Article

Multibeam Processing for Nautical Charts (Using CUBE and “Surface Filter” to enhance multibeam processing)

By LCDR Aluizio Maciel de Oliveira Junior [1,2] and CDR Izabel King Jeck [1]

Abstract

The Brazilian Navy Directorate of Hydrography and Navigation (DHN) performed extensive experiments during 2008 in order to find a reliable and efficient work flow for processing multibeam data to update its nautical charts. A work flow using CUBE (combined uncertainty and bathymetric estimator) and “Surface filter” tools demonstrated excellent results when compared to traditional processing methods. CUBE can enhance processing speed and highlight critical areas for navigation, in which a hydrographer’s careful analysis is required. The “Surface filter” can eliminate bad soundings, but still keeps a shoal biased surface to be represented in nautical charts.

Résumé

La Direction d’hydrographie et de navigation de la Marine brésilienne a réalisé des expériences approfondies au cours de l’année 2008 dans le but de trouver un flux d’opérations fiable et efficace pour le traitement des données multifaisceaux aux fins de mise à jour de ses cartes marines. Un flux d’opérations à l’aide des outils CUBE (estimateur mixte des facteurs d’incertitude et de bathymétrie) et « filtre de surface » a eu d’excellents résultats par rapport aux traditionnelles méthodes de traitement. CUBE peut améliorer la vitesse de traitement des données et mettre en relief les zones critiques en matière de navigation pour lesquelles une analyse approfondie est nécessaire. Le « filtre de surface » peut éliminer les sondages défectueux, mais adopte toujours la surface basée sur les profondeurs moindres pour être représentée sur les cartes marines.

Resumen

La Dirección de Hidrografía y Navegación de la Marina Brasileña (DHN) realizó amplios experimentos en el 2008 para encontrar un flujo de operaciones fidedignas y eficaces en el procesado de datos multihaz para actualizar sus cartas náuticas. Un flujo de operaciones que utilice los instrumentos CUBE (Estimador Mixto de Incertidumbres y Batimetría) y un “Filtro de Superficie” tuvo excelentes resultados al compararlo con los métodos tradicionales de procesado. CUBE puede mejorar la velocidad de procesado y destacar las zonas críticas en materia de navegación, para las que se requiere un análisis detallado por parte del hidrógrafo. El “Filtro de Superficie” puede eliminar los malos sondeos, pero sigue manteniendo una superficie basada en las profundidades mínimas que se representará en las cartas náuticas.

[1] Directorate of Hydrography and Navigation (DHN)
[2] Universidade Federal Fluminense (UFF)

1. Introduction

DHN has been using multibeam echosounders since 1998. After taking several steps necessary for acquiring a high quality data such as calibration procedures, focus has been pointed towards establishing a standard work flow for processing multibeam data. While delivering good views of the seafloor, multibeam echosounders dramatically increase the number of soundings acquired during surveys. For a comparison, single beams systems normally get approximately 3,600 soundings per hour and shallow water multibeam echosounders record around 13 millions soundings per hour. This exponential increase in the data acquisition rate requires the development of new methodologies to analyze multibeam data.

Traditional multibeam echo sounding processing methodologies that were used 10 years ago checked the behavior of the beams over the swath extension. Further improvements tried to match adjacent survey lines in order to identify outliers (Mallace and Gee 2004). More recently, automatic tools such as CUBE (Calder and Mayer 2003) have been implemented, using algorithms that include new concepts such as the total propagated errors (Hare et al. 2004), disambiguation methods, depths at nodes, etc., to build a robust methodology for speeding up multibeam processing.

These new automatic processing tools are not easily adopted by hydrographers. Traditionally, hydrographers are very conservative, as they have a responsibility to guarantee the safety of navigation. The relatively simple job of scanning single beam echograms to identify spikes became a hard and tedious task of analyzing millions of soundings.

Automatic processing tools such as those of the CUBE algorithms provided an intelligent way of analyzing multibeam bathymetry. It separates the meanings of soundings and depths. Soundings are interpreted as the real measurements performed by the echosounder. They include all random errors inherent in a measurement. On the other hand, depths are calculated within regularly spaced nodes, being estimated after analysis of soundings. But, these depths estimates can be altered when CUBE parameter settings are tuned (Vásquez 2007), which reinforces the hydrographer's concern for using automatic processes.

During tests performed, CUBE parameters were always used in standard settings and have been applied to different seafloor morphologies. CUBE was not intended to provide final depths; instead, it was primarily used as a solution to highlight more critical areas for navigation. This approach can considerably diminish processing time, as CUBE is able to solve depths in flat seafloor areas and also highlight critical areas (e.g. rocks and wrecks) where hydrographers need to pay special attention and make a careful analysis. This approach normally allows research ships to leave the survey area with all the data processing completed.

CUBE calculations are intended to provide "the best depth estimate" surface, which is an averaging solution that represents a depth located close to the middle of sounding points. As merchant ships have increased draughts and under-keel clearance is becoming tighter, requirements for hydrographic offices are more demanding. The shallowest soundings cannot be rejected as they are required to guarantee navigation safety.

The "surface filter" (Caris 2007) has been found to be most useful in generating the shoal-biased surface. It builds a screen around the CUBE surface that is used for validating good soundings and filtering out bad soundings. Sounding uncertainties and standard deviations are used as the main parameters to determine screen filtering size. During tests performed, several sizes were tested in order to find a suitable configuration that could produce results similar to manual processing.

The traditional manual work flow and the implemented semi-automated work flow have been tested and compared by many hydrographers in several survey areas. Results allowed DHN hydrographers to rely on the semi-automated work flow.

2. Discussions about defining depths in multibeam processing

Before comparing traditional and semi-automated work flows, some discussions about defining depths in multibeam processing may be useful.

Figure 1 demonstrates multibeam sounding points from a subset area, as they are represented in many hydrographic programmes. In this example, soundings points have three different colors showing that they were extracted from three different survey lines. Soundings are matching closer locations, but present variations of about 1 m. There are two main reasons for these variations: natural random noise of measurements and seafloor roughness (ex. sandwaves, ripples, etc) in several spectral wavelengths.

Hydrographers must decide within these sounding points which are the most appropriate to be shown on nautical charts. If the two shallowest isolated points, located in the top of *Figure 1*, are chosen, it would represent a reduction around 0.5 m with relation to average depths. Alternatively, if these two points are not considered, the top of sounding points will be only about 0.2 m shallower than the average depths. So, this decision has to be made and requires great effort by hydrographers

Considering the issues discussed about defining depths, we are now ready to analyze different ways of processing multibeam data. First, the traditional work flow that uses manual cleaning will be briefly presented. Later, the implemented semi-automated work flow that uses CUBE and the "surface filter" tool will be discussed.

3. Traditional work flow for multibeam data processing

Traditional work flow uses manual cleaning techniques. *Figure 2* presents the main steps. Notice that hydrographers have to manually interact twice during data processing. In the first step, cleaning uses a line-by-line basis and three editors are available: navigation, attitude and swath editors. In the second step, an area basis methodology is used with subset editor.

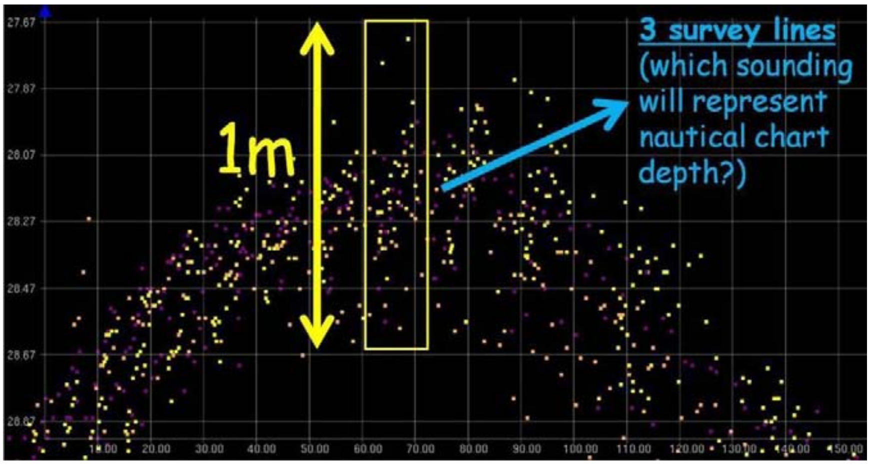

Figure 1: A seafloor subset presenting soundings points of 3 survey lines. Soundings values vary around 1m. Hydrographers have the task to decide which soundings are going to represent depths in nautical charts

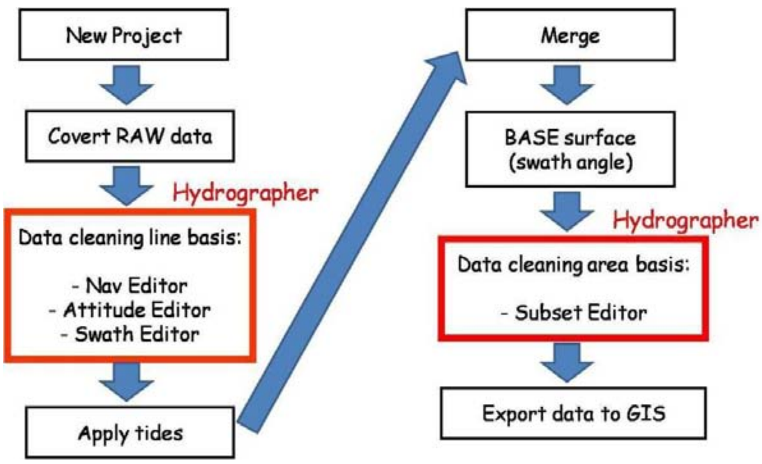

Figure 2: In traditional work flow, hydrographers are required to manually interact twice during data cleaning

3.1 Manual cleaning editors used in traditional workflow

The first editors used for multibeam processing resemble tools available for single beam processing, as they require that each line be checked separately. They include editors for analyzing positioning, motion sensor movements and swath coverage. Further improvements allow a manual area basis analysis, where adjacent survey lines may be compared.

The line basis editors are the ones that require the most time for processing data. While checking each survey line in different steps, soundings can be cleaned manually or using filters, as presented in *Figure 3*. It is a very subjective method and hydrographers can get different results when using distinct processing criteria. As an example, if zooming factors are modified, the way data is presented in the screen can lead to a different interpretation. Also, if data needs to be cleaned faster, it is possible that more outliers will be accepted. On the other hand, these editors are useful to find systematic errors from specific sensors (Mallace and Gee 2004).

The area based or subset editor allows comparison between adjacent survey lines. When lines are matching coherently, it indicates that the system was properly calibrated and that data were acquired with high quality standards. On the other hand, when lines show mismatching, it indicated that specific errors (e.g. tide and sound speed) occurred during data acquisition. *Figure 4* presents the "subset editor" tool, which permits a better overview of soundings distribution than using the "swath editor" tool, but it is still a very subjective process.

After finishing this quick overview on traditional work flow and its manual cleaning techniques, the discussion will proceed to the semi-automated work flow implemented during this study.

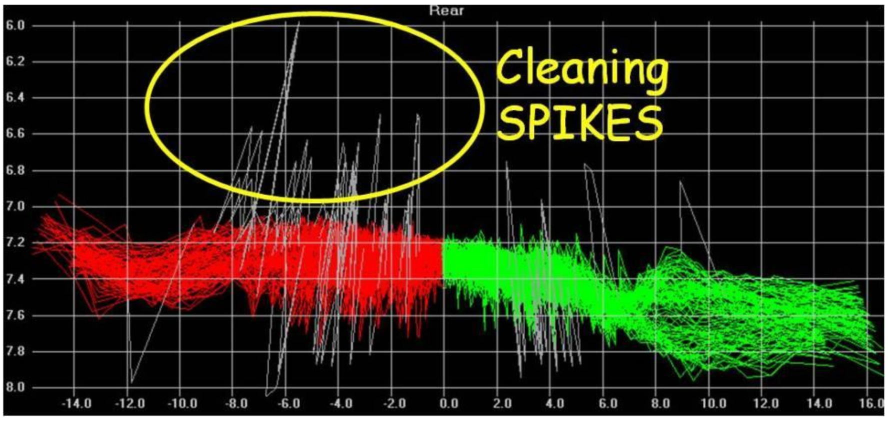

Figure 3: The "swath editor" tool is used for cleaning spikes. Each line represents one multibeam ping, with starboard side in green and port side in red. Cleaned beams are signaled in gray. This cleaning process is tedious and very subjective

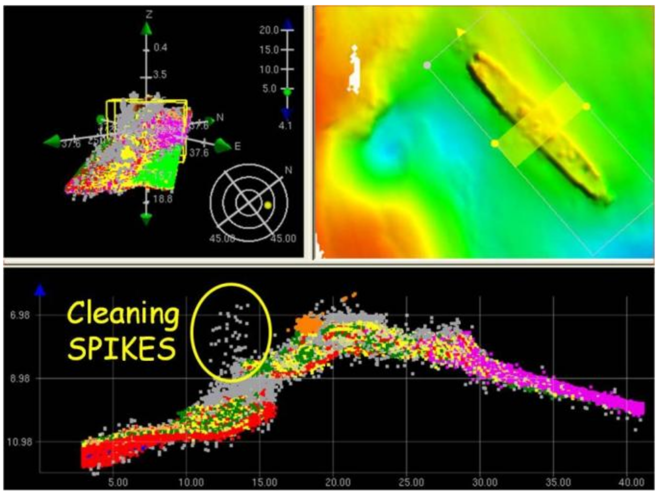

Figure 4: The "subset editor" tool is used to check coherence between adjacent survey lines. (Top right) Shows a wreck and a yellow box where analysis is being performed. (Below) Subset editor presents a frontal view of soundings contained inside yellow box area (Top left). Points have different colors indicating distinct survey lines

4. Semi-automated workflow using CUBE and "surface filter" for multibeam processing

This work flow was referred as semi-automated, because it uses automated tools (e.g. CUBE and surface filter) and also hydrographer's manual decisions. After extensive trials with several datasets, the semi-automated work flow presented in *Figure 5* proved to be a good solution for processing multibeam data for nautical charting. With this approach, hydrographers are required to interact only once during workflow. In addition, their efforts are concentrated in restricted areas that are critical for navigation. These areas are pointed out after CUBE processing. Established procedures also include a surface filter for removing outliers and keeping validated soundings that are used to build a shoal-biased surface.

This semi-automated work flow has some steps that are also used in traditional work flow, but a few changes could reduce the number of times that hydrographers have to execute manual editing, so that processing time can be reduced. The resulting bathymetric surfaces resemble the surfaces generated by traditional methods. This approach is very objective, so that different hydrographers can produce similar depth results. The main tools used in this work flow are CUBE and surface filter, which are described below.

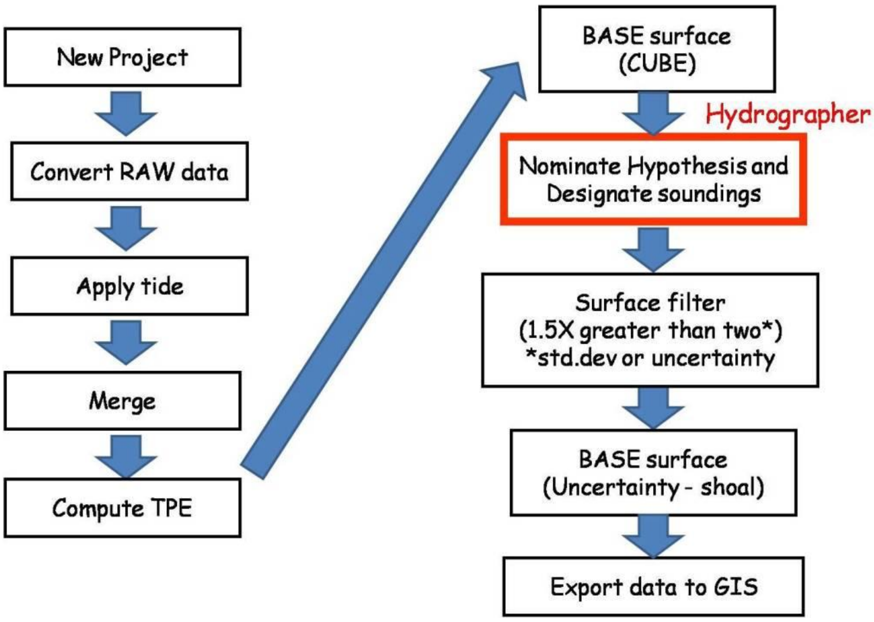

*Figure 5: Semi-**automated work flow using CUBE and "surface filter" tool for multibeam processing allows hydrographers to interact fewer times than using traditional workflow***

CUBE automatic processing

The CUBE algorithm was developed first at the University of New Hampshire in 2000 and aimed at reducing multibeam processing time. It has been implemented in several hydrographic programmes since then (Calder and Wells 2007).

As CUBE uses uncertainty concepts, it is well suited to the International Hydrographic Organization (IHO) standards, defined in S44 publication. The total propagated errors (TPE) of the soundings that are calculated from each multibeam sensor uncertainty (Hare 2001 and Collins 2004) are used to run the CUBE engine. The concept of TPE also aligns with IHO standards.

It is important to highlight that CUBE algorithms were developed to work with random errors that are inherent to every measurement. Systematic errors (e.g. misaligned sensors) must be solved before the survey or, when possible, they should be flagged out before running the CUBE processing algorithm. Outliers theoretically would be marked by CUBE as an invalid or alternative hypothesis, and then would not be used to represent the final depths.

CUBE identifies soundings as the measurements performed by each beam (Wells 2004). Each sounding also has its associated uncertainty, calculated from the total propagated errors algorithms. CUBE builds a bathymetric mesh (Calder and Mayer 2003), with regularly spaced nodes as illustrated in *Figure 6*. Soundings and their uncertainties are propagated to the nodes. Uncertainties are degraded as they are propagated from original positions to the nodes positions. Each node receives neighbouring soundings and uncertainties and keeps accumulating more robust statistics. If all soundings are coherent, they build one single estimated depth solution termed as null hypothesis. But, if soundings are not coherent, alternative hypotheses are built, then a disambiguation engine has to work to point out which hypothesis has the biggest probability to be correct. During tests performed in this study, the disambiguation engine was configured to check for the number of soundings within each hypothesis and the coherence of estimated depths with neighbouring nodes for deciding the best hypothesis solution.

CUBE defines depth as the most probable hypothesis for each node. The invalid hypothesis that were discharged by the disambiguation engine are termed alternative hypothesis. Hydrographers can later nominate this invalidated hypothesis to be the true hypothesis. This scheme of valid (null) hypothesis and invalid (alternative) hypothesis is one powerful advantage in using CUBE. Normally, flat areas with small depth oscillations have one hypothesis. Therefore, CUBE algorithms are able to complete depth estimation processing. Otherwise, areas with frequent depth variations usually present at least two hypotheses. So, these areas are highlighted for the hydrographer's analysis. In *Figure 7*, one can observe a survey area where the position of a wreck is highlighted. Hydrographers can concentrate efforts to analyze only this wreck area, keeping CUBE solutions as true for the places where there is only one hypothesis. This scheme allows hydrographers to save time and also to concentrate their energy in areas where real navigation safety issues are present.

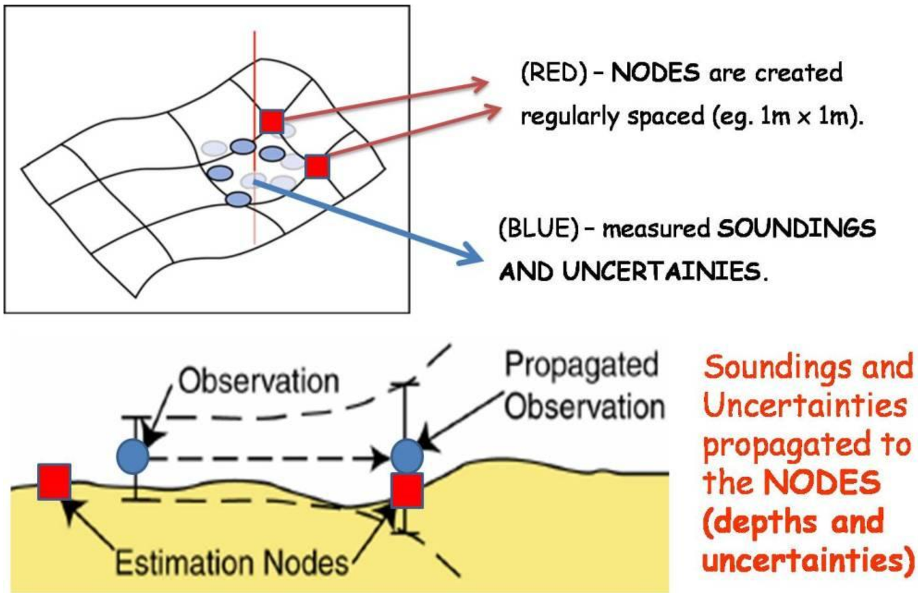

Figure 6: CUBE generates a bathymetric grid. Each grid's node has depth values, which are calculated from surrounding soundings and uncertainties (compiled from Calder and Mayer 2003)

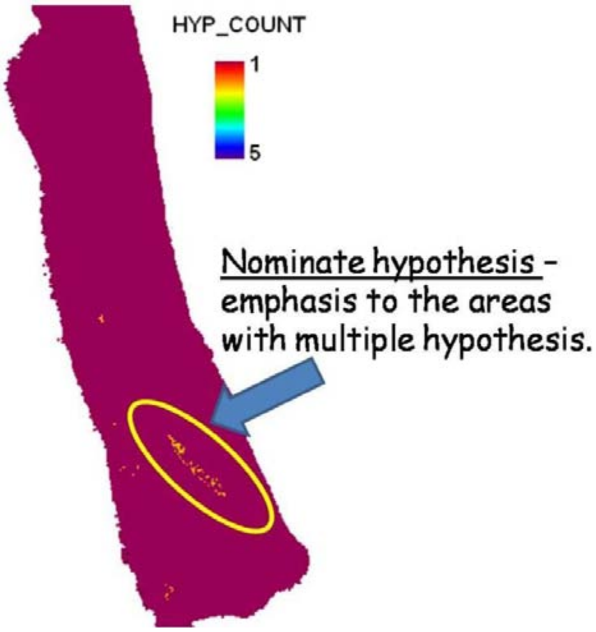

Figure 7: Area surveyed in Guanabara Bay (Rio de Janeiro). This plot is an example of the number of hypothesis within this area. Notice that most parts in the map have only one hypothesis and don't require hydrographer's analysis. While the signaled area (ship wreck) demands hydrographer's efforts to decide if nominating alternative hypothesis will be necessary

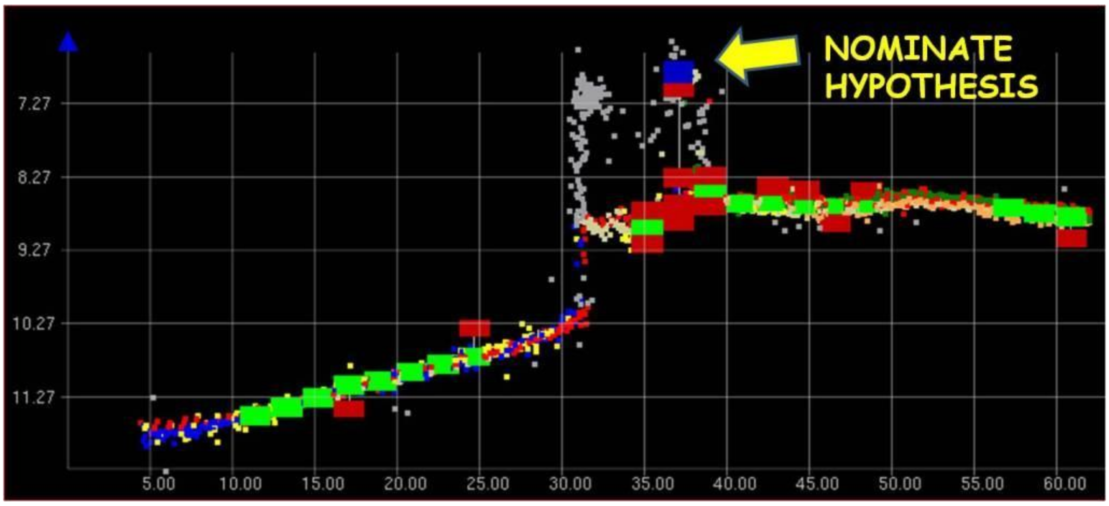

Figure 8: Visualizing and editing CUBE hypothesis. (Green) valid hypothesis; (Red) invalid hypothesis; and (Blue) hydrographer nominated hypothesis

Figure 8 presents a plot of hypothesis over the wreck area where a hydrographer has the ability to nominate an alternative hypothesis to be true. CUBE disambiguation engine certainly decided that soundings in the bottom of the wreck were true because sounding densities are greater on the bottom than on the top. Although, the hydrographer has the knowledge to visually understand this situation (eg. wreck area) and nominate the points in the top to be valid.

CUBE estimated depths correspond to an average biased result as presented in *Figure 9*, being calculated from surrounding soundings. The soundings closer to the node and with smaller uncertainties have higher weights for depths calculations.

As Hydrographic Offices require shoal-biased depths for navigation safety reasons, then an additional tool is required. In Caris HIPS software, "surface filter" is a very appropriate tool for this task.

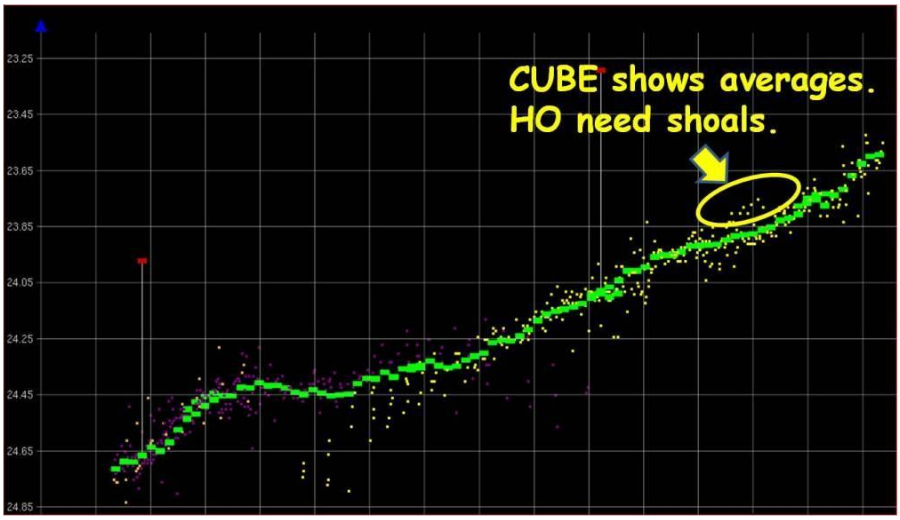

Figure 9: CUBE surface (green squares) usually is located in an averaged biased position in the middle of sounding points. But, for nautical chart production, Hydrographic Offices (HO) require shoal biased soundings located in the top of points

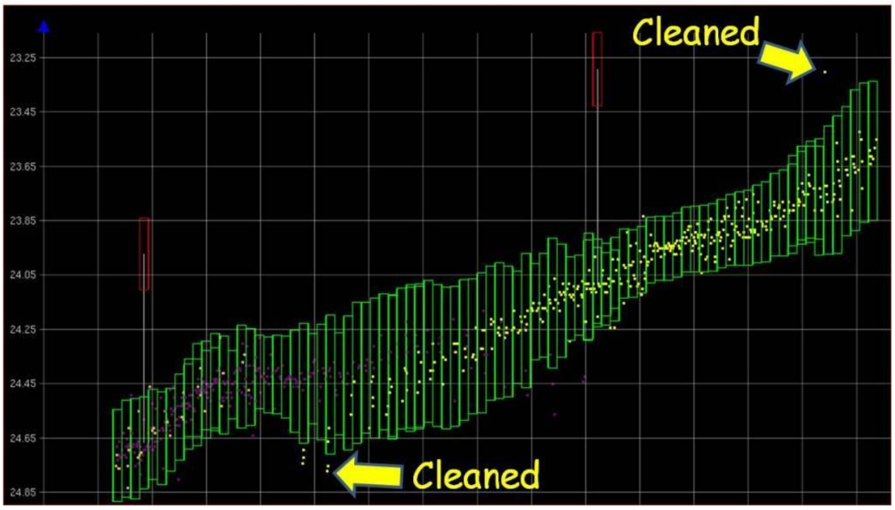

Figure 10: "Surface filter" tool is used to build a filtering screen around CUBE surface. Each filtering screen size can be adjusted based on nodes uncertainties or standard deviations. Soundings located out of filtering screen ranges are automatically cleaned

4.2 "Surface Filter" tool

The idea of creating a shoal-biased surface for navigation has already been proposed by Peter Kielland (Calder and Wells 2007) by reducing CUBE depth estimates from 95% of uncertainty values.

The "surface filter" tool does not reduce depths from a fixed uncertainty value. Instead, it builds a filtering screen around CUBE depths. Then, soundings contained inside this filtering screen can be validated and picked up to build a shoal-biased surface. On the other hand, soundings outside the range of the filtering screen can be flagged out as invalid and removed from processing. The filtering screen size can be adjusted using standard deviation or uncertainty information from soundings. After extensive trials, a configuration using 1.5 times the greater of the two values (standard deviation or uncertainty) proved to be able to generate results very similar to manual cleaning performed by a hydrographer.

Figure 10 presents an example of surface filter cleaning. Soundings located outside the filtering screen are automatically cleaned and points located in the interior are kept as real soundings, which can be used for building the shoal-biased surface used for nautical charts.

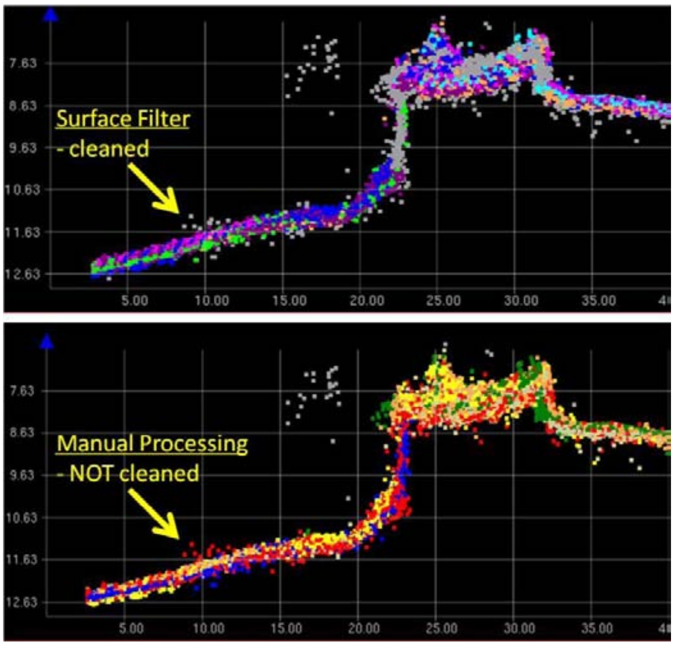

Figure 11: "Surface filter" clean small dots flying above the main seabed surface better than manual cleaning

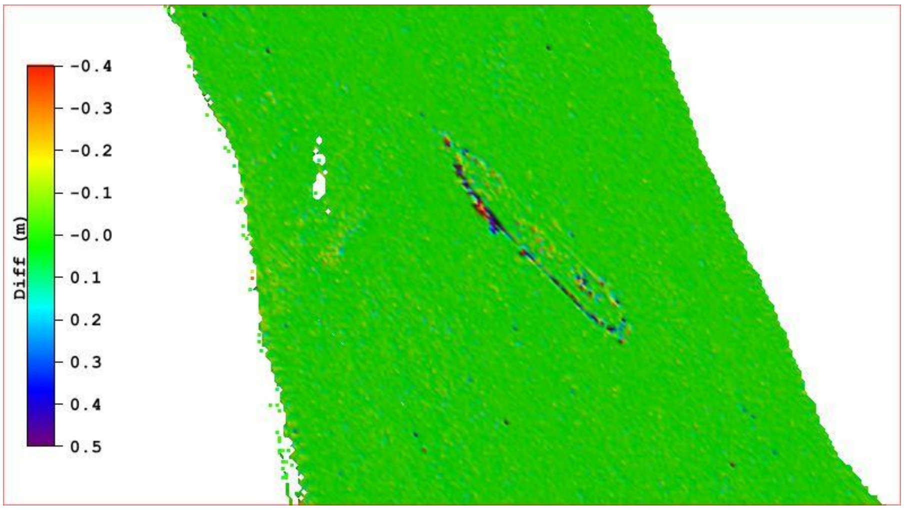

Figure 12: Depth differences between surfaces produced with traditional workflow versus semi-automated workflow

5. Comparison between traditional and semi-automated work flows

Several multibeam data sets were processed by experienced hydrographers and also by thirteen new hydrographers, who were undertaking DHN IHO-Cat.A course. Surveys were performed in Brazilian ports, including Rio de Janeiro, Paranaguá, Itajaí and Laguna, and near Comandante Ferraz Brazilian station in Antarctica. All regions analyzed have both flat and rough seafloor areas.

Since the beginning of tests, CUBE demonstrated its power to reduce processing time. It generally solves depths in flat areas (ie. solutions presenting only the null hypothesis) and highlights critical areas (i.e. solutions present multiple hypotheses) where targets are on the seafloor. In multiple hypotheses situations, the CUBE disambiguation engine is normally capable of determining the right estimated depths. But, occasionally (e.g. wrecks or very sharp outcrops) an experienced hydrographer is required to intervene, being necessary to nominate an alternative hypothesis or designate a golden (ie. very important) sounding. Therefore, CUBE has allowed a significant reduction in processing time, since flat areas were larger than rough and critical areas within areas studied here.

The surface filter enabled a reliable cleaning for navigation purposes. Results demonstrated that filter configuration established here (i.e. 1.5x greater of the two) was able to produce a shoal-biased surface very similar to the surface obtained using the traditional work flow. But, implemented semi-automated work flow has slightly better results than traditional work flow, as shown in *Figure 11*. It also permitted that several hydrographers could obtain similar results as they followed fixed steps and rules during the processing work flow.

The depth differences between surfaces produced with traditional and semi-automated workflows are presented in *Figure 12.* Differences are usually smaller than 10 cm. But, in some spots, differences can reach 20-30 cm. These higher differences were normally related to some points that were left by hydrographers during manual cleaning, as previously presented in *Figure 11.*

Before these trials, DHN hydrographers had the same concerns as other HO hydrographers for using automatic processing for cleaning data. But, after these trials, there is a greater confidence in using this semi-automated process with CUBE and "surface filter" tools for cleaning multibeam data.

6. Conclusions

Several multibeam data sets collected by the DHN in 2008 have been processed using traditional work flow and a new implemented semi-automated work flow that uses CUBE and "surface filter" tools.

Results demonstrated that semi-automated workflow is fast and reliable for processing multibeam data for nautical charting, which requires a shoal biased approach.

Implemented semi-automated work flow has the following advantages when compared to the traditional workflow:

a) Reduces drastically the processing time. Ships can finish data processing quickly and resurvey doubtful regions before leaving the survey area.
b) Solves depths in flat regions and points out critical areas where hydrographers need to perform a careful analysis.
c) Allows great objectivity, so several analysts can obtain similar results.

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Biographies

LTCR Aluizio M. Oliveira Jr. is the chief of the Bathymetry Division in the Directorate of Hydrography and Navigation (DHN) for the Brazilian Navy. He has a B.Sc. in Electronics and a M.Sc. in Geomatics. He is currently a Ph.D. student, studying marine Geophysics at Universidade Federal Fluminense (UFF).

Centre of Hydrography (CHM/DHN)
Rua Barao de Jaceguai, s/n – Ponta da Armacao
Niteroi – RJ - Brazil
CEP 24048-900

Tel 55 21 21893230, Fax 55 21 21893237,
aluizio94@yahoo.com.br

CDR Izabel King Jeck is the chief of the Survey Division in the Centre of Hydrography, Directorate of Hydrography and Navigation (DHN), Brazilian Navy. She has been working with multibeam since 1999, when the first multibeam echosounder was installed in a Brazilian Hydrographic Ship. She has been graduated in Geology and got a M.Sc. in Marine Geology and Geophysics at Universidade Federal Fluminense (UFF), processing and interpreting multibeam data.

Centre of Hydrography (CHM/DHN)
Rua Barao de Jaceguai, s/n – Ponta da Armacao
Niteroi – RJ - Brazil
CEP 24048-900

Tel 55 21 21893026, Fax 55 21 21893237,
izabelkj@hotmail.com

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