

# ALGORITHMIC IMPLEMENTATION OF THE TRIANGLE TEST FOR THE VALIDATION OF CHARTED SOUNDINGS

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## Abstract

*The selection of soundings to be shown on nautical charts is one of the most important and complicated tasks in nautical cartography. From the vast number of source soundings the cartographer is called to select all those important for the safety of navigation and to verify the “shoal biased” pattern of selection against the source soundings. A long-term goal of the cartographic community has been the automation of the tasks involved in nautical chart production, including that of the selection and validation of charted soundings. With the aim to contribute to that effort, this paper presents an implementation of the triangle test for the automated validation of selected soundings which has improved performance on the detection of shoals near depth curves and coastlines.*

**Keywords:** *Sounding selection, Data generalization, Nautical cartography, Computer cartography, Analytical cartography, Delaunay triangulation.*

## INTRODUCTION

The nautical chart “is a special-purpose map specifically designed to meet the requirements of marine navigation, showing depths of water, nature of bottom, elevations, configuration and characteristics of coast, dangers and aids to navigation” (IHO, 1994). The nautical chart is one of the fundamental tools in navigation used by mariners to plan and safely execute voyages. Due to its importance in navigation, the charts for the intended voyage are a mandatory carriage requirement (IMO, 2000) for compliance with Chapter V of the convention for the Safety of Life at Sea (SOLAS). Charts are issued by the authorized national hydrographic office (or other relevant government institution) supported by the standards published by the International Hydrographic Organization (IHO).

The nautical chart, as with every other map product regardless of how detailed it is, is an abstract representation of the real world. The selection of features for inclusion on charts and their representation is driven by the purpose and the scale of the chart (e.g., berthing, approach, coastal). Two of the most important features always shown on charts are those of depth curves and soundings which are used for the representation of the submarine relief.

The charted depth curves and soundings are derived from a more detailed dataset, either the survey data or a larger scale chart, with generalization. The cartographer generates the depth curves by generalizing the depth contours delineated on the source data, and then selects the soundings that complement the generalized curves in maintaining and emphasizing the morphological details and characteristic features of the seafloor. The final step is the validation of the “shoal biased” pattern of selection which is achieved with the “triangular method of selection”, where (IHO, 2017):

1. No actual sounding (hereinafter: source sounding) exists within a triangle of selected soundings which is less than the least of any of the soundings defining the edges of the triangle (hereinafter: triangle test); and
2. No source sounding exists between two adjacent selected soundings forming an edge of the triangle which is less than the lesser of the two selected soundings (hereinafter: edge test).

To perform the above tests, the cartographer typically generates a network of non-overlapping triangles for the set of selected soundings, i.e., a Triangulated Irregular Network (TIN). There are many ways for generating a TIN from a set of planar points, however it makes more sense for the cartographer -and the mariner, who mentally performs the triangulation in order to interpolate depths in the area- to form triangles from near rather than distant soundings and to refrain from creating “skinny” triangles. Clearly, paraphrasing Tobler’s first law of geography (Tobler, 1970), near soundings are more related than distant soundings and that must be taken into consideration for the triangulation. The triangulation that reduces skinny triangles is that described by Delaunay (1934) characterized by the empty circle criterion. Another advantage of Delaunay triangulation is that the topology of the triangulation is unique for a given set of generating points, with the exception of degeneracy which occurs in the presence of four or more co-circular points.

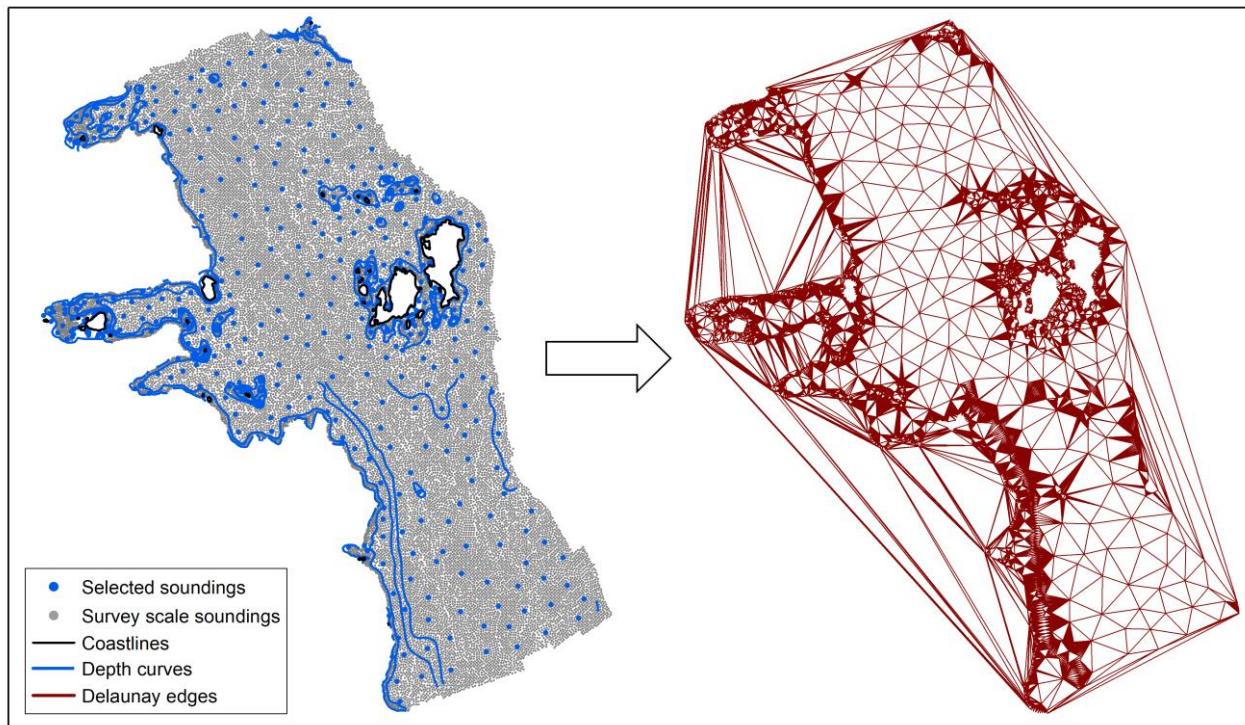
The selection and validation of charted soundings is a process tedious, time consuming and prone to human error. To date, many advances have been made towards the automation of those and other generalization tasks (e.g., Zoraster and Bayer, 1992; Tsoulos and Stefanakis, 1997; Du et al., 2001; Zhang and Guilbert, 2011; Wilson et al., 2016; SCALGO, 2017). These efforts have significantly improved the cartographers’ work and have transitioned nautical charting from a manual to a semi-automated process consisting of tools that require some level of human involvement. For some of the generalization tasks involved in nautical cartography it is questionable whether automation can replace human thought processes (see e.g., Ungvári et al., 2013), but concerning the validation of selected soundings a fully automated solution seems feasible.

In the context of a developing project that includes the study of features portrayed on published nautical charts and the software implementation of long-standing cartographic practices of hydrographic offices, this paper presents an algorithmic implementation of the triangle test for the validation of selected soundings. For the triangulation and the validation process, the proposed implementation incorporates the entirety of the available bathymetric information which, as this paper presents in the following sections, results in increased performance near and within depth curves and coastlines.

## IMPLEMENTATION & RESULTS

This Section presents the algorithmic implementation of the triangle test in the Python programming language utilizing the computational geometry structures of Delaunay triangulation and its dual the Voronoi diagram. For the evaluation of the proposed solution a case study is used with data provided by the NOAA/Office of Coast Survey covering an area of 58km<sup>2</sup>. The dataset comprises of 407 selected soundings for validation, 175 closed and floating depth curves and coastlines, and 28,516 source soundings (it is noted that modifications have been made to the latter so that the various cases described within this section can be examined).

1. Import the selected soundings and the features that will be used for the validation (Figure 1). In detail:
  - a. The selected soundings to be validated.
  - b. The linear features that are used for the representation of the bottom configuration and the adjacent coastal areas, e.g., depth curves and coastlines (hereinafter: curves).
  - c. The source soundings.
2. Determine the succession of depth curves in the area for later use. For the dataset of step (1b) the succession of curves is 0m, 5.4m, 9.1m, 18.2m, 91.4m, and 182.8m (it is noted that these values are the metric equivalent with decimeter precision of the charted curves in US standard units, i.e., 0ft, 18ft, 30ft, 60ft, 300ft, and 600ft).
3. Extract the vertices forming the curves of (1b). The extracted vertices must inherit the depth and id information of their curve of origin.
4. Merge vertices of step (3) with the selected soundings of (1a). The resulting point features dataset constitutes the set of generators for the Delaunay and Voronoi tessellations.
5. Generate the Delaunay triangulation for the set of generators (Figure 1).



*Figure 1: The input features and the Delaunay triangulation for the set of selected soundings and the vertices forming the depth curves and coastlines.*

6. Select the Delaunay triangles that contain source soundings (the purpose of this step is to reduce the number of spatial queries in the following steps).
7. Iterate through the subset of Delaunay triangles and for each triangle  $D_i$  do the following:
  - a. Select the source soundings within  $D_i$  (Figure 2).
  - b. Compare the depth of the selected survey soundings to the least depth value  $d_{\min}$  of the three generators (i.e., the three Delaunay vertices) of  $D_i$  (e.g., in the case of the triangle of Figure 2,  $d_{\min} = 66.3\text{m}$ ). When a source sounding  $s_i$  is shoaler than  $d_{\min}$ , examine the id of the curve of origin for the three Delaunay vertices of the  $D_i$ :
    - (1) If all three vertices do not have the same id of origin (i.e., they do not comprise part of the same curve),  $s_i$  is shoaler than what the mariner would expect by interpolating the depth information in the area and, therefore,  $s_i$  is stored in a dataset containing the confirmed shoals (hereinafter: flags). For example, the soundings 56.7m and 61.8m are two confirmed flags (these are shown in red in Figure 2).
    - (2) If all three vertices have the same id of origin (i.e., they comprise part of the same curve), the triangle  $D_i$  is “flat” and further investigation is required to determine whether  $s_i$  is an actual flag (hereinafter: candidate flag). It is noted that a triangle is “flat” when all three vertices defining the triangle have the same depth value but within the context of this work the term is used specifically for the triangles generated by vertices extracted from the same curve. As shown in Figure 3, flat triangles can be generated on both sides of a curve; soundings within triangles on the shallow-water side of a curve (cyan “SW” area in Figure 3) are expected to be shoaler than the depth value of the curve (but may also be deeper), whereas soundings on its deep-water side (yellow “DW” area) must only be deeper. The source sounding  $s_i$ , along with the id of curve of origin, is stored in a dataset containing candidate flags.

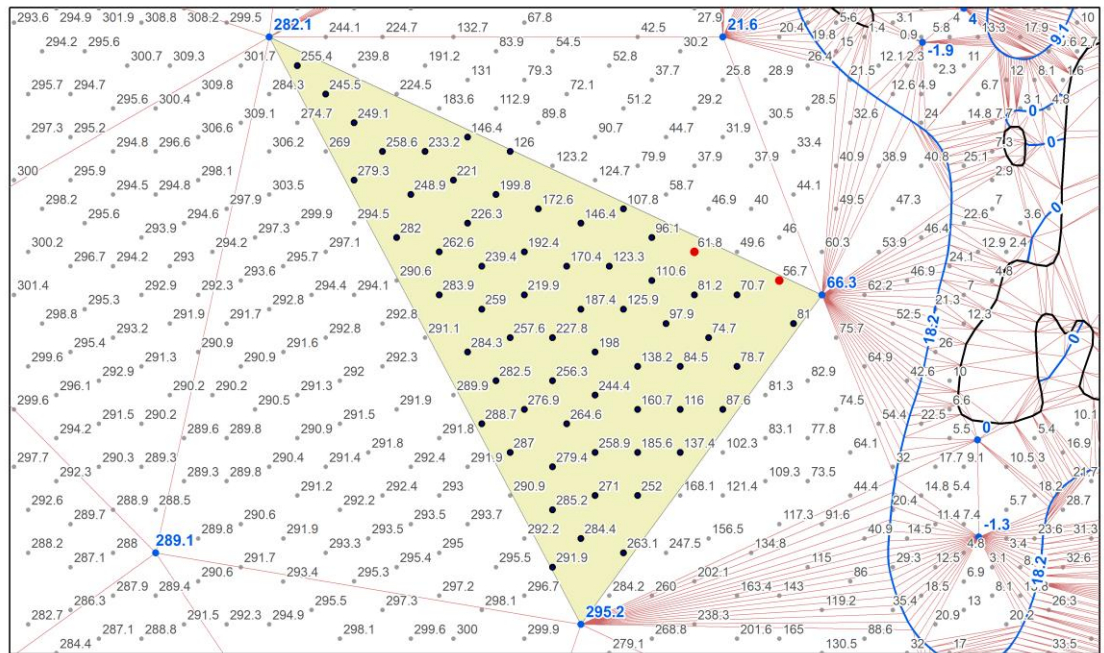


Figure 2: Within each triangle, the triangle test identifies the source soundings that are shoaler than what the mariner would expect by interpolating the depth values of the three vertices defining the triangle.

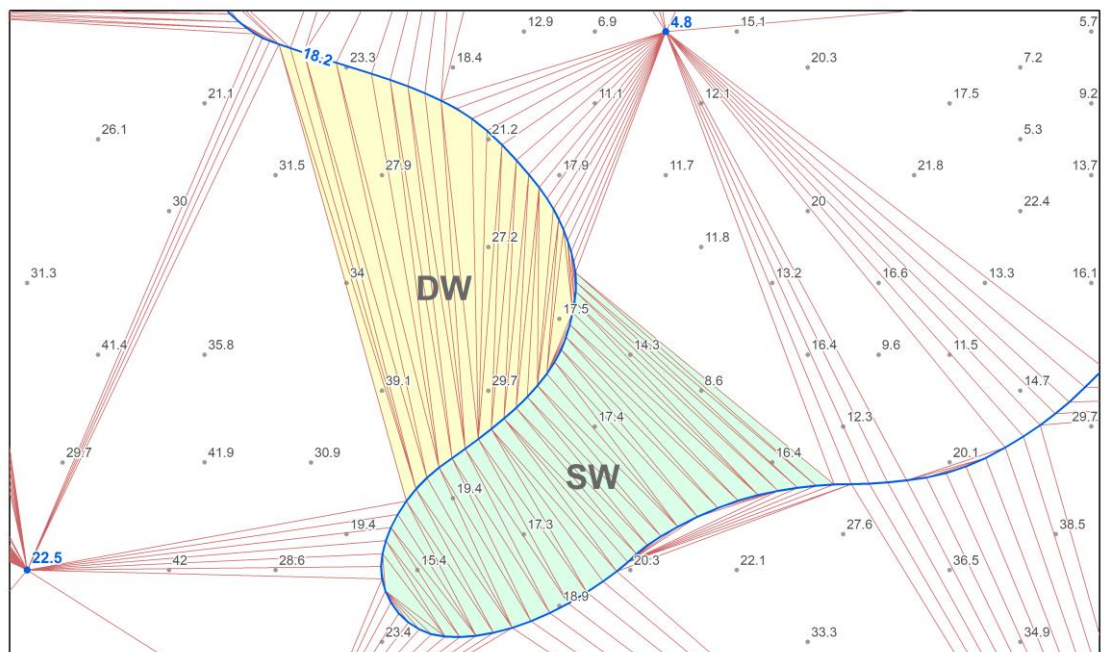
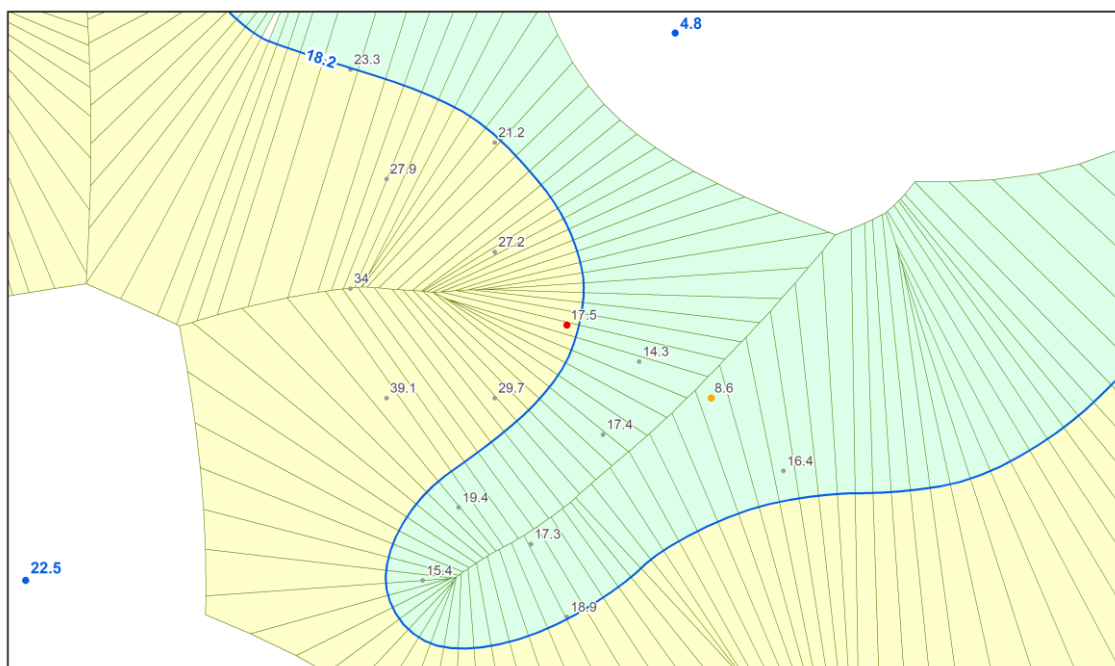


Figure 3: Shoal soundings within flat triangles require further investigation in terms of their location relative to the curve before characterizing them as actual flags.

8. Generate the Voronoi diagram for the set of generators of step (4). The resulting Voronoi polygons will be used for the evaluation of candidate flags found in step [7b(2)].
9. Split Voronoi polygons by the polylines of step (1b). After splitting the Voronoi polygons generated in step (8), polygons on one side of a curve can be selected and the location of the candidate flags of step [7b(2)] relative to the curve can be examined.



10. Evaluate the candidate flags of step [7b(2)] for their position relative to the curves that generated the flat triangles. The candidate soundings on the shallow-water side of the polyline are, as previously explained, expected to be shoaler than the curves's assigned depth value and will not be flagged, whereas those on the deep-water side of the curve will be flagged. In detail, for each id of curve in the list of candidate flags, the algorithm performs the following:
  - a. Select the split Voronoi polygons of step (9) on the shallow-water side of the corresponding curve.
  - b. Select the candidate soundings within the selected Voronoi polygons. Remove the soundings in the selection from the list of candidate flags, except those shoaler than the depth of the next shoaler polyline in the chart [based on the succession of depth curves determined in step (4)]. These soundings indicate a discontinuity of the succession of depth curves in the area and must be brought to the attention of the user for the digitization of the respective curve. Figure 4 illustrates the results of the validation for the flat triangles of Figure 3. The candidate soundings in grey color are not flags, the one in red (17.5m) is located on the wrong side of the curve and therefore is flagged, whereas the sounding in orange (8.6m) is located on the shallow-water side of the curve but, due to the absence of a depth curve 9.1m surrounding it, constitutes a warning for the cartographer.



*Figure 4: A confirmed flag (17.5m) on the deep-water side of a curve and a warning on the shallow-water side of it (8.6m) The sounding 8.6m is returned as “warning” to the user due to the absence of a contour 9.1m surrounding the sounding.*

11. For the remaining candidate flag soundings (if any), the procedure described in step (10) is repeated, but, instead of the Voronoi polygons, the Delaunay triangles generated in step (5) are now utilized. With the Voronoi approach described in step (10) candidate flags on the shallow-water side of the curve under investigation but not within the Voronoi polygons generated by that curve (thus within the Voronoi polygon of a selected sounding) would not be selected and evaluated. With the completion of this step, all candidate flags of step [7b(2)] will have been evaluated.
12. Export results, i.e., the source soundings that are shoaler than what the mariner would expect with interpolating the bathymetric information in the area (i.e., confirmed flags) and the warning soundings which imply the discontinuity of depth curves in the area (Figure 5).

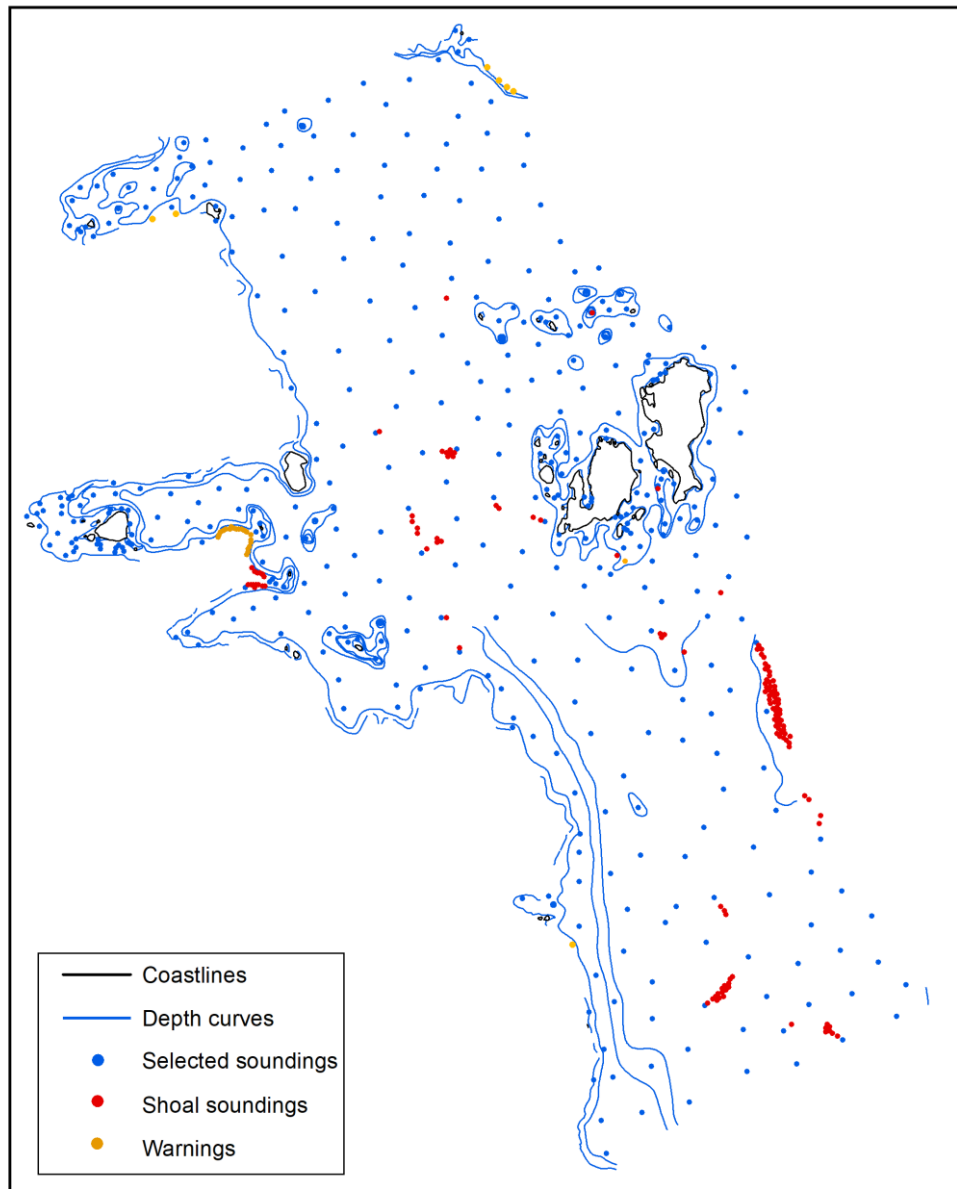


Figure 5: The confirmed flags and warning for the study area.

## DISCUSSION & FUTURE WORK

- The direction of the curves constitutes a constraint for the current implementation. More precisely, it is assumed that curves have been digitized so that the deep water lies on the left side of the curves in traversal order and the shallow water (or land) on the right side. The direction of the digitization is important for the distinction between deep-water and shallow-water in the evaluation of candidate flags. However, in future implementation the direction of each curve will be determined prior to the evaluation of candidate soundings and will no longer constitute a constraint.
- With incorporating the entirety of the available bathymetric information, as this is derived from the selected soundings and the vertices forming the depth curves and coastlines, the soundings shoaler than what the mariner would expect and the soundings indicating the discontinuity of depth curves in the area are successfully identified and flagged (Figure 5). Moreover, as illustrated in Figure 6, the current implementation eliminates false errors near and within curves which would be found utilizing the selected soundings only (Figure 6a) or the selected soundings and part of the bathymetric information from curves (Figure 6b). However, the evaluation of selected and source soundings near the limits of the area in question remains unsatisfactory. In future work, the charted soundings from the adjoining charts will be used for the evaluation and validation of the selected soundings in the studied area.

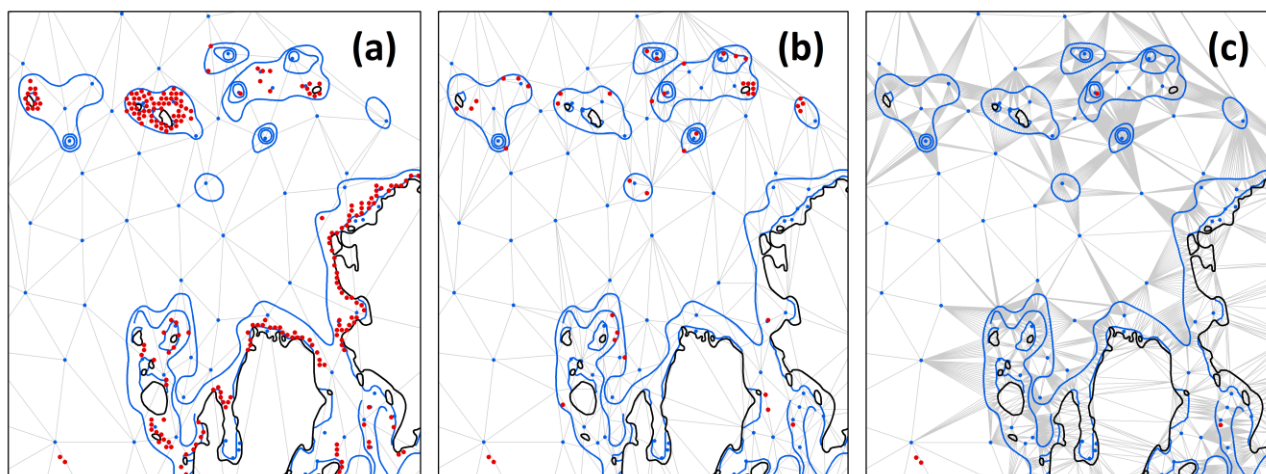


Figure 6: (a) The triangle test using only the selected soundings for the triangulation, (b) The triangle test with incorporating part of the bathymetric information from contours, and (c) the proposed implementation which incorporates all the available bathymetric information from the selected soundings, depth curves, and coastlines.

- As described in the Introduction, a shoal biased pattern of soundings selection is achieved through the triangle and edge tests. The implementation of the edge test and other validation tests that are necessary to achieve the overarching principle that no depths shoaler than the mariner would expect by interpolating the depth in any position from the charted soundings and curves, will be considered in the future.

## CONCLUSION

This paper presented the implementation of the triangle test for the validation of the soundings selected by the cartographer to be shown on the nautical chart. For the triangulation, besides the selected soundings, the vertices forming the depth curves and coastlines in the area are utilized. By incorporating the bathymetric information from the depth curves and coastlines, the proposed solution detects shoals and eliminates false positives near and within curves, thereby increasing significantly the areas that are automatically validated. Lastly, this paper discussed the constraints of the current implementation and the way forward towards a fully automated solution for the validation of soundings including the areas near the limits of the surveyed area.

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## BIOGRAPHY

Christos Kastrisios graduated from the Hellenic Naval Academy (HNA) in 2001 with a B.Sc. in Naval Science. After his graduation he served aboard frigate HS Aegean and submarines HS Protefs and HS Poseidon, mostly as the navigator and sonar officer, and participated in several deployments at sea. In 2008 he was appointed to the Hellenic Navy Hydrographic Service where he served in various positions. He holds a master's degree in GIS from the University of Maryland at College Park and a Ph.D. in Cartography from the National Technical University of Athens (NTUA) for his work on the scientific aspects of the Law of the Sea Convention. From 2014 to 2017 he worked as a part-time lecturer in GIS and Cartography at the HNA and NTUA. In September 2017 he started employment at the CCOM/JHC as a post-doc researcher focusing on data generalization and computer nautical cartography.

Brian Calder is the CCOM/JHC's Associate Director. He has a Ph.D. in Electrical and Electronic Engineering, completing his thesis on Bayesian methods in Sidescan Sonar processing in 1997. Since then he has worked on a number of signal processing problems, including real-time grain size analysis, seismic processing, and wave-field modeling for shallow seismic applications. His research interests include methods for error modeling, propagation and visualization, and adaptive sonar backscatter modeling. His work has focused on developing methods for textural analysis of seafloor sonar data, as well as exploring innovative approaches to target detection and seafloor property extraction. Dr. Calder is currently focusing on statistically robust automated data cleaning approaches and tracing uncertainty in hydrographic data.