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Sailing the Rough Seas of Automated Electronic Navigational Charts Compilation

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Abstract: Advancements in geospatial technology have benefited the hydrographic and maritime professions in many ways. Yet, compared to hydrographic data collection and processing, chart compilation workflows remain relatively slow, mainly due to limited human resources and the availability of automated algorithms that respect nautical charting constraints and Electronic Navigational Chart (ENC) database requirements. This work presents our research efforts to streamline the nautical chart compilation process through the introduction of automated processes and improving the efficiency and accuracy of existing. Among these processes are fundamental generalization tasks such as those for soundings, islands, and depth contours; ENC product specific requirements, such as those for reducing file size through the removal of collinear vertices forming polylines and polygons; and the updating of dependent features in the ENC database after generalization of one of their shared geometries.

Keywords: Cartographic Generalization, Computational Cartography, Nautical Cartography, ECDIS, ENC

1. Introduction

Accurate and reliable nautical charts are essential to seafarers whether for commerce, defence, fishing, or recreation. Developments in information technology have led to the use of electronic charts on ships' bridge, first with raster versions of paper charts and later with the vector Electronic Navigational Charts (ENCs). The benefit of ENCs is that they allow users of the dedicated onboard Electronic Chart Display and Information Systems (ECDISs) to customize chart display, easily plot and monitor routes, utilize data layers to perform safety related tasks, and provide warnings based on the ship's own characteristics. Another advantage of ENCs is the ease of distributing and applying chart updates, contrary to the tedious manual paper chart update process.

Likewise, advancements in hydrographic data collection systems and processing algorithms have contributed significantly to our knowledge about the seabed and updating of chart suites in support of navigation safety. Data collection for nautical charting and ENC compilation, production, and dissemination follows guidelines published by the International Hydrographic Organization (IHO) (an overview in Kastrisios et al., 2022). This ensures consistency among charts regardless of the producing national Hydrographic Office (HO), thus simplifying international shipping and promoting navigational safety.

On the other hand, the increased speed that new surveys are delivered to charting organizations, combined with limited human resources, leads to a bottleneck situation where new data may wait for months before they are assigned to a cartographer for compilation. Even when a source is assigned for compilation, it undergoes processes that are predominantly manual, which can be tedious, time-consuming, and prone to human error. This has been largely due to the absence of automated algorithms and workflows for various generalization tasks. Furthermore, research efforts that have tried to automate algorithms and workflows are not readily available or do not fully satisfy fundamental application constraints and/or ENC database requirements set forth by IHO standards (e.g., file size, polygons-lines topological relations).

Towards facilitating chart compilation workflows and safety of navigation efforts in nautical chart compilation, we have been researching several compilation tasks. These efforts include: (1) fundamental generalization tasks for the safety of navigation application related to soundings, islands, and depth contours; (2) ENC product specific requirements such as those for reducing the file size through the removal of collinear vertices forming polylines and polygons; and (3) the incorporation of algorithms in the workflows through automatically updating the dependent feature classes in the database.

2. Background Information

One of the crucial and time-consuming generalization tasks is that of sounding selection, i.e., the selection of spot depths that are used with the other charted information to illustrate the seafloor characteristics. Sounding selection is one of the most explored generalization tasks in nautical cartography (see, e.g., (Du et al., 2001; Jingsheng & Yi, 2005; M. Li et al., 2021; Lovrinčević, 2017; Skopeliti et al., 2020; Sui et al., 1999; Tsoulos & Stefanakis, 1997). Ideally, that task should be accomplished with the least number of soundings necessary to avoid clutter and ensure readability. Maximum and minimum depths, hereinto referred to as prime soundings, should always be shown. This includes least depths over shoals, banks, or bars in navigable channels as well as lines of deepest depths for navigation in narrow passageways. Appropriate soundings must also be selected to illustrate changes in bottom slope away from least depth, shoal, and deep soundings, referred to as supporting or background soundings. Lastly, the so-called, fill soundings are used to portray seabed between widely spaced depth contours and where seafloor is smooth. In the sounding selection process, it is essential that other chart features are taken into account to achieve the necessary representation of the seafloor while avoiding overplot and crowding the chart.

Another task of high importance for nautical cartographers is that of depth contour generalization, which also receives much attention for atuomation (see e.g., the works by (J. Li et al., 2018; Miao & Calder, 2013; Peters et al., 2014; Skopeliti et al., 2021). Depth contours complement soundings in representing seafloor characteristics. To ensure safety of navigation, generalized depth contours must be displaced toward deeper-water. Depth contours are the shared geometries of depth areas in ENCs. Traditionally, they are derived manually by employing a combination of generalization operations such as simplification, smoothing, aggregation, and exaggeration. In producing generalized contours in an automated manner, two paradigms exist: generalizing the source surface and extracting the contours from the generalized surface; and extracting the contours from the source surface and subsequently generalizing the vector polylines to the chart scale. The former provides an intrinsic form of feature simplification and aggregation; however, there is no apparent correlation between the level of surface generalization (number of iterations) and the target scale, which makes it difficult to determine the seaward displacement of the contours and level of generalization in areas of different seabed slopes. As such, shallow areas in confined waters can be transformed into non-navigable waters (0-depth contours). On the other hand, working with vector lines can be computationally efficient but may result in self-line and inter-line crossings.

The continuous representation of seabed through the succession of coastlines and depth areas on charts is essential for smooth operation of ECDIS. Depth areas are utilized by ECDIS, along with the vessel's characteristics (e.g., draft, squat) and other situational information (e.g., tides), to separate safe areas from those unsafe to navigate. Except for the geographical situations where abrupt changes are expected (e.g., in the crisp boundaries of shoreline constructions or dredged areas and the adjoining depth areas), the sea-bottom surface should be smooth and continuous (i.e., in the fuzzy boundaries of two depth areas or a depth area and the shoreline). Any error in their compilation is carried over to the analysis performed by ECDIS. If seabed continuity is not achieved on charts, waters may be portrayed deeper, thus posing a risk to the vessel navigating them, or may appear shallower, thus triggering meaningless ECDIS alarms contributing to what is known as "mariner's deafness".

The charted bathymetry must not give mariners the false impression that the expected water depth, at any location, is deeper than the source information. This is referred to as the safety constraint and is crucial for safe navigation. According to IHO guidelines, this is achieved through the "triangular method of selection" (IHO, 2021), specifically through two tests, the "Triangle" and "Edge" Tests. For the triangle test the cartographer verifies that, within a triangle of selected soundings, no source sounding is shallower than the least depth of the triangulated soundings. Likewise, for the edge test, no source sounding may exist between two selected soundings shallower than the least of the two selected soundings forming an edge of the triangle. The limitation of the two tests is that source soundings in high-resolution datasets may satisfy the two tests, yet they can significantly deviate from the expected (interpolated) depth.

Another generalization task is that of land, including islands and coastlines (see e.g., the works by (Skopeliti et al., 2021; Yang et al., 2018; Zhang et al., 2019). Land is one of the prominent geo-features in ENCs for marine navigation and passage planning. The process typically begins by prioritizing islands with areas and/ or dimensions surpassing a set threshold. Subsequently, the remaining islands are selected with the aim to maintain the distribution range and extension direction. Another key objective is to preserve the shape characteristics of the original feature as much as possible. Furthermore, the spatial relationships with relevant chart features, (e.g., dredged areas, recommended tracks, lights and other aids to navigation) must be respected. Also, minimum separation distances for legibility must be maintained.

Besides tasks crucial for creating nautical charts in support of the safety of navigation listed above, adhering to specific ENC database requirements (see (IHO, 2014, 2020)) are also time consuming and can cause frustration to cartographers during compilation. A characteristic example is the file size requirement, as this is expressed through maintaining a minimum length of straight-line segments forming polylines and polygons and removing collinear vertices along these polylines and polygon boundaries. In detail, per ENC requirements, straight-line segments must be longer than 0.3mm at the compilation scale. Although not a critical error in the context of the ENC validation process for the smooth operation of ECDIS, cartographers invest considerable time to reduce this redundant information in ENC data. The database requirements pose a challenge for the incorporation of previous automation efforts into the chart compilation workflows. For example, depth contours generalization algorithms can result in an excessive number of vertices, generally higher than the source polyline's, with length of segments below the ENC requirement. Although many of the algorithms perform well and produce aesthetically pleasing results, the cartographer would need to manually simplify their outputs making these algorithms ineffective in an operational setting.

Another compilation task includes the generation of the polygons that hold the Category Zone of Confidence (CATZOC) information. CATZOC classifies bathymetric data in terms of quality and the confidence that a national charting authority places in them. The data is categorized through six categories based on horizontal and vertical uncertainties, achieved seabed coverage, and feature detection. The ENC is divided into polygons encoded with the meta-object Data Quality Polygon (M_QUAL) with each polygon assigned the CATZOC that meets all the respective criteria of the category. Currently, deliverables of a new survey include the survey polygon, normally a gridded polygon generated by the grids containing depths. Cartographers are called to manually perform the simplification of the survey polygon for generating the ENC M_QUAL polygons.

The overarching challenge cartographers face in the use of available generalization tools is that they may be applied to one feature class each time and without considering the topological relationships among features (e.g., depth contours with depth areas, sea areas, and data quality polygons). If they are run separately on dependent geometries, generally, they affect different vertices among the features. This necessitates manually modifying dependent geometries to maintain topology. Automation of this and the above tasks can benefit charting authorities in their efforts to keep charts up to date.

3. Automation Efforts

3.1 Generalization Efforts

3.1.1 *Bathymetric Change Detection*

To facilitate the prioritization of registered datasets for compilation by charting organizations, this research effort investigated methods to illustrate how bathymetry changed compared to the existing chart. For that, the algorithm builds a model of the seabed from the chart features carrying bathymetric information (soundings, depth contours, shorelines, wrecks, rocks, etc.), referred to as the nautical surface, which is subsequently compared to the seabed surface as represented in the new survey. The output is a color-coded layer of the source soundings, as illustrated in Figure 1. When a new survey demonstrates significant bathymetry change, it may be assigned a higher priority by lead cartographers, whereas a survey similar in bathymetry to what is already portrayed on the chart may be assigned a lower priority. Also, the bathymetric change tool may be used to assist a manual selection of soundings with highlighting the areas that require the cartographer's attention.

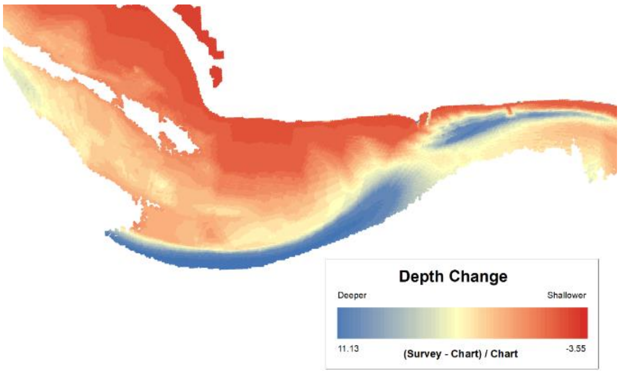

Figure 1. Example of bathymetry change between existing charted bathymetry and new survey.

3.1.2 *Spot Soundings Selection*

This research effort focused on automating the sounding selection task, separating the problem into two distinct processes: the hydrographic and cartographic sounding selections. The hydrographic selection is the process of deriving, from the source survey the maximum number of soundings that can be displayed at the target scale without sacrificing sounding legibility and is meant to facilitate the subsequent final selection for charting. For the hydrographic selection, the method utilizes the label footprint at scale and shoal-bias, while it ensures legibility by maintaining a minimum separation between soundings based on human perception limits (Dyer et al., 2022). Figure 2 illustrates an example of the hydrographic sounding selection derived from a high-resolution survey using our label footprints and shoal-biased.

The cartographic sounding selection process leverages the digital surface model of the bathymetry and the cartographic portrayal of features on ENCs (Dyer et al., 2024). The near ENC-ready sounding selection is extracted from variable quality multi-source bathymetry data using a hierarchy and taxonomy of soundings, current ENC characteristics and features, and cartographic constraint correction procedures to enforce shoal-bias. This approach results in zero safety violations (see Section 3.4 for safety constraint), the most important for safe navigation, and minimizes legibility violations. Moreover, the incorporation of ENC bathymetric features (rocks, wrecks, and obstructions) affecting sounding distribution and calculating metrics from current chart products produces a selection complementary to the specific waterways of the chart area.

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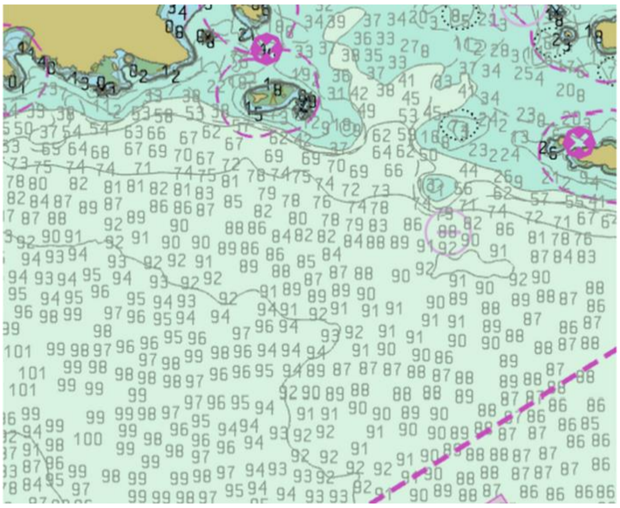

Figure 2. Example of the hydrographic sounding selection from a high-resolution survey.

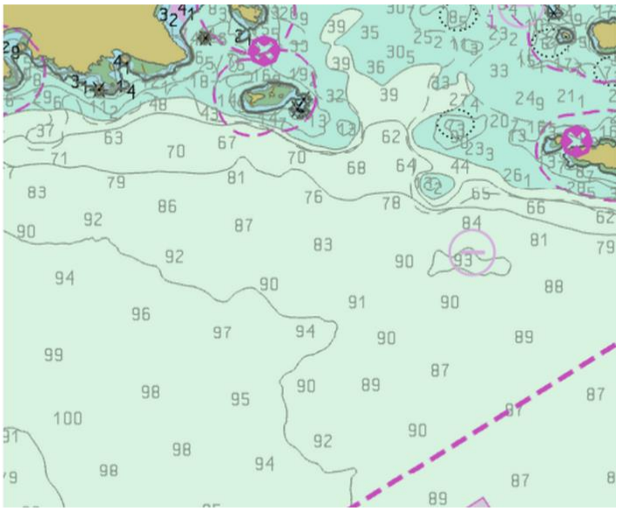

Figure 3. Example of the cartographic sounding selection.

ENC soundings are defined as least depth, shoal, deep, supportive, and fill. Least depth, shoal, deep, and supportive soundings indicate unexpected local depths and changes in seafloor slope and correspond to the critical points of a bathymetric surface model. Fill soundings have been traditionally selected to simply fill gaps between other selected soundings and depth contours, where this work instead follows both aesthetic and data driven criteria to select fill soundings. Fill soundings are selected by first applying a variable-radius generalization, followed by a refinement based on a given safety constraint validation test. Following, the initial selection is assessed based on safety and legibility constraints, and all safety violations are eliminated while minimizing any issues with legibility. This process leads to the following workflow: (1) Critical point identification; (2) least depths selection; (3) generalization leveraging the cartographic representation of features; (4) Shoal, deep, and supportive sounding selection; (5) Fill sounding selection; and, (6) Assessment and correction of cartographic constraint violations. Figure 3 illustrates an example of the final set of soundings for charting.

3.1.3 *Depth Contours Generalization*

For the generalization of depth contours, the developed algorithm leverages line deviation angles to force the generalized line to move seaward (Kastrisios, 2025). In detail, after identifying the deep-water side of the line, it evaluates the azimuth change between source and candidate baselines (generalized segments) to (safely) eliminate line vertices (Figure 3). Furthermore, it shifts appropriately selected vertices to ensure that line segments are longer than 0.3mm at scale per ENC requirements and to enforce the safe generalization of convex bends, something that available depth contours generalization algorithms struggle with.

The algorithm utilizes a tolerance to limit the displacement of the candidate baseline from the source line (vertices). This prevents the unbound conversion of deep waters into shallower waters, thus avoiding the issue discussed in the Background Section with the surface-based techniques. Furthermore, to avoid visual coalescence of two parallel segments, a minimum distance between parallel straight-line segments is maintained. Essentially this also serves as the minimum opening of mouth of bends. Bends with an opening smaller than this tolerance and larger than a user-defined size are generalized and retained in the output as new closed deep contours. Contrary to other approaches that compare the area or dimensions of a bend to a given tolerance (size, or length and width), this approach incorporates an "inscribed circle" criterion where a bend is sufficient in size if a defined circle fits within the bend. This ensures that the retained bend is not elongated and narrow. Furthermore, for the bends that do not meet the inscribed circle (size) criterion but are long enough to (visually) affect the line, the algorithm generates two safe segments within the bend to retain the trend of the line in the output. An example of a depth contour generalized through scales is illustrated in Figure 4.

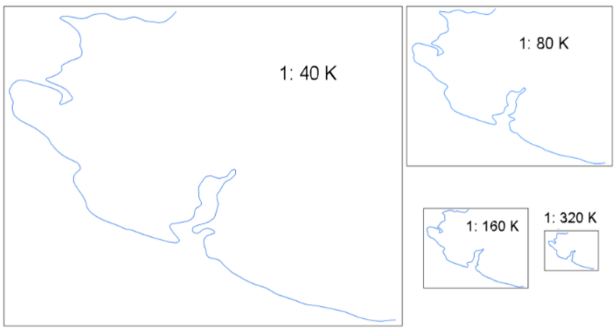

Figure 4. Sample 1:40,000 contour generalized through scales using the developed algorithm.

3.1.4 *Islands Generalization*

The method for the generalization of islands utilizes the benefits of the Voronoi diagram and buffer rings, while it also involves shape recognition based on island dimensions and location (Nada et al., 2025). The method begins with classifying land masses into large (large islands and mainland) and small islands based on size. Subsequently, with evaluating the intersection between their Voronoi diagram and buffer rings, small islands are classified into islands near large land masses and isolated

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islands. Isolated islands are retained in the output as they present navigational significance. Isolated islands smaller than a minimum size tolerance are exaggerated to the minimum size for the target scale. Small near-islands with dimensions below a predefined tolerance are collapsed to points. Those that exceed the dimension tolerance and are closer to larger islands than a near distance threshold, are amalgamated with the mainland or larger islands. In the above processes, the algorithm incorporates relevant chart feature classes (e.g., recommended track as illustrated in Figure 5) to respect topology relations.

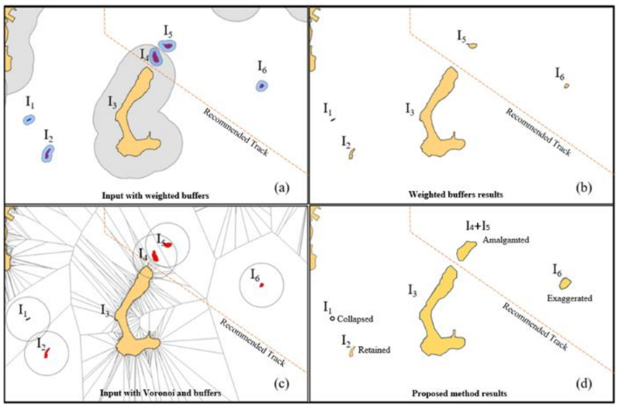

Figure 5. (a) Input data with influence domain buffers (b) Influence domain results (c) Input data with their Voronoi diagram and scale buffers (d) the proposed method results.

3.1.5 *Quality Polygons Simplification*

The quality polygon simplification algorithm aims to simplify the outline of gridded survey polygons.

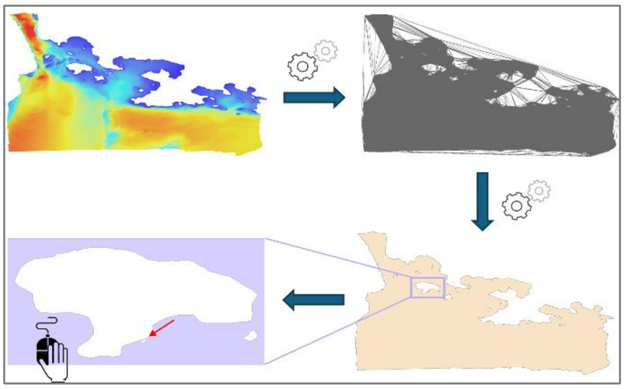

Figure 6. The process from survey data to simplified ENC data quality polygons.

The process begins with computing the Delaunay triangulation of the survey points. Accordingly, calculates the centroids of triangles and removes those whose centroids do not intersect the raw survey polygon. The remaining triangles are dissolved and collinear vertices from the dissolved polygon are eliminated. Using the raster cell size as tolerance, data holes in the dissolved polygons are eliminated. Point density is below 0.3mm and vertical displacement of line segments are within half grid cell size. However, small holes may have been retained which necessitates visual inspection and manual fixing where necessary. Figure 8 illustrates the derived simplified version of the coverage polygon (purple polygon) form the gridded bathymetric surface (top left in Figure 6) after the processing steps described above.

3.1.6 *Collinear Vertices Removal*

For the removal of collinear vertices from linear and polygon ENC features, the algorithm iterates through vertices and removes candidate vertices if the distance of the new segment from the deleted vertex is less than the set collinearity tolerance. The removal of vertices is applied to all skin-of-the-earth ENC features (i.e., depth areas, dredged areas, land areas, un-surveyed areas, floating docks, hulks, and pontoons) and the dependent geometries of depth contours and coastlines (natural and man-made). The algorithm ensures that the same vertices are removed from the coincident geometries which is necessary for ENC compilation. The collinear vertex reduction tool does not include a shoal bias; however, the modifications to polylines are small enough at scale to have no negative effect on safety of marine navigation. The developed solution addresses the problem holistically, i.e., removing the collinear vertices from all ENC objects directly in the production environment (Figure 7), without the need for importing and exporting feature classes from and to the database. Also, it allows users to modify the collinearity tolerance, based on generalization level and file size reduction needs.

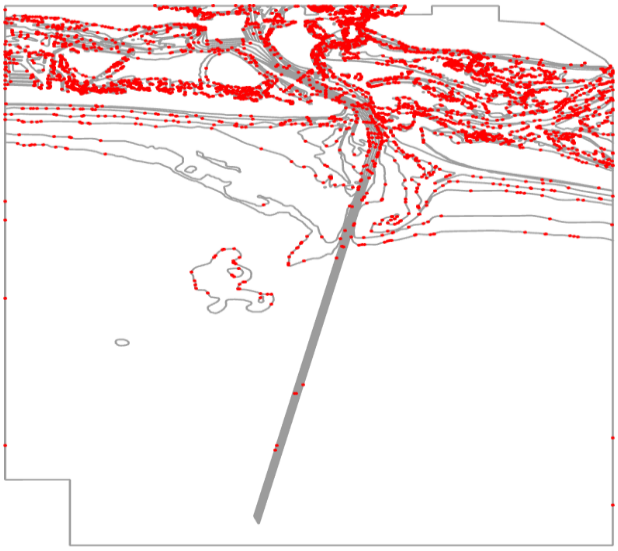

Figure 7. Example of deleted collinear vertices from all skin-of-the-earth ENC features (~4,900 unique vertices).

3.2 Validation Efforts

3.2.1 *Safety of Charted Bathymetry*

To facilitate validation of safely charted bathymetry in an automated manner, an implementation of the triangle test was developed with increased performance near and within depth curves and coastlines (Kastrisios et al., 2019a; Kastrisios & Calder, 2018), and the first automated implementation of the edge test described in the literature. The work showed the significance of the edge test in the validation process, as it identifies discrepancies that the triangle test fails to detect. It also revealed a fundamental, “intrinsic”, limitation of the two tests that prevents the construction of a fully automated solution based solely on these tests, regardless the

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implementation. In practice, the two tests use a gridding approach with an enormously large element. Each element is assigned the depth value of the shallowest of the two or three vertices forming the edge or triangle respectively and is compared to all source soundings within the specific element for the validation process, without considering the location of the source depths. Due to this, a sounding may pass both tests and yet deviate significantly from the expected depth in the area based on the charted bathymetric information.

As a solution, a new test was developed, which accounts for the configuration of the seabed at the appropriate charting resolution and captures the relevant discrepancies between the source and the charted bathymetric information (Kastrisios et al., 2019a, 2019b; Masetti et al., 2018). Unlike the triangle and edge tests, the surface test compares source soundings to the expected (interpolated) depth at the exact location of the source soundings. The output consists of the locations where interpolated depths appear deeper than the source soundings, symbolized with graduated symbols to illustrate the magnitude of the deviation from the source (as a percentage of depth) (Figure 8).

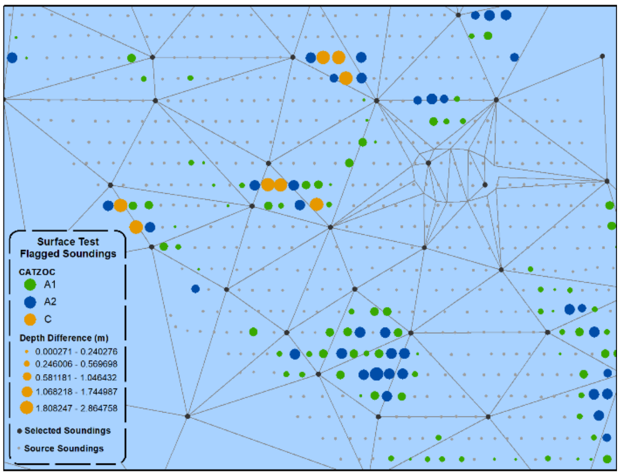

Figure 8. Soundings flagged by the surface test tool color and size coded for CATZOC depth deviation (where 1 in label represents 100% difference between the expected depth and source depth).

3.2.2 *Seabed Surface Continuity*

For the quality control of the vertical continuity of depth areas in ENCs, the developed solution follows an iterative approach (Kastrisios et al., 2020). First, it identifies the edges where discontinuities exist. For this, the algorithm incorporates objects, such as depth areas, land areas, depth curves, coastlines, and shoreline constructions, and determines their common geometries (i.e., edges) encoded with different depth values. Locations where discontinuities are expected (e.g., piers) are excluded from the error identification process. Subsequently, the algorithm iterates over the polylines and identify errors, while correcting for those that attribute changes fix or improve the current situation. Lastly, for the remaining errors, it makes changes to the geometry of the respective depth areas. The algorithm determines the areas of dominance of each edge (represented by their Voronoi polygons) with errors, which are provided as suggestions to cartographers for implementation with the recommended depth ranges (Figure 9).

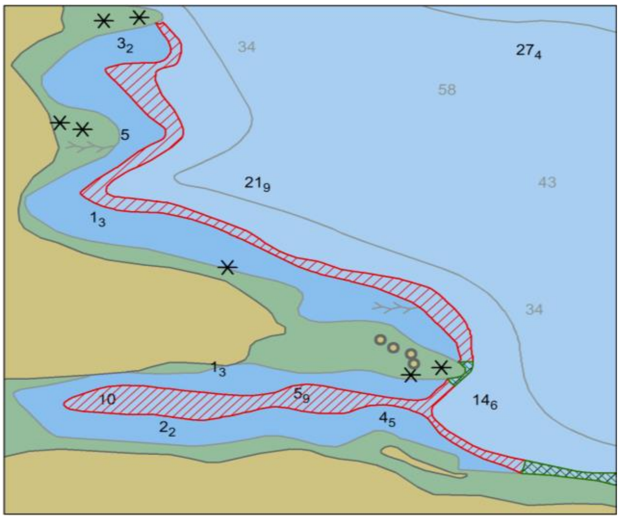

Figure 9: Example of a depth area previously encoded as 0-10m which is divided by the automated methodology into 4 areas of depth ranges 0-10m (in green) and 5-10m (in red).

3.3 Other Automation Efforts

3.3.1 *Combining and Generalizing ENCs*

This work assessed the viability of a fully automated nautical chart production workflow from larger scale ENC cells to one cell of the next smaller scale with no topology errors (Nada Tamer et al., 2024) (Figure 10).

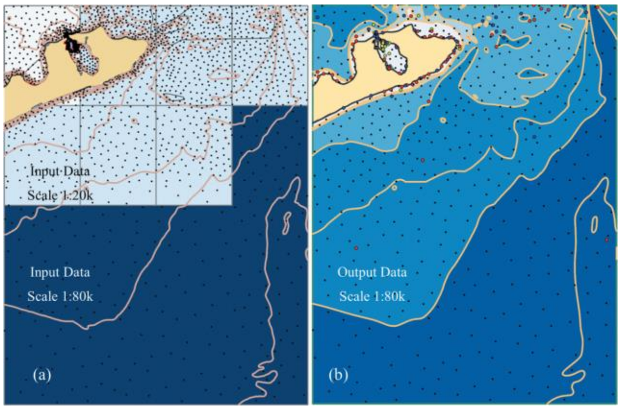

Figure 10. Example of seven 1:20K ENCs combined with one 1:80K ENC and generalized to the target scale with no topology errors.

Nautical chart generalization guidelines were extracted, categorized, and translated into machine readable rules, utilized by a multi-agent model to perform the generalization. Organized into five main phases, each phase of the Automated Nautical-chart Generalization model consists of various sub-models that employ generalization operations following a pre-determined sequence as defined into a Generalization Rules Spreadsheet (GRS). The GRS is the input that drives the data generalization for the desired output scale, using the available generalization algorithms and tools. It contains the required information about the selected feature classes for the target scale, their hierarchy, generalization tolerances, and operations that need to be applied.

3.3.2 *Updating Dependent Features*

This research effort investigated methods to facilitate the incorporation of individual generalization tasks into the production environments. Normally, research works focus on a generalization task without any consideration of the dependent feature classes. For example, any modification to a depth contour through a depth contour generalization algorithm generates the need for the adjustment of coincident depth areas, and/or coastlines, land areas, sea areas, M_QUALs, to name a few. The methodology developed in the context of this project is incorporated in the aforementioned projects, such as the Collinear Vertices Removal effort presented in Section 3.8 where all coincident Group 1 and dependent depth contours and coastlines are updated. Figure 11 illustrates an example of a depth area that has been modified following a change to the coincident depth contour.

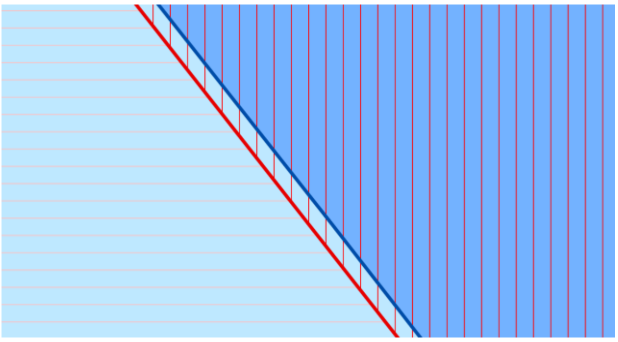

Figure 11. Example of depth areas auto adjusted to the modifications made to a depth contour (in red the before and blue the after the modification situation).

4. Concluding Remarks

The research projects presented in this paper comprise building blocks toward our overarching goal to reduce the data collection-to-chart update cycle through streamlining nautical chart production. Automating chart compilation tasks may ensure consistency among charts while allow cartographers to focus on the validation of the product, apply their cartographic expertise, and improve the aesthetics of the final product.

The benefits of the efforts described hereinto to automate chart compilation was demonstrated at an international charting competition organized by the Canadian Hydrographic Service, the Canadian Hydrographic Association, and the Canadian Ocean Mapping Research and Education Network in early 2022. Our team presented a semi-automated solution for the rapid processing of bathymetric and relevant data (Kastrisios et al., 2023) which received the first prize unanimously by all judges (Figure 12). The competition was an opportunity for the Team to apply research, identify deficiencies, make improvements, and test cartographic concepts on complete datasets into the greater context of chart compilation, rather than addressing each individual task in isolation, as it is normally the case for most research efforts. This included workflows/ algorithms for generalizing shorelines without topology errors, sounding selection, validation of results, and visualization.

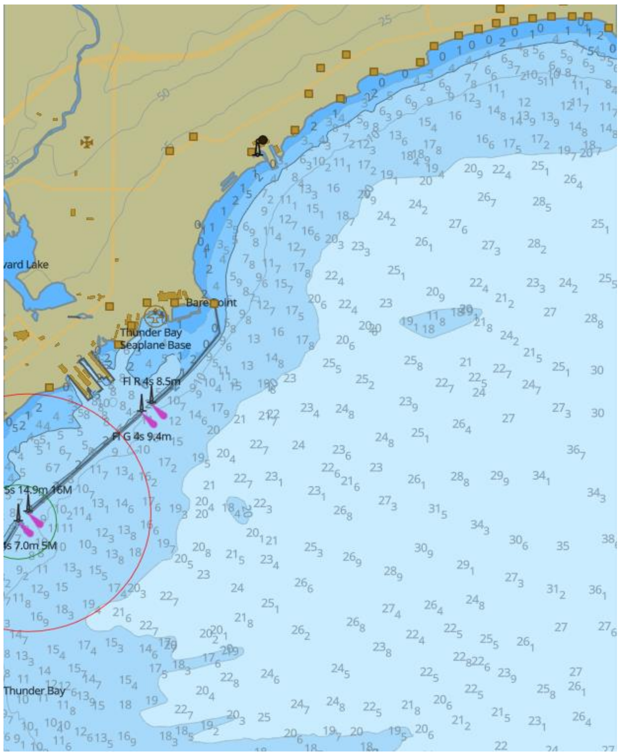

Figure 12. The output of our semi-automated workflow in Thunder Bay, Canada that won the 2022 Speed Mapping Challenge international charting competition.

Many of the efforts presented in this paper are already in use by and/or the Research to Operations phase with the National Oceanic and Atmospheric Administration/Office of Coast Survey, the USA's national charting authority. Future work includes making improvement to the presented algorithms, the incorporation of those not yet part of NOAA/OCS's workflows, and the development of automated solutions for other generalization tasks, such as those for the land topography, buildings and roads

5. Acknowledgements

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