lines can be identified and the difference between the overlapping lines quantified.
If it is not possible to display a cross section in the online coverage, a pre-post-processing of the adjacent survey lines should be performed.
A cross section investigation of several lines should be performed frequently and on different positions along the lines.
If the difference between the lines exceeds the acceptable limit (e.g. half the S44 accuracy), the error source has to be identified and rectified (e.g. collect new sound speed profiles).
Since the sound speed profile can hardly be recreated, frequent sound speed profile casts must be taken, alternatively, a moving profiler could be used to store profiles frequently. This will give the possibility to change the profile in order to rectify any sound speed error in the depth data. Attempts could be made to adjust within the profile but in difficult areas with several temperature and salinity layers it is not advisable.

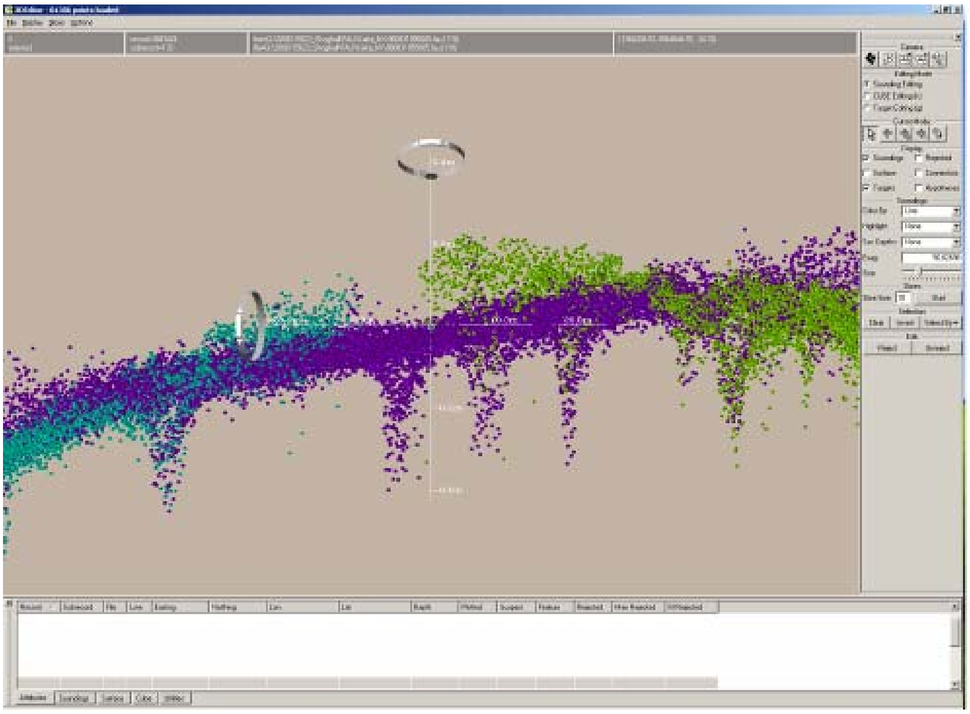

Fig.4 IVS Fledermaus, Cross profile.

Height
If the GPS height is used as a reference to the collected depths, it is essential that the height is displayed in a graphical window. Any incorrect height difference (i.e. phase difference or drifting height) will be clearly visible.
The necessary RTK “fix” solution are sensitive for any satellite change. Changes in DOP values and a height variation will be the first signal that the position is becoming degraded. The loss of an accurate height for a longer period (i.e. more than 10 seconds) may cause the operator to stop the survey line and resume only after a steady height has reoccurred.
Note that before the survey, the GPS height should be referenced to the survey datum by using a geoidal model and in addition adding a known offset (between the specific height system and survey datum). The received height shall be checked either by levelling from a benchmark to the vessel or by comparing the vessel GPS tide to the tide from a tidal station. Any difference in height should be entered as an offset. Frequent check of the height on a daily basis during the survey is needed to verify the variation of the offset. A mean value of the found offset could be used in post processing of the height or calculation of the GPS tide.

Heading
If the heading information comes from a standard survey gyro compass with a floating rotating sphere, there will be a drift with a certain amplitude and cycle time. By comparing to an “RTK gyro” (two GPS antennas), the gyro drift can be monitored. Note that if the “RTK gyro” is not roll and pitch stabilised, post processing including a transformation may be needed to get an accurate heading for comparison, especially if the GPS antennas are not mounted on the same height.

Position
Two GPS antennas can give redundancy in position and also monitor the difference between the two positions in the reference point.
It should be noted that the internal transport of the position from the GPS antenna to the reference point will be calculated using roll, pitch, heading, and the lever arms. If using RTK a detailed comparison between the positions will monitor those sensors as well. In this case the antennas must be placed wide apart (several meters) to be able to show an obvious difference in positions. A timing error may also be included in the position difference.

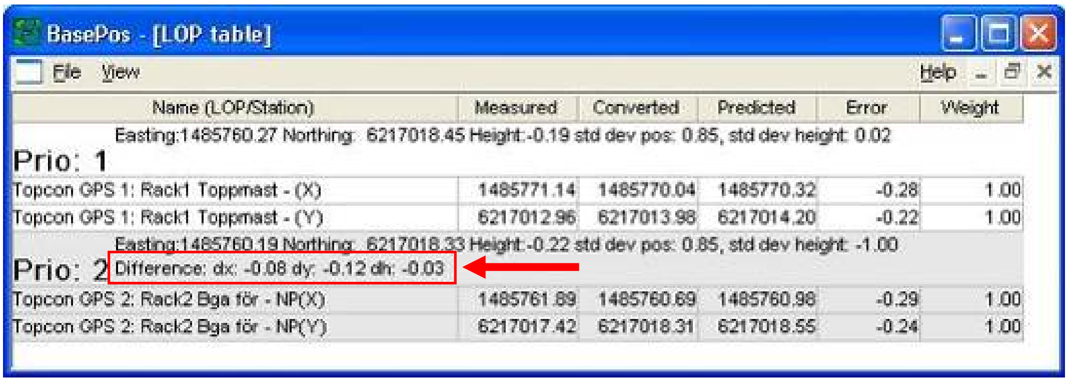

Fig.5 Eiva Navipac NT. Comparison of RTK GPS position between two antennas approximate 10 meter apart.

Timing
In some data collecting software, a calculated time delay in the system can be displayed. The value should not vary and remain close to constant. If the software calculates two sensor inputs of the same unknown quantity, e.g. GPS height merged with heave, a timing error could be visualized. In this case the GPS height should be compensated with the heave value and the vertical movement of the height minimized only leaving the remaining noise of the height. In case of a timing error, the heave compensated height may result in larger variation then the uncompensated height. The timing error doesn't have to be a latency error in the system but could be a result of temporary software or hardware failure or prioritising of the internal processes in the computer.

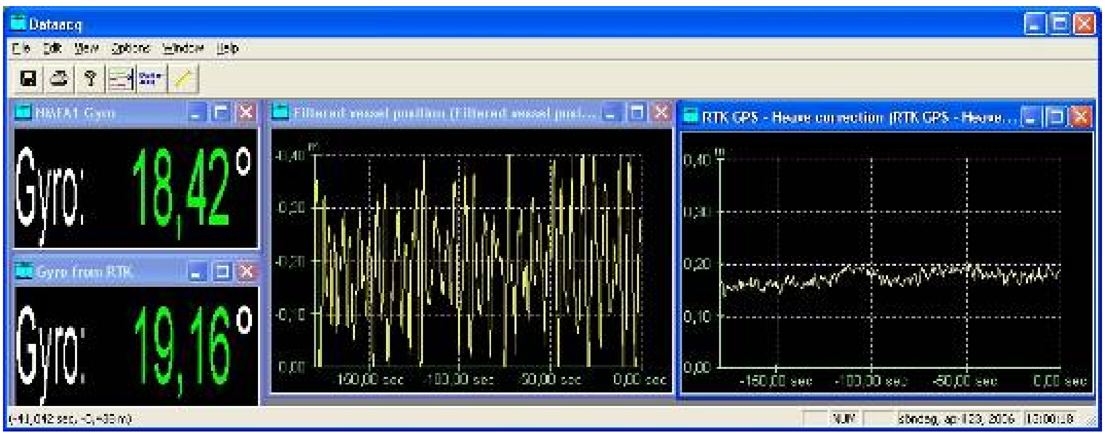

Fig.6 Eiva Navipac NT. RTK GPS height and RTK GPS height merged with heave.

Heave

The heave value from the motion sensor has traditionally a low accuracy compared to other sensor values in the vertical error budget. The accuracy depends partly on how well the heave filtering parameters corresponds to the present wave pattern.
If the vessel is affected by other dynamic forces than the normal wave pattern, the heave value will contain larger errors. Dynamic forces like speed change and passing vessels will greatly affect the accuracy of the heave value. Presentation of heave and RTK GPS height in a graphical window will detect erroneous heave values. Comparison of uncorrected and heave corrected RTK GPS height will also monitor an incorrect heave.

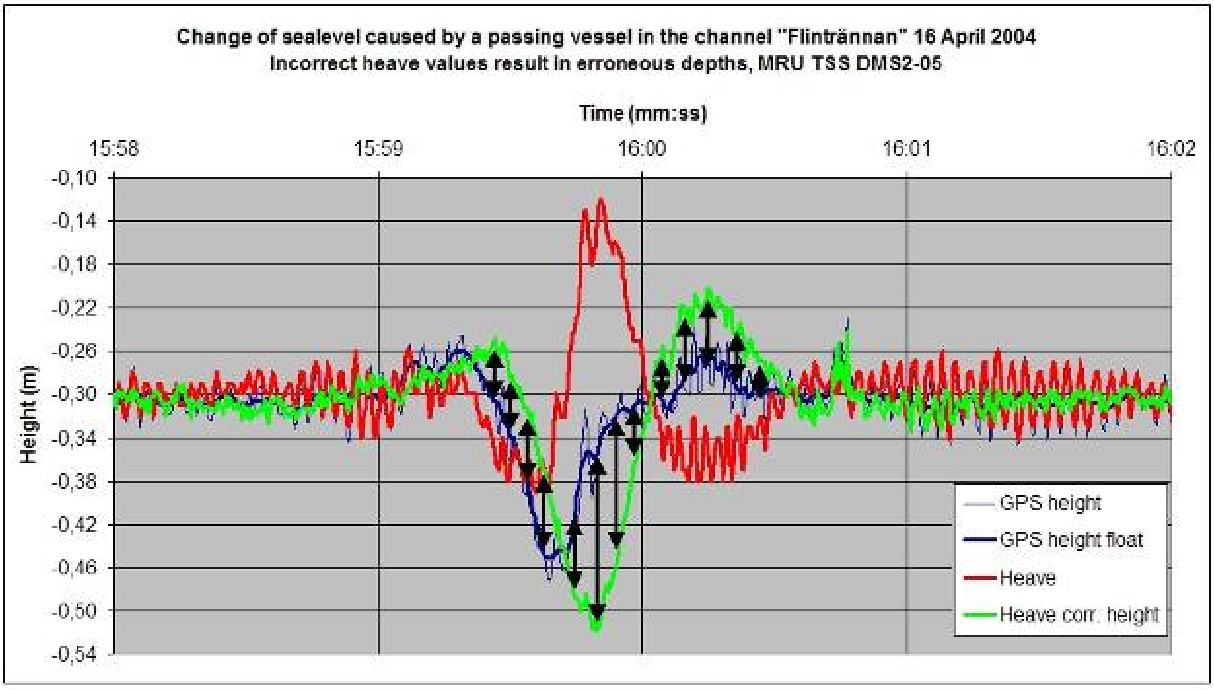

Fig.7 Heave error (black arrows) caused by a passing vessel. “GPS height float” is floating mean value of “GPS height”.

QUALITY ANALYSIS OF SENSORS IN POST-PROCESSING

Quality analysis of sensor data in post-processing is a natural step in the data cleaning. Sensor errors are rectified where possible and recalculation of the depth data is performed with corrected sensor values. Most sensor post-processing software’s has the possibility to correct sensor errors with removal and interpolation, or adjustment.
A quality analysis of sensors will also give documented quality assurance to the dataset even if the sensors or values have performed well.

Height

If using GPS height as reference for collected depths, height errors have to be corrected. Single height spikes may be removed and a temporary height difference adjusted. If the height errors are continuous for a longer period of time, the GPS height may not be suitable to use. In these cases

the depth could be referenced to chart datum by applying tide, provided the necessary data has been recorded, such as vessel current draught and squat.
Even if the GPS heights are used, the tide from tidal stations should be recorded and used in quality analysis of the height.

Position
Horizontal position jumps must be removed and smoothed. As an alternative, the secondary position could be used, if present.

Heading
Any error in the heading information must be corrected. Depending on the type of compass, the behaviour of errors will have a different character. A gyro with floating rotating sphere will have a drifting error and a modern IMU may have spikes if the position is corrupt.
The drifting error on a traditional gyro with a sphere can be found by comparing to an “RTK gyro” (obtain heading by comparing two GPS’s) at the sensor calibration. The drift error consists of cycle time with amplitude. The cycle time could vary between some 3-24 hours up to a couple of months and the amplitude according to the maker’s specification.
Analysis could also be performed in the post-processing software or it could be calculated from externally collected data files for each survey line.

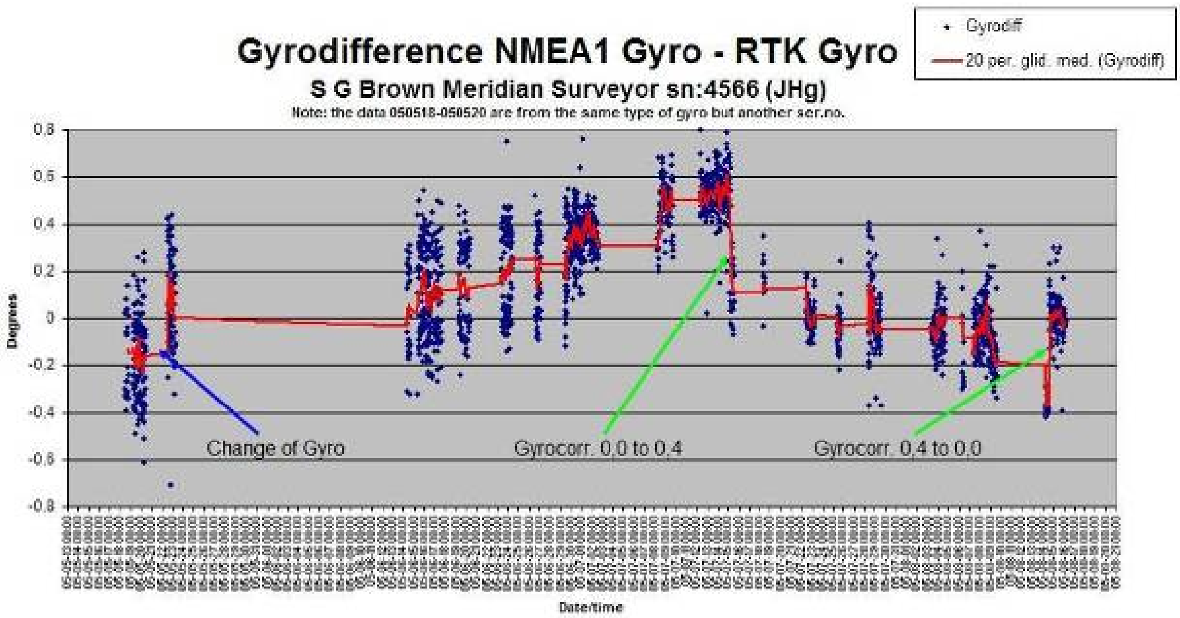

Fig.8 Drifting gyro monitored for 3 months. Each point represents a mean difference in heading between a survey gyro and “RTK gyro” on a survey line.

Roll and Pitch
Roll and Pitch error are difficult to detect in a visual sensor analysis unless the data consists of spikes and corrupted data. In general, a systematic attitude error must be identified in the depth data analysis.

Heave
As discussed above, the heave values may have larger errors that will affect the overall accuracy in the dataset. If the GPS height is merged with heave, the depth error will be of a smaller magnitude. On the contrary, if the heave value are used to correct the depth and merged with tide to chart datum, erroneous heave values could affect the accuracy of the depth considerably. In this case, a larger speed change of the vessel or a dynamic influence from a passing vessel could result in rejection of data.
Heave values that do not have a sinusoidal form and an irregular cycle time should be marked for a closer evaluation. In general, when the vessel is dynamically influenced by a speed change or passing ship in shallow water and/or narrow channels, the heave value will be more or less corrupt and that part of the survey line may have to be resurveyed.

Sound speed
In the online quality control of depth difference by cross sections, a sound speed error can be identified. There are a few alternatives when choosing the method for sound speed correction. Depending of the software used, several sound speed profiles can be used and interpolated by time, distance, position or by selected areas. The depth data analysis will show the remaining depth difference that may be caused by error in the sound speed profile. Changing the method of sound speed correction or change to an alternative collected profile may reduce the depth error.

QUALITY ANALYSIS OF TIDE

Quality analysis of traditional tide consists of comparing tide series from different tidal stations. Spikes have to be removed and the series may be smoothed if it’s clear that a variation in the data is caused by a local phenomenon e.g. vessel traffic.
Any offset or time shift between the tide series should be analysed before applying tide to the collected depths.
If using RTK GPS height as a reference to the depths, the tide error may be reduced provided an accurate geoid model and a proper offset to survey datum are used.
When surveying with RTK GPS and using the horizontal position only, the height could be used to calculate GPS tide and compared to traditional tide from tidal stations. If the difference is of importance, the GPS tide should be used locally or for a longer period.
GPS tide is derived from the height (i.e. in the reference point) by adding static draught and dynamic draught (i.e. squat) for each individual survey line. The height could be used from within the raw data or could be collected externally for each specific survey line. Spikes must be removed and a mean calculated for a desired length (i.e. 1, 2, 5, 10 minutes).

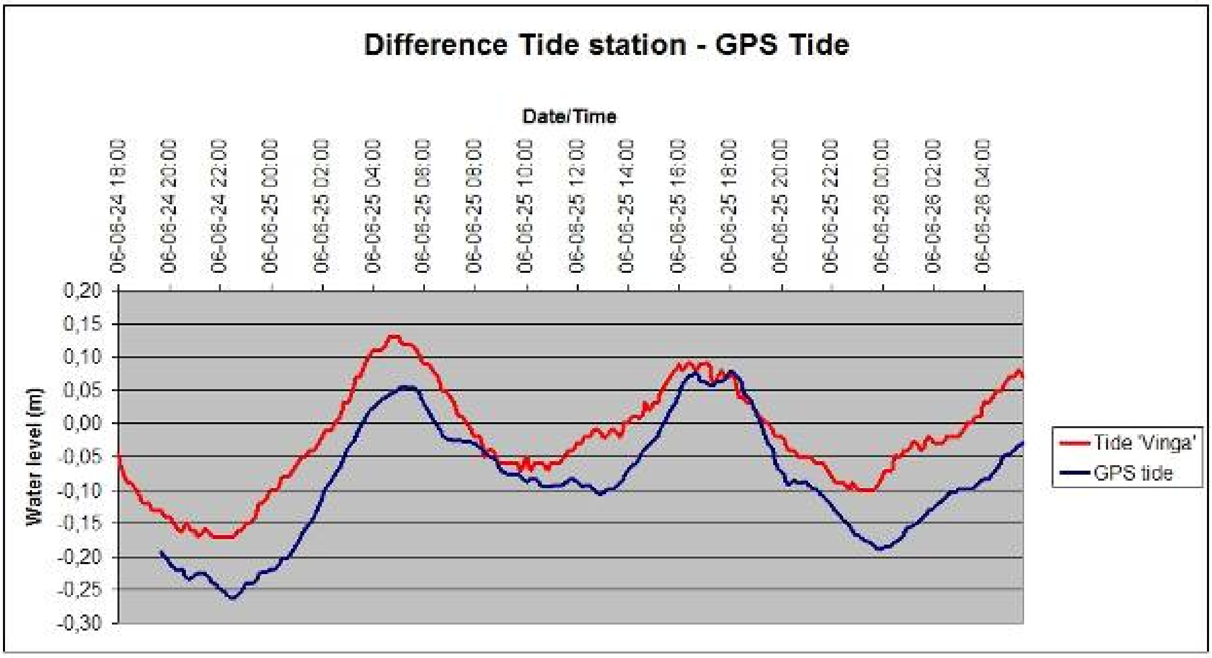

Fig.9 Difference between tides from a tidal station and GPS tide. GPS tide calculated from RTK GPS on the survey vessel “Ale”.

QUALITY ANALYSIS OF DEPTH DATA

The quality analysis of post processed depth data must produce a quantified result of the horizontal and depth accuracy of the survey area. The result shall be compared to the prescribed accuracy standard in the survey specification and to the error budget. If the result shows a larger error than prescribed in the accuracy standard the error source has to be identified and rectified. The result of the analysis must be noted in the survey report.
The post processing procedure (i.e. sensor editing and data cleaning) should include a frequent pre processing step that visualizes any systematic error or data gaps. It is important to look at the collected data as early as possible to identify any accuracy or coverage problem. Some post processing software do not allow changes of position and attitude data hence it saves time to rectify any such problem before the actual cleaning of the data.
Once the depth data has been cleaned the quality analysis should be performed. Some survey areas may be extensive and contain several smaller areas. To keep track of the analysis result of all the survey area a checklist should be used. The checklist may be enclosed to the survey report as an assigned quality for the survey.
There are several steps in the analysing process that should be performed and the most important will be discussed below.

Density and data gaps

To perform a stable statistical analysis, the analysing software needs a sufficient number of depths per bin cell (e.g. minimum 5 depths). In the case of object detection a sufficient number of pings need to hit the target for it to be identified as an object (e.g. minimum 5 hits).The number of hits on the target to fulfil the object detection demand in the survey specification must be decided unless stated in the specification.

The number of depths per area in a grid cell is dependent of depth, survey speed, echo sounder, etc. The size of the grid cells used in the quality analysis must be determined based on depth, object detection capability and a stable statistic calculation e.g. one by one meter to 20 meter of depth and below that 10% of depth. In areas with a wide range of depths various sizes of grid cells may have to be used. A software that is able to create variable depth dependent grid cell size will greatly reduce the analysing time and improve the statistic analysis when comparing at different depths.
The size of data gaps resulting from removed outliers must be analyzed and resurveyed if found larger than specified in the survey specification. For a 1*1 degree multibeam system the maximum size of a data gap may be in the order of 5% of the depth and for a 1.5*1.5 degree system it may be maximum 10% of the depth. Depending on the bottom topography the limits may be different but in critical areas with limited under keel clearance data gaps should not be allowed. Data gaps resulting from lack of overlap between the survey lines should always be resurveyed.
Bottom coverage, density and data gaps should be analysed at an early stage of the survey in pre post processing, to avoid extensive resurveying, as well as after data cleaning.

Sun illumination
Sun illumination should be used from two directions, in the directions of the survey lines as well as perpendicular of the lines. The systematic error seen in the data, even if very small, should be quantified by analysing cross sections preferably in flat areas. The result in the areas with the largest error should be recorded.

Min-Max difference
To identify remaining outliers surface differences analysis of max depths and min depths of the grid cells should be performed. Any remaining outlier could be identified by colour coding and/or by analysing the resulting difference surface, if provided by the software. The surface difference analysis could also give a statistical measurement of the max and min variation of the depths per bin. The mean difference and standard deviation should be recorded.
The depth variation is dependent of the bottom characteristics, frequency of the multibeam echosounder, and remaining systematic errors.

Standard deviation
Colour coding of the depth surface visualising the standard deviation identifies any irregularity in the depth data. The standard deviation could be set to less than half the accuracy standard at current depth visualising areas where the depth variation may cause the depth accuracy to fall outside the limits (2 x standard deviation approximate equal to 95 % confidence level). In steep slopes the size of the grid cells may cause the standard deviation to rise above the limit even though the depths are acceptable. At the investigation of any anomalous area remaining outliers can be removed and a detailed investigation of any steep slope, object or wreck can be performed.
In flat areas the value of the standard deviation in the depth data could be found by changing the colour coding limits.

Crosscheck lines and overlap of adjacent lines - Statistics

In the crosscheck analysis the depth between a crossing line is compared to the lines in the main survey direction. Some crossing lines should be surveyed separated in time from the main lines to identify any error in the tide modelling.

Most analysing software has the possibility to compare different surfaces. Some software also compares a reference surface to single points. The surface, i.e. DTM, should be created with appropriate cell size (i.e. grid cell) with a sufficient number of depths to achieve the highest resolution possible.

In the case of surface to surface comparison it is important to use the same type of surface e.g. mean surface. One of the surfaces is the reference surface and the comparison produce a depth difference for each grid cell. The mean value and standard deviation of the difference can be calculated.

When comparing single points to a reference surface this must be a mean surface. Care must be taken not to include the cross line in the reference surface. Each single point will be compared to the depth in the corresponding surface grid cell. Statistics calculation gives a mean value of the difference between point and surface, i.e. offset, as well as the standard deviation of the depth differences between the reference surface and the points in the cross line.

Statistics could also be calculated of the depth difference in the overlap of the adjacent lines. The most true comparison in this case will be achieved in a survey with 200 percent coverage i.e. the outer beam on a line is reaching the centre beams of the adjacent line. The reference surface should consist of every second line and used in comparison to all the other lines.

The resulting depth differences could be binned in different categories and compared to the accuracy standard (i.e. S44) stated in the survey specification. In general accuracy standards are depth dependent, therefore it is important to separate the depth differences in categories based on the true depth of the reference surface bin cells. Any depth differences exceeding the limits in the accuracy standard could be visualised on top of the resulting depth data.

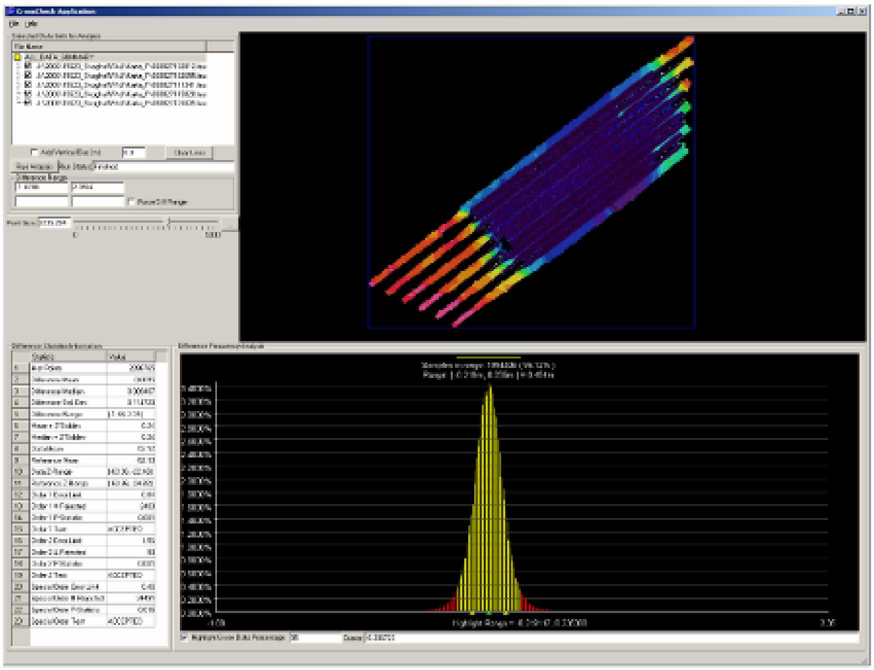

Fig.10 IVS Cross Check tool. Statistics for the overlap differences of adjacent lines.

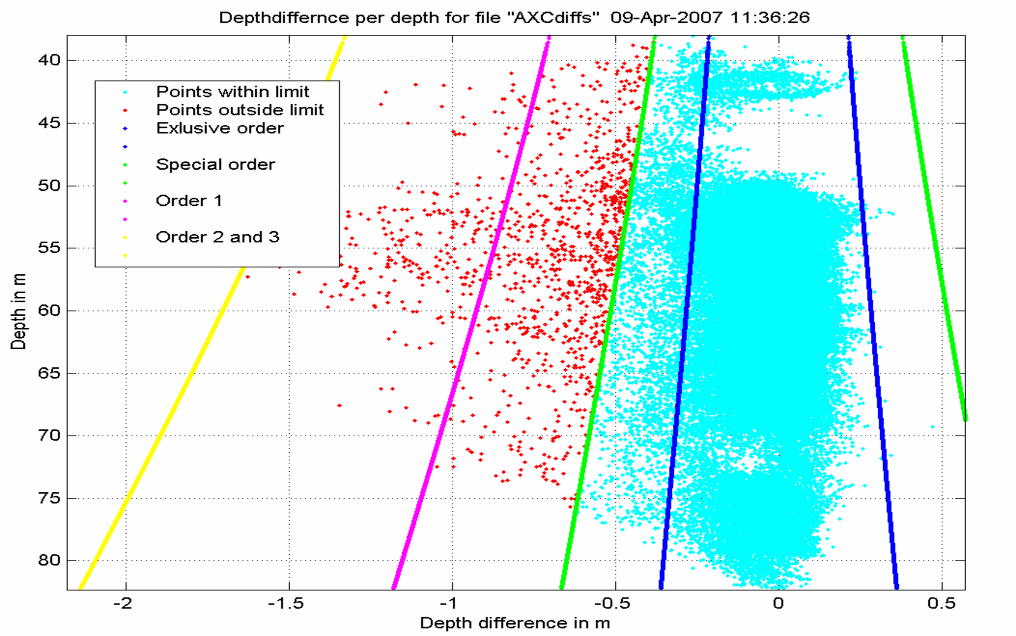

Fig. 11 Example of analysis from IVS Cross Check tool output file. Depth differences between the reference surface and the check line/s.

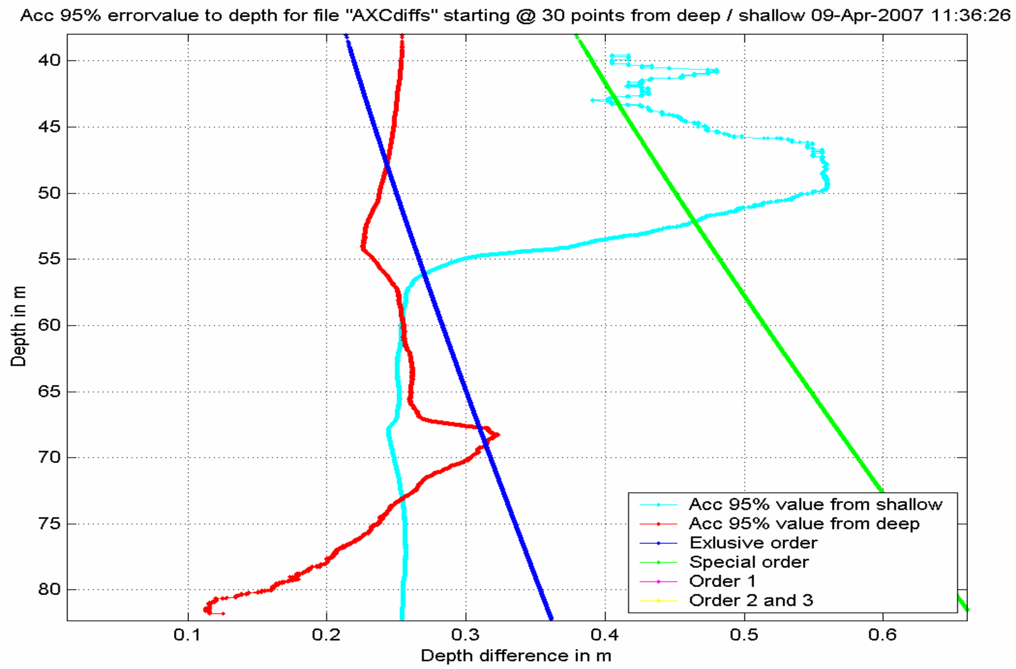

Fig. 12 Example of analysis from IVS Cross Check tool output file. The shallowest point in diagram is the 95% value of the differences for the 30 shallowest depths between the reference surface and the check line/s. Next point in diagram is calculated in the same way for the 31 shallowest depths. The following points are calculated the same way by adding the depths in sequential order and corresponding differences.

Difference single beam – multibeam
If the vessel collects single beam data in addition to multibeam data a depth comparison could be made. The differences may vary depending on several factors such as different frequencies, bottom characteristics, roll and pitch stabilization, etc. However, the comparison will give redundancy and notify the surveyor of possible errors in the system. If using different methods of referencing the depth to the chart datum for the singlebeam and multibeam (i.e. tide corrections and RTK height) the difference between those methods could be found.
The comparison between singlebeam and multibeam can be performed in the same way as described above i.e. surface to surface or surface to point.

Bar sweeping
Verification of the depth accuracy of the multibeam data could be made by an independent, stable and accurate barsweeping system. Barsweeping should be performed after a multibeam survey in selected shallow areas with limited under keel clearance. The error budget for barsweeping is less than two third compared to multibeam. However, it requires a calm sea during the survey. Areas to be covered by the sweep are normally depths less than fairway construction depth plus 1.5 times the minimum allowed under keel clearance. The bar should be set to a depth corresponding to the construction depth in the fairway. To increase the confidence level of the safe swept area the barsweep could be lowered to a depth including the error budget.
The barsweep result is a depth layer and a confirmed minimum depth in shallow areas. The result should be visualised on top of the multibeam data and horizontal as well as depth differences should be analysed.
By using a barsweep, the probability increases of finding features that are dangerous for navigation that are not found by the multibeam system. Remaining outlier in the multibeam data, not detected by any other cleaning or statistical method, could be removed in the areas covered by the barsweep. In critical areas this could increase the maximum allowed vessel draft and/or decrease the minimum under keel clearance.

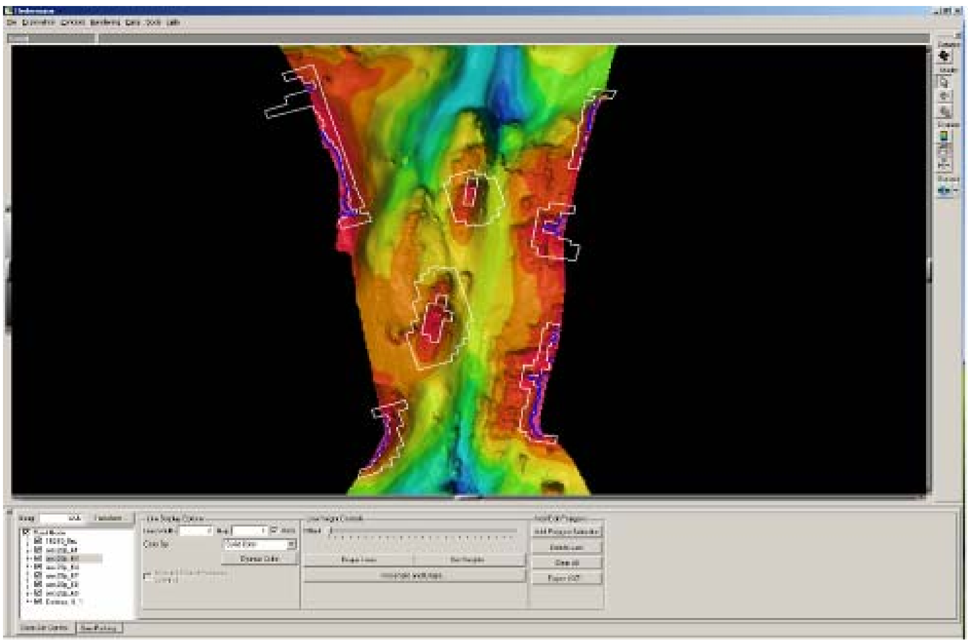

Fig.13 IVS Fledermaus. Barswept areas (white polygons) overlaid on multibeam data.

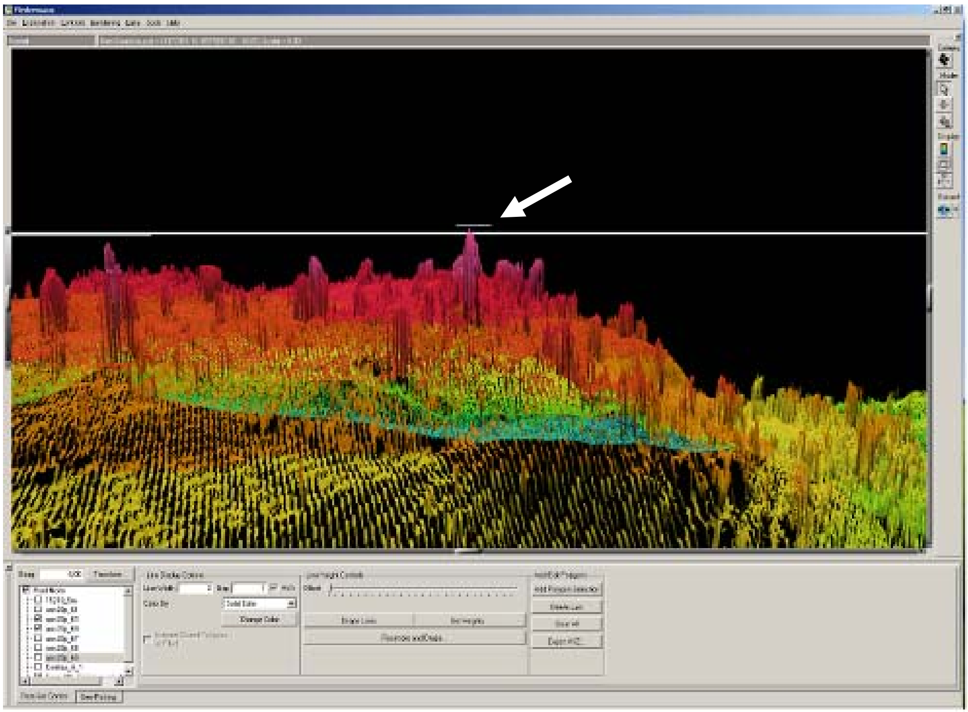

Fig.14 IVS Fledermaus. Barswept layer (white). The smaller white line (at the white arrow) is 10 cm above the underlying swept layer (long horizontal white line) and represent the minimum clear swept depth in the area.

DISCUSSION

The question whether the measured depths are within acceptable accuracy limits or not is still very difficult to prove. The statistics on the resulting depths may show excellent agreement but do they represent the true depth? A possible way to get closer to the truth is to verify the depth accuracy of the multibeam system on a ground truth object on the seafloor. However this object is not likely to be in the survey area and will only verify the true depth on the object at that time. Another independent depth measuring method could be used to get redundancy in depth. If the second method is used in critical and selected areas and the resulting depths from the two systems have acceptable agreement, we are statistically approaching a true depth.

SUMMARY

To verify that collected depth data is within the accuracy standard prescribed in the survey specification a quality analysis must be performed. The main aim of the Hydrographic Offices is to keep a high navigational safety standard in the charts produced. But it is also important for other end users to have reliable data and quality assurance on the product they may have paid for and are using in other projects (e.g. dredging). Established procedures and prescribed deliverables for the surveyors in the field are essential to be able to prove the quality of the data and deliver a more complete end product.
Quality control and quality analysis must be performed throughout the survey process to ensure high quality charts, safe for navigation, and to minimise resurvey due to failing sensors or

anomalous data. The possibility of visualising the performance of sensors and comparing different values in the data collection software should be used extensively online.
There are many existing analysing methods and new ones will be developed. It is important that the methods used are efficient and easy to perform. Some of the methods described may be seen as the same and give similar results. Depending on the circumstances (e.g. survey system and available software) some methods may be more suitable than others.
Different depth measuring methods provides redundancy in depth but to be able to prove a "True Depth" is still a matter of statistics.

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