Alternative use of CUBE; how to fit a square peg in a round hole

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Abstract

The traditional bathymetric products from multibeam sonar surveys have varied depending on the segment of the ocean mapping industry, but they have all relied on what has generally been described as a “clean” dataset. Products are then generated from these data and the type will depend on the field of the user; from a shoal bias selected sounding set for nautical charting to various types of grid for geologic analysis.

The CUBE algorithm and resultant grid attributed with uncertainty are the beginning of a paradigm shift in the approach to multibeam sonar surveys. However, there are a number of factors that prevent the immediate widespread acceptance of the approach, and not least is the requirement in nautical charting for the acceptance by the user that a sounding is not depth. In addition there are a number of cases where the observational uncertainty is not available or the existing data format does not support the parameters required for computation of the horizontal and vertical uncertainty. It will also take some time for clients to adapt new quality control procedures to analyze a CUBE produced surface, and there is also some confusion with the relationship between CUBE and the Navigation Surface given their simultaneous development.

However, the CUBE algorithm can be used as a data-cleaning tool provided it is implemented in a hybrid approach that produces the attributed grid and also allows its use as a filter for the sounding data. Using CUBE, whether to produce an attributed grid, to clean soundings or just to produce a DTM in the shortest possible time requires a flexible approach and software. The CUBE algorithm will only allow multibeam data to be processed quickly if the surveyor has the tools to examine the resultant surfaces in combination with soundings to make rapid decisions where necessary to adjust parameters, re-run the algorithm in selected areas and if necessary delete sounding blunders. With the volume of data now being collected by modern multibeam systems it is not feasible to adjust CUBE parameters and re-run the algorithm on the entire dataset. It is also not feasible to trust implicitly the CUBE results, as somewhere in the data the CUBE algorithm will fail.

Using the Fledermaus implementation of CUBE has significantly improved the time from acquisition to final product during use on a number of multibeam sonar projects over the last three years. The implementation takes advantage of the area-based approach and 3D quality control tools to minimize the human resources required for processing and focuses their attention on examining the results of the CUBE algorithm. The surveyor has the tools to examine the resultant surfaces in combination with soundings to make decisions where necessary to adjust parameters, re-run the algorithm and if necessary delete sounding blunders. On completion the options are available to output a BAG, filter soundings based on the accepted surface, and produce decimated sounding datasets for the traditional products.
Introduction

The development of the Combined Uncertainty and Bathymetry Estimator (CUBE) algorithm at the Center for Coastal and Ocean Mapping and NOAA/UNH Joint Hydrographic Center (CCOM/JHC), the University of New Hampshire, and the resultant attributed grids have begun a paradigm shift in the approach to the processing of multibeam sonar surveys. Since the first presentation of the algorithm at the US Hydrographic Conference in 2001 [1], the focus has primarily been its use in pure hydrographic processing with a close relationship to the Open Navigation Surface and the Bathy Attributed Grid (GRID) [2][3]. However, it will take some time for all organizations undertaking hydrographic surveys to accept the shift to a product based on a statistical surface, instead of the traditional selected set of soundings. Currently, it is understood that only the NOAA Office of Coast Survey has accepted the BAG as a product, although a number of others are investigating the shift to the new approach. Other factors, such as the unavailability of particular sonar uncertainty models and existing data formats that do not fully support the computation of horizontal and vertical uncertainty, may prevent the immediate widespread acceptance and use of the approach.

The hydrographic survey works that NetSurvey currently undertake have multiple deliverable requirements, but neither a BAG or the derived Navigation Surface have been requested. To this end the deliverable from a hydrographic survey for charting purposes has been a full density sounding set with both accepted and rejected soundings, as well as all peripheral sensor information. For Oil and Gas survey operations the main requirement is either a high resolution digital terrain model (DTM) or soundings, from which the top of pipeline and surrounding seabed locations are picked. Notwithstanding, it was important to incorporate a well-implemented CUBE algorithm to our workflow to optimize the overall processing throughput. This allowed us to benefit from some of the key CUBE features; the rapid processing of the increasing volumes of data, the fact that most of the data are good and require no interaction, and the direction of the surveyors to where they needed to apply their hydrographic skills to fix or support the algorithm [4]. NetSurvey worked with IVS 3D on the implementation of CUBE in Fledermaus and it now forms the main processing component of our workflow.

The draft CUBE User’s Manual [5] outlines three modes of operation and notes the alternate use of the CUBE surface model as a basis for cleaning the soundings, and this is the approach NetSurvey is taking until clients accept the delivery of a gridded product. This alternate approach is outlined below, and allows us to use CUBE as a “power tool” to generate clean soundings as quickly as possible, while retaining full quality control. We create and work on a CUBE surface and when this is correct we use this surface to reject soundings by placing a “window” around the surface with the size related to the IHO Order accuracy of the survey. Soundings that fall shallower or deeper than this window are then rejected.

Our experience has shown that the CUBE algorithm needs to be adapted to suit the terrain and the deliverable. It almost always fails in a few isolated areas, normally due to adverse physical conditions (for example, bubble wash) or due to the sparse and predominantly poor quality soundings in an area (outer beams). The ability to change the algorithm whereby CUBE decides which potential depth is correct (the disambiguation engine) for either the whole area or a small subset is critical to enhancing the processing flow. The ability to deleted rogue soundings and re-CUBE an area is also critical if your surface model is going to be used to filter soundings, or will be the final product.
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Notes on node spacing

The CUBE algorithm calculates depth estimates at nodes. The initial rule of thumb was that the nodes should be spaced at an interval suitable for capturing features of a certain size based on the deliverable but no denser than necessary (to retain sufficient soundings for statistical analysis). However if you are using the CUBE surface as a filtering window to reject soundings and your seabed topography is rocky or includes sharp sand wave peaks or steep slopes then by following the guidelines you run the risk of deleting good soundings over these features. The node spacing must really be at the highest resolution possible in order to avoid deleting the tops of sand waves and information on slopes from being deleted. Another approach to this, if you have flexible software, is that you can filter tightly over the flatter areas and then relax the filter over the steeper areas.

Changing the Disambiguation Engine

Once the CUBE algorithm has been run and multiple depth estimates (hypothesis) at node locations exist the next stage in the processing is to determine which depth estimate is going to be the best estimate.

The disambiguation engine has three "metrics" or tests that are used to resolve which hypothesis is most likely the correct one at each node. These metrics are:

- The popularity contest. Which hypothesis is consistent with the greatest number of incoming soundings at that node?
- The local consistency test. Which hypothesis is closest to a prediction based on nearest neighbour nodes that have only one hypothesis?
- The external consistency test. Which hypothesis is closest to an “external” (probably lower resolution) reference surface? This is normally the average depth surface.

Fig 1: Predicted Surface Metric result
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Very rarely do you know what the seabed topography is going to be like before conducting the survey, so when you initially build your CUBE surface you have to take a guess as to which metric will work best. What happens if you guess incorrectly (Fig 1)? You either have much more editing to do and therefore it defeats the point of the CUBE, or you have to start your CUBE build again. With modern shallow water multibeam systems that is a time consuming approach. What happens if your survey area is not homogenous? You spend more time than necessary editing the CUBE output and therefore lengthening your processing time. What is required is the ability to change the disambiguation engine on either the whole survey or just the part of it that needs refining. To be able to achieve this a spatially aware data structure is required that maintains the link between the soundings and the surface.

The Fledermaus software uses the PFM data structure for multibeam/lidar data processing. This is a bin and index structure, and provides the benefit of a dynamic and fully attributed set of surfaces and the direct link back to all the underlying data points. [6] In this way changes to the underlying data automatically change the surfaces and because PFM knows which cells are affected by changed data only the surfaces in that area are changed. It is also possible to load up a portion of a survey area thus allowing even the very largest surveys to be viewed and analysed at a time. This link between the surface cells and the underlying data allows for processes to run on either a manually selected region, the section of the survey area loaded up into the program, or the entire survey area. Using this technology allows us to re-CUBE a small area to which disambiguation metric works best. Once we know which metric works better we can re-CUBE the survey (Fig 2) either by selecting an area manually (based on the topography of the seabed), the area currently loaded into the program or the entire survey area.

![Fig 2: Changing Hypothesis Resolution Algorithm](image)

It is our experience that the *number of soundings* (Fig 3) metric works best on rock terrain with the *predicted surface* working better on flatter terrain. Apart from long pipeline surveys across the North Sea, the terrain is normally a combination of the
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two so we choose one metric (normally number of soundings) and then re-CUBE sections based on the topography.

Analyzing and choosing the correct hypothesis

Once the surface has been built and the correct metrics chosen for the right sections of the seabed, the surface needs be analysed for features. This process we perform in three ways.

Firstly we colour the surface by Uncertainty and look at the surface in 3D, increasing the exaggeration if needs be (Fig 4).
There are nearly always a few areas where the Uncertainty is very high and this skews the colour map which makes it hard to see the small features. The colour map can be changed to a better spread manually to enable the surveyor to focus attention to areas requiring remediation. In this way we can very quickly and intuitively see where the main errors are and we can also spot systematic errors due to incorrect sound velocity, tidal inaccuracies or a number of sensor alignment problems. If we suspect that there is a problem we can also colour the surface by *roll, pitch or heave* and see which sensor changes colour with the artefact. The *Uncertainty* surface also highlights wrecks, small contacts and man-made features (such as pipelines) as all these features have a high degree of uncertainty. After the main ones have been dealt with we then colour the surface based on the *Number of Hypothesis* in a cell.

When we find an area that has more than one hypothesis and looks like there is a feature, we select the area around the feature and load this area into the 3D editor within Fledermaus. Within the 3D editor you can view and edit the soundings, CUBE hypothesis, and also if available a target or contact editor. Soundings are still the best method of deciding whether the potential feature is a wreck/shoal/pipeline or just a bad burst of soundings. If we have enough overlap we can colour the soundings by line and if it appears on more than one pass then it is most probably a feature. If we do not have enough overlap for multiple passes we use the 3D Editor to view the feature from multiple aspects to gain a better understanding of the data. If we have a wreck listing for the area and know the dimensions of the wreck, it is possible to measure between points to see if it corresponds.

Once we have determined what it is we can decide on the action to be taken. If it is noise and the CUBE algorithm has selected the noise as being the best hypothesis (it might have more soundings around it than on the seabed) then we must check that CUBE has chosen an alternative that is correct. If it has then we can select the alternative hypothesis and *Override* the one chosen by the algorithm. If there are multiple instances in the area loaded then we can chose one of the correct
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alternative hypotheses and Link these hypotheses. We can then Override all of them in one go, which can save a great deal of time. This works best when the seabed is relatively flat.

When we have finished making our edits in the 3D editor, we can either select and load another area or close the editor. Either way when we save our edits the CUBE surface updates the area edited immediately. We can then view this in the main 3D display as a final piece of quality control to check that it fits in with the neighbouring areas. Note that we have not edited a single sounding during this process and we are only editing the model surface.

What happens when the CUBE algorithm fails?

When the CUBE algorithm fails it is either due to there being too many bad soundings to mask the good data, or that the data is too sparse and noisy so the CUBE chooses the wrong value as it didn’t have enough to statistically make the right decision. These soundings by their very nature may well be the ones that are hardest to acquire e.g. right up the beach, or tucked away in an inlet; very useful to have, but very hard to survey.

![Fig 6: Views of CUBE failure in both the surface and in the 3D editor](image)

When this happens there is no other option but to delete the rogue soundings manually and re-CUBE the affected area. You could just delete the rogue soundings but then if you are using the CUBE to filter your soundings you will delete those good soundings because you haven’t updated the CUBE surface. To re-CUBE the whole survey area for just these few failures is far too time consuming.

![Fig 7: Deleting Soundings and recubing](image)
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Fig 8: The result of the re-CUBE in the 3D editor (left) and on the surface (right)

The problem area is selected as before and loaded into the 3D editor. On this occasion we want to use the Sounding Editing mode and we can colour by lines (if we have overlap) or just view the soundings coloured by depth. We can also colour them by their TPE value but rarely does this give any more information. Once we have deleted the rogue soundings we then select the CUBE editing mode and re-CUBE the area currently loaded into the 3D editor. When cleaning out obvious blunders the robustness of CUBE allows us to be “rough and quick” because we are just trying to ensure that the algorithm gets data that is mostly good, i.e an “improved signal to noise ratio” [2]

When we exit the editor the surface is again immediately updated and we can see if the right decisions have been made. The Uncertainty and Number of Hypothesis values for this area will also have been updated so we will see that we can now move onto another area.

**Dealing with wrecks**

Wrecks can be dealt with in two ways depending upon the final deliverable.

- Create *Custom Hypothesis (or golden soundings)* over the shoalest section of the wreck and ensure that the shoalest hypothesis is chosen for all the other parts of the wreck.
- Insert a *Target* (or more than one) at the wreck, manually delete the rogue soundings around the wreck and re-CUBE the area. When we filter soundings at the end we choose not to filter around targets.

The *Custom Hypothesis* approach is definitely the correct way to go when the BAG or DTM is the required output but is a slower process than the target approach. If your deliverable is set of soundings then you will want to ensure that all wreck data is preserved (useful for the wreck database and the Report of Survey).
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When a wreck is found the soundings and hypotheses are displayed in the 3D editor and then you can choose either route. With the Custom Hypothesis approach the soundings deemed to be shoalest over the wreck is selected in Sounding Edit mode and set to Custom Hypothesis. When the CUBE edit mode is selected the CUBE estimate is now shown at that depth and it is possible to colour the estimates by Custom to ensure that the correct cell is chosen. An option is also provided to set the shoal sounding as Features, in the 3D editor. Once all Features have been set they can be globally set the associated Custom Hypotheses. These feature soundings have the dual benefit of creating a contact listing on the fly. With the Target approach, the soundings are coloured by line to aid identification and the rogue soundings deleted. This is normally performed during the Custom approach to ensure that the correct shoalest sounding is selected (especially with large beamwidth multibeam). Depending on the size of the wreck one or more targets will be inserted, with one at the shoalest sounding location. When the time comes to filter soundings an option is selected not to filter a certain radius from a target, thereby ensuring that your manually deleted soundings around the wreck are retained.
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Filtering from the Surface

Once you have a CUBE surface that looks visually and statistically to be correct the time has come to actually delete soundings. Up to now the only time we have deleted soundings has been around a wreck or where the CUBE has failed. The CUBE surface will be used to create running window and any soundings that fall outside that window are flagged as rejected by the filter.

![Filter to reject soundings over a selection](image)

This part is quite tricky, in that you can either delete too many soundings or not enough. The area where this normally occurs is over steep slopes or rock outcrops. Even though the filter works perpendicular to the slope if the DTM is not following the soundings close (the node spacing is critical) then the filter will "cut into" the slope and delete too many soundings. To ensure that this does not happen a trial area is selected and the Filter Soundings option selected (Fig. 11). This option has been improved recently with the option to filter based on an IHO accuracy. The depth of the cell is taken, the appropriate Order selected and the depth accuracy calculated. This is then the Window size for the filter for that cell. This value is computed for every cell in the survey area.

As we have PFM as the underlying architecture to the process, we also have the ability to select the Shallow Edited surface and the Deep Edited surface. These two surfaces show the shoal and deep biased values for each cell and are derived from soundings not CUBE. To view the outcome of the filtering the Shallow Edited surface is selected. When the filter has been run the Shallow surface will update immediately, both the shoalest value and also the standard deviation and number of soundings (Fig. 12). A quick check by colouring the surface based on the number of soundings will determine whether we have enough soundings to meet the IHO target detection...
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criteria for that depth. We can also bring the area into the 3D editor and tick the rejected soundings box. Both the accepted and rejected soundings are displayed and a check can be made that the filter has not taken out too many soundings. This is an iterative process so it can be repeated as often as we like. If the filter value needs to be a static one it is possible to view the CUBE surface (not hypothesis) in the 3D editor with the soundings and measure how close to the surface the soundings are and then select that value.

![Image of 3D editor]

Fig 12: Filter soundings result by checking the Shallow Edited surface coloured by standard deviation

Once the filter has been trialled and proven to work the filter is run again but this time on either the loaded surface or the entire survey area. Once the filter has finished operating the Shallow Edited surface is selected again, and the quality controlled by colouring by the number of soundings (if the IHO target detection criteria is a consideration) and also by the Standard Deviation value for each cell. This quality control can also be performed by the Surveyor-in-Charge as a further quality check prior to delivering the data.
Conclusions

There is no doubt that the CUBE algorithm will have a significant effect on the processing of multibeam sonar data, with order of magnitude improvements in the throughput of data and reduced user interaction and less subjective editing. However, its widespread acceptance relies on clients and organisations realizing that they need to change from the traditional soundings to a realistic depth surface with associated uncertainty. Does that prevent the use of CUBE in the interim, and is there an alternate beneficial use that can contribute to its general acceptance in the intended mode?

The CUBE algorithm is every bit as important for efficient bathymetric processing when sounding products are required, and the approach used by NetSurvey in the last three years has been to use CUBE as a power tool for “data cleaning”. This has been achieved with a flexible implementation of the CUBE algorithm in the Fledermaus software, where it has been combined with the PFM spatial data structure and intuitive 3D visualisation environment. This provides a close coupling of the 3D analysis of surfaces and soundings, and direct access to the soundings, for easy rectification of any problems. The flexibility also allows changing parameters and re-running of the CUBE algorithm only where necessary on sections of the data, noting the bathymetry and data do not normally allow a single set of parameters to be used throughout a typical survey.

The processing workflow used by NetSurvey produces the depth surface, and uncertainty estimates, and uses them in the next step to produce the traditional products. So transition to a workflow with the depth surface product will be simple, and only requires the removal of the last steps of filtering the sounding data. This approach also allows us to deliver the depth surface (BAG) and complete cleaned sounding data, and provides clients and organisations the option to assess the approach and gain confidence in the depth surface, and associated uncertainties, as a stand-alone product.

References