INSPECTION AND ERROR REMEDIATION OF BATHYMETRIC RELATIONSHIPS OF ADJOINING GEO-OBJECTS IN ELECTRONIC NAVIGATIONAL CHARTS

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Abstract
Depth areas are utilized by the Electronic Chart Display and Information Systems (ECDIS) along with the vessel's characteristics (e.g., draft, squat) and other situational information (e.g., tides) for separating safe areas from those unsafe to navigate. Any error in their compilation is carried over to the analysis performed in the ECDIS. As a result, waters may be portrayed deeper, thus posing a risk to the vessel navigating them, or may appear shoaler, thus triggering useless ECDIS alarms which contribute to the situation known as "mariner's deafness". With the exception of crisp boundaries where abrupt changes are expected, the transition between depth areas should be smooth and continuous. In this paper we present a research toward a mechanism for identifying discontinuities and an error remediation approach that proposes changes to the encoded depth range and the geometry of depth areas with identified discontinuities, for the cartographer's attention.

Keywords: *ENC validation checks, Automated nautical cartography, Digital terrain modelling, Topographic surface, Nautical surface, Depth areas, Safety of navigation*

INTRODUCTION

The electronic navigational chart (ENC) contains essential information about the marine and coastal environment for the safe navigation of vessels. ENCs are loaded on shipborne Electronic Chart Display and Information Systems (ECDIS) that, besides displaying the information included in the ENCs, integrate navigation-related systems and sensors aboard ships, such as GPS, AIS, and RADAR/ARPA. ECDIS address limitations and dependencies of the traditional paper chart, such as the need to manually apply corrections and continuously plotting fixes (i.e., vessel's position), allowing the mariners to easily and accurately perform simple or composite tasks such as plotting the vessel's course or activating alarm functions when the vessel is in proximity to hazards (e.g., shallow waters) or impending dangers (e.g., collision course with vessel sailing alongside) (Kastrisios and Pilikou, 2017). With ECDIS, mariners have a complete picture of the instantaneous situation of the vessel and charted dangers in the area (Alexander, 2003).

The electronic chart is a database that consists of a set of point, linear, and polygonal features encoded using the chain-node topology (IHO, 2000). The spatial objects in the ENC are divided into two groups, namely Group 1 (known as the "skin of the earth") and Group 2 features. Group 1 features are the area-type geo-objects: DEPARE (depth area), LNDARE (land area), DRGARE (dredged area), UNSARE (unsurveyed area), FLODOC (floating dock), HULKES (hulk), and PONTON (pontoon). For Group 1 features, each area covered by a meta-object M_COVR (coverage) with CATCOV = 1 (i.e., that continuous coverage of spatial objects is available within this area) must be totally covered by a set of the above geo-objects that must not overlap so that the required topology is not violated.

To ensure that the topological structure of ENCs is valid, the IHO has developed a number of checks defined in Publication S-58 ENC Validation Checks (IHO, 2018). Software that performs S-58 validation (e.g., SevenCs Analyzer, ESRI ArcGIS for Maritime, Teledyne CARIS S-57 Composer, C-MAP dKart Inspector) provide reports for errors among the Group 1 and 2 objects of the ENC in question as well as errors with objects in the adjoining ENCs. The classification of errors is in three categories according to the risk they pose for the safety of navigation (i.e., *warnings*, *errors*, and *critical errors*). In detail, a *warning* is "an error which may be duplication or an inconsistency which will not noticeably degrade the usability of an ENC in ECDIS", an *error* "may degrade the quality of the ENC through appearance or usability but which will not pose a significant danger when used to support navigation", whereas a *critical error* "would make an ENC unusable in ECDIS through not loading; or causing an ECDIS to crash; or presenting data which is unsafe for navigation" (IHO, 2018).

As the NOAA Nautical Chart Manual points out, "the most important concept about the formation of depth areas is that the overall succession of depth areas and their defined range values must be continuous. There can be no gaps, overlaps, or discontinuity in the range values of connecting depth areas" (NOAA, 2018). Thus, with the exception of crisp boundaries where abrupt changes are expected (e.g., between piers and depth areas), the transition between depth areas should be smooth and continuous, i.e., the maximum encoded depth of one depth area should be equal to the minimum depth of the adjoining depth area.

S-58 provides many checks that deal with the vertical component of the ENC, however, with the current set of validation checks, the depth continuity of depth areas is not guaranteed and discontinuities of the sea bottom may exist (Kastrisios et al., 2020). For instance, check number 1771 requires that the depth value of a depth contour (i.e., attribute VALDCO) must be equal to the least of the two maximum depth values of the conincident depth areas (i.e., attribute DRVAL2). For a 10m depth contour and two coincident depth areas encoded with depth ranges 5m-10m and 20m-30m will pass the validation check (as the minimum of the two DRVAL2 is also 10m), but the continuous transition in depth ranges of the areas is not achieved.

In the following sections we discuss the situations where depth discontinuities occur in an ENC, their effect on the analysis performed in ECDIS, and research on a mechanism for the identification and remediation of depth discontinuities in chart compilation.

DEPTH AREAS DISCONTINUITIES

Humans have the ability to infer the depth range of areas by looking at the charted linear features. For instance, in the paper chart of Manele Bay, Hawaii (Figure 1a), between the depth curves of 5ftm and 10ftm the depth range is 5-10ftm. Likewise, one can interpret that the depth in the marked area between the shoreline and the 3ftm depth curve is 0-3ftm. In ENCs the depth range is encoded with the depth areas (DEPAREs) which serve as the principal feature object for the determination of water safe and unsafe to navigate. Any error in the encoding of depth ranges is carried over to the analysis performed in ECDIS and may be negligible or significant depending on the specific geogrpaphic configuration. To illustrate this, figure 1b shows the bathymetry encoded in the ENC for Manele Bay, Hawaii, where for visualization purposes the 2-3ftm depth area is colored red, 3-5ftm brown, and 5-10ftm green. For a vessel with a draft of, e.g., 1.8m (i.e., 1ftm), the ECDIS would classify the plotted route (shown in dark blue in Figure 1b) as safe due to the underlying depth areas and soundings that are deeper than the set value. In the ENC, the area near the shorelines (the marked area in Figure 1a), is represented with depth range 2-3ftm instead of 0-3ftm. Although the ideal would be the encoding of two separate depth areas (one with 0-3ftm depth range adjoining the shorelines and one with 2-3ftm for the remaining area), the current situation has no imminent effect to the plotted route and the analysis performed in the ECDIS. However, if the entire 2-3ftm depth area was encoded as 0-3ftm (since it adjoins the shorelines), for all vessels trying to approach the berth, ECDIS would set off alarms for crossing non-navigable waters.

The scenarios discussed with the support of Figure 1 are common depth discontinuities in ENCs, examples of which are presented in the next section of this work. Although the mariner is able to disregard this and similar alarms in ECDIS, they contribute to what is known as "mariner's deafness", i.e., the situation where the mariner is called to investigate a considerable number of ECDIS alarms which entails the risk that important alarms do not receive the proper attention, thus increasing the risk of a maritime accident. In addition, depth discontinuities complicate automation of individual generalization tasks in chart compilation, e.g., the validation of the shoal-biased pattern of sounding selection (see e.g., Masetti et al., 2018; Kastrisios et al., 2019).

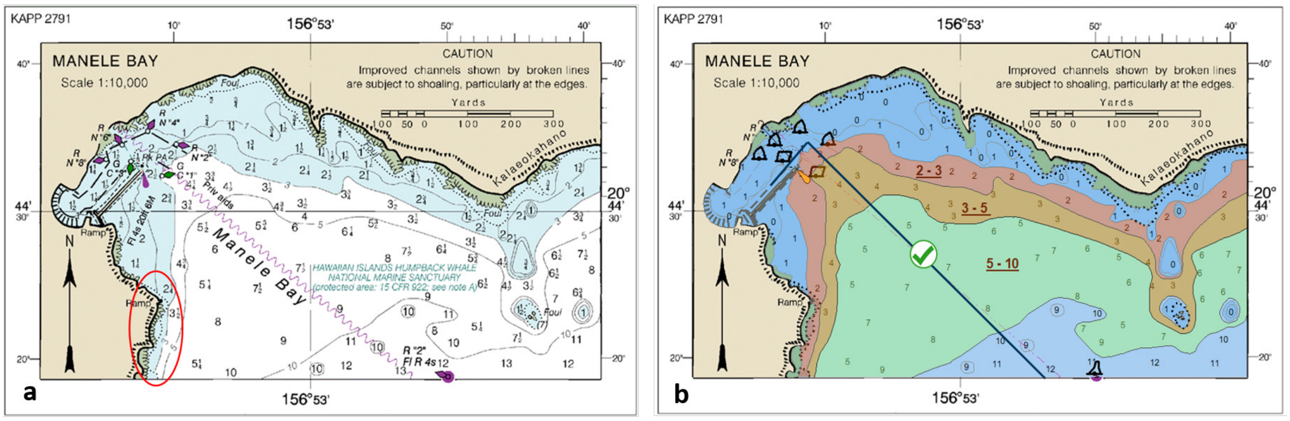

Figure 1: Bathymetry on paper (a) and electronic chart (b) of Manele Bay, Hawaii.

Figure 2a illustrates the ideal situation where the continuous seabed is represented with a continuous transition between depth ranges in the ENC. Contrary to Figure 2a, Figures 2b and 2c illustrate a discontinuous representation of the seabottom on the chart. In Figure 2b, the depth area adjoining the land area is encoded with least depth other than zero, depicting the water depth to be deeper than in reality. Figure 2c illustrates the opposite situation, where the water depth on the chart appears shoaler than the reality. A different situation of discontinuities occurs when depth areas or depth curves have been encoded in incorrect units, e.g., fathoms instead of meters. Based on the encoded values, the depth areas may appear deeper or shoaler.

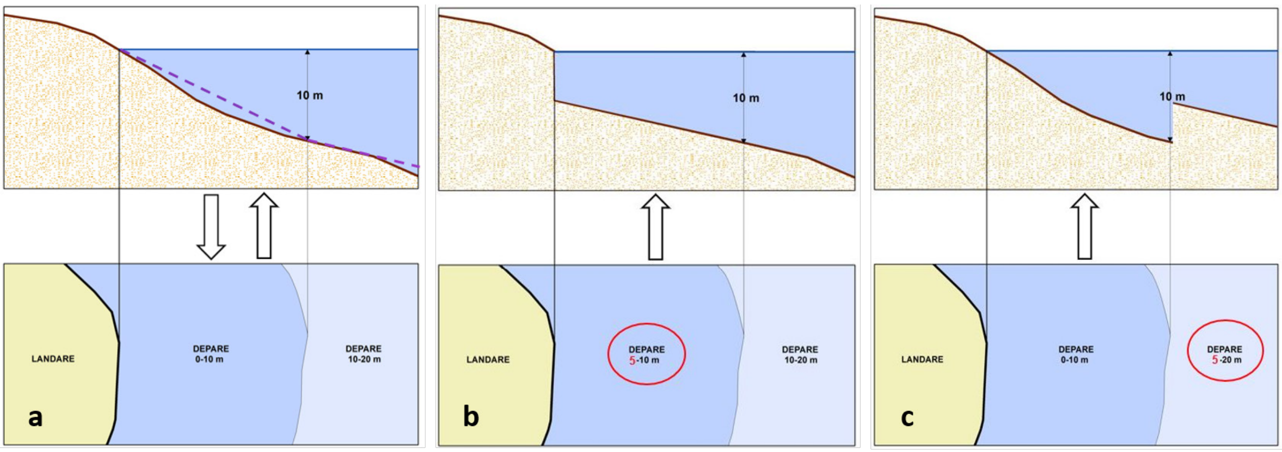

Figure 2: Depth ranges of encoded depth areas and seabottom representation in ENCs:(a) continuous/ideal, (b) discontinuous/waters appear deeper than reality, (c) discontinuous/waters appear shoaler than reality.

Here we have developed a mechanism that identifies the coincident geometries where discontinuities occur. For that, we compare the depth values of adjoining depth areas and shorelines, depth curves, and other geo-objects (e.g., dredged areas). With the exception of the geographical situations where vertical discontinuities are expected (e.g., in the crisp boundaries of shoreline constructions or dredged areas and the adjoining depth areas), the algorithm captures the discontinuities of the sea-bottom surface that should not, in principle, occur (e.g., the fuzzy boundaries of two depth areas or a depth area and the shoreline).

The research effort focuses on solutions for the identified discontinuities, and providing them as suggestions to the cartographer. The initial approach is iterative and begins with finding corrections for the attribute values. That includes, in the first iteration, the depth areas encoded in incorrect units and, in the second iteration, the depth areas that adjoining land areas. For the former, the algorithm compares the depth value to hard-coded dictionaries of the succession of depth curves in U.S. charts in meters, fathoms, and feet, and converts the value in the wrong units to the proper value in the units of the chart under validation. For the latter, the algorithm substitutes the minimum depth value (DRVAL1) of the depth area to zero and if this value change solves or improves the current situation, the change is accepted.

Once the attribute corrections steps are complete, the algorithm determines the final list of the shared edges with errors. Following the idea of medial line delineation described by others (see e.g., Gold, 2000; Cosquer and Hangouët, 2003;

Lygeros, 2012; Kastrisios and Tsoulos, 2017; Kastrisios and Tsoulos, 2018), the algorithm then determines the areas of dominance for each edge with errors which are returned as suggestions for implementation by cartographers. The cartographer is responsible for reviewing the individual polygons, splitting the depth areas, and assigning the new depth ranges based on these recommendations. The complete elimination of discontinuities may potentially be incompatible with legibility constraints and cartographic design principles. Therefore, this work currently focuses on a mixed machine/human process, but future work will investigate the feasibility of a fully automated solution.

TEST CASE

This section presents the results of the error identification and remediation process for US5AK4DM, a large scale ENC for the northern part of Tlevak Strait and Uloa Channel, west side of Prince of Wales Island, AK. For this particular ENC, the algorithm identified a total of 53 depth areas and 553 coincident geometries (edges) with errors. As Figure 3 shows, the output table of the error identification process includes the identifier of the adjoining features, i.e., the long names of the depth contour (DEPCNT_LNAM), shoreline (COALNE_LNAM), or depth area (DEPARE_LNAM) that share a depth discontinuity. It also includes the encoded depth values that are identified as discontinuities (i.e., VALDCO, DEPARE_DRVAL1, DEPARE_DRAVAL2).

Table

US5AK4DM_Shared_Edges_Errors

OID *	Shape *	DEPCNT_LNAM	VALDCO	COALNE_LNAM	DEPARE_LNAM	DEPARE_DRVAL1	DEPARE_DRVAL2	TYPE	Shape_Length	Length_M
65	Polyline	US099515257512345	0	0	US075746485412345	5.4	9.1	DEPCNT	0.002505	278.897047
66	Polyline	US070038545812345	0	0	US075746485412345	5.4	9.1	DEPCNT	0.018949	2109.441929
67	Polyline	US088840287012345	0	0	US075746485412345	5.4	9.1	DEPCNT	0.00321	357.313823
68	Polyline	US046034698812345	0	0	US091717752710017	9.1	18.2	DEPCNT	0.002247	250.131073
69	Polyline	US011623061512345	0	0	US091717752710017	9.1	18.2	DEPCNT	0.005774	642.800699
70	Polyline	US002275769712345	0	0	US091717752710017	9.1	18.2	DEPCNT	0.000917	102.065352
71	Polyline	US096102986012345	0	0	US091717752710017	9.1	18.2	DEPCNT	0.00214	238.241698
72	Polyline	US074367197312345	0	0	US091717752710017	9.1	18.2	DEPCNT	0.000775	86.253777
73	Polyline	US089417345712345	0	0	US091717752710017	9.1	18.2	DEPCNT	0.001386	154.265792
74	Polyline	US099272617312345	5.4	0	US091717752710017	9.1	18.2	DEPCNT	0.017995	2003.155879
75	Polyline	US011677662712345	0	0	US091717752710017	9.1	18.2	DEPCNT	0.001166	129.765263
76	Polyline	US067706742512345	0	0	US091717752710017	9.1	18.2	DEPCNT	0.001292	143.813924
77	Polyline	US033099764410017	0	0	US091717752710017	9.1	18.2	DEPCNT	0.001052	117.139623
78	Polyline	US055022088912345	0	0	US091717752710017	9.1	18.2	DEPCNT	0.002366	263.414483
79	Polyline	US035034879012345	0	0	US091717752710017	9.1	18.2	DEPCNT	0.004452	495.638253
80	Polyline	US030149364012345	5.4	0	US091717752710017	9.1	18.2	DEPCNT	0.003671	408.6177
81	Polyline	US072524941012345	5.4	0	US091717752710017	9.1	18.2	DEPCNT	0.005622	625.832401
82	Polyline	US099620475712345	5.4	0	US091717752710017	9.1	18.2	DEPCNT	0.003099	344.949075
83	Polyline	US092102858312345	0	0	US082178747112345	9.1	18.2	DEPCNT	0.000119	13.194436
84	Polyline	US030378490512345	0	0	US082178747112345	9.1	18.2	DEPCNT	0.001589	176.917826
85	Polyline	US082314336112345	5.4	0	US082178747112345	9.1	18.2	DEPCNT	0.0017	189.188485
86	Polyline	US083993303712345	0	0	US082178747112345	9.1	18.2	DEPCNT	0.003907	434.944299
87	Polyline	US022479393112345	0	0	US073917884610017	9.1	18.2	DEPCNT	0.001557	173.349217
88	Polyline	US086060005112345	5.4	0	US098888468512345	9.1	18.2	DEPCNT	0.005603	623.703049
89	Polyline	US010517324712345	0	0	US066799155310017	18.2	548.6	DEPCNT	0.003284	365.584103
90	Polyline	US084360025312345	0	0	US066799155310017	18.2	548.6	DEPCNT	0.005425	603.910638
91	Polyline	US013233047712345	0	0	US066799155310017	18.2	548.6	DEPCNT	0.000807	89.790845

1 (0 out of 553 Selected)

US5AK4DM_Shared_Edges_Errors

Figure 3: The output table for US5AK4DM for which the application identified 53 depth areas and 553 coincident edges with errors in depth continuity.

The following three figures show examples of the identified discontinuities. Figure 4 illustrates a depth area which has been encoded with depth range 9.1–18.2m (shaded area). However, it is apparent that the populated depth range is incorrect for many parts of the specific depth area (e.g., where the outline of the depth area touches that of land features). Discontinuities such as the discussed may pose a threat to navigation as the water depth appears deeper than reality. For instance, for a vessel with a safety contour set to 9.1m, ECDIS will treat the water within the entire extent of the shaded depth area as navigable and will not trigger any alarms, although the water depth is apparently less than 9.1m in many parts of the depth area.

In a different situation of depth discontinuity, and opposite to that illustrated in Figure 4, Figure 5 shows a depth area that appears shoaler than the reality. The shaded depth area is populated with minimum depth value of 18.2m (depth range 18.2m – 91.4m) and adjoins a depth area with depth range 18.2m – 36.5m. The coincident depth curve has populated depth value of 36.5m, thus the depth area in question should be split and, where appropriate, be assigned a depth range of 36.5m – 91.4m. Cases like this may make navigable waters appear as non-navigable in ECDIS and trigger useless ECDIS alarms, contributing to "mariner's deafness".

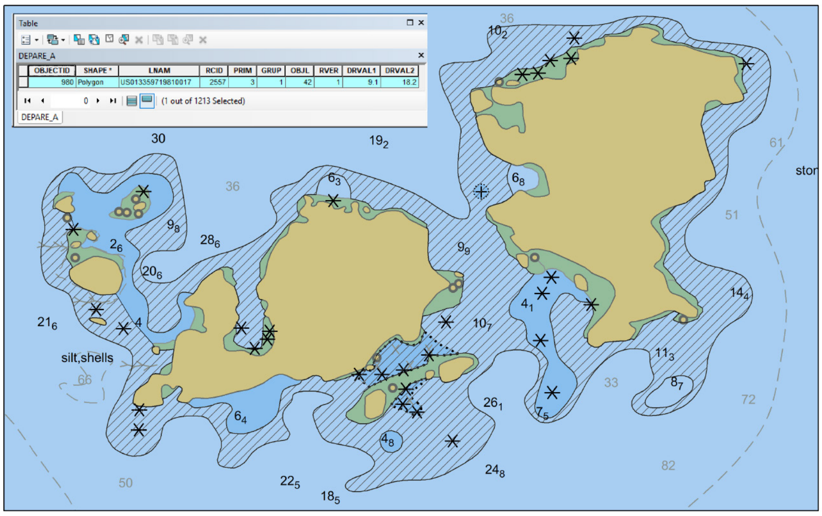

Figure 4: Depth area (depth range 9.1m – 18.2m) inconsistent with the adjacent land and depth areas.

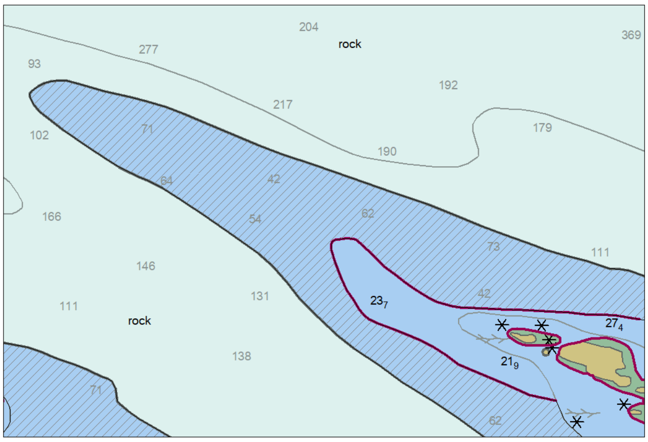

Figure 5: Depth area encoded shoaler than the actual depth in the area (i.e., 18.2m – 91.4m instead of 36.5 -91.4m).

Figure 6 illustrates an example of a depth area that has been encoded in units different than the adjoining depth areas; here, fathoms instead of meters. The shaded area has populated depth of "3" (apparently in fathoms) contrary to the proper 5.4 (in meters) whereas the adjoining depth areas have been properly encoded in meters. Cases of vertical discontinuity like the discussed may be encountered in ENCs produced by hydrographic offices that use more than one systems of units in their folio of charts (NOAA's Office of Coast Survey is one of those).

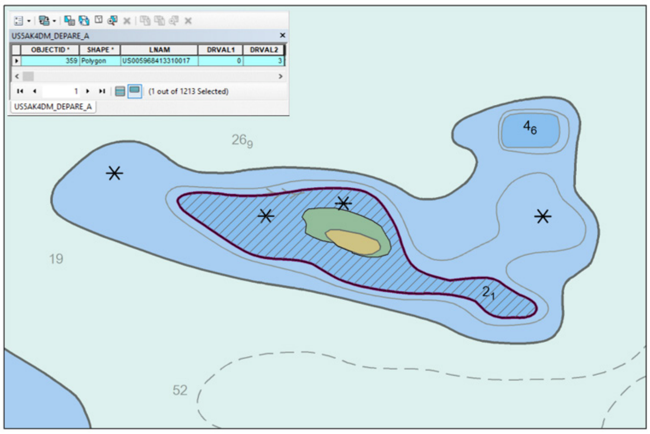

Figure 6: Depth area encoded in different units than the adjoining depth area and depth curve (i.e., fathoms vs meters).

After applying the attribute fixes of the error remediation, the number of common geometries with errors are reduced to 365 (i.e., a reduction of 33%). Figure 7 shows that the populated DRVAL2 depth value of 3 fathoms discussed previously has been corrected to 5.4 meters.

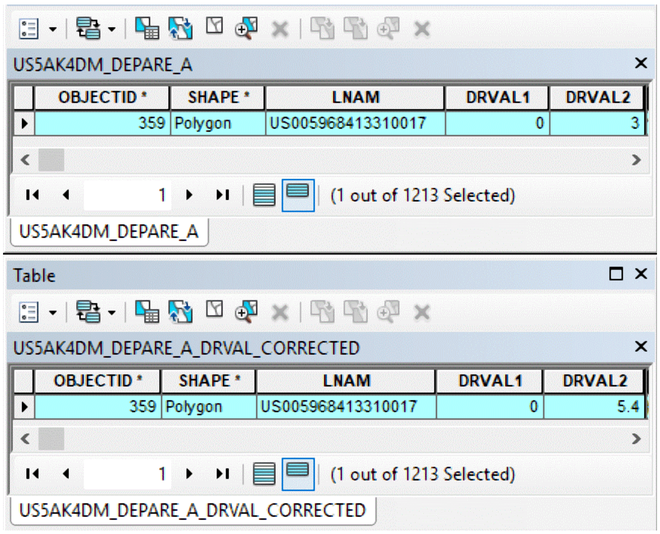

Figure 7: The attributes table of the depth area in Figure 6 before and after the attribute fixes.

Subsequently, the tool iterates between the edges with identified errors suggesting fixes and altering the geometry of the depth areas. That includes splitting the respective areas and assigning the proper depth range to each new depth area. Figure 8 illustrates the dominating polygons that may be used as the guide for the splitting of the shaded area of Figure 4. Figure 9 shows the attribute table of these polygons, along with the current and recommended depth ranges.

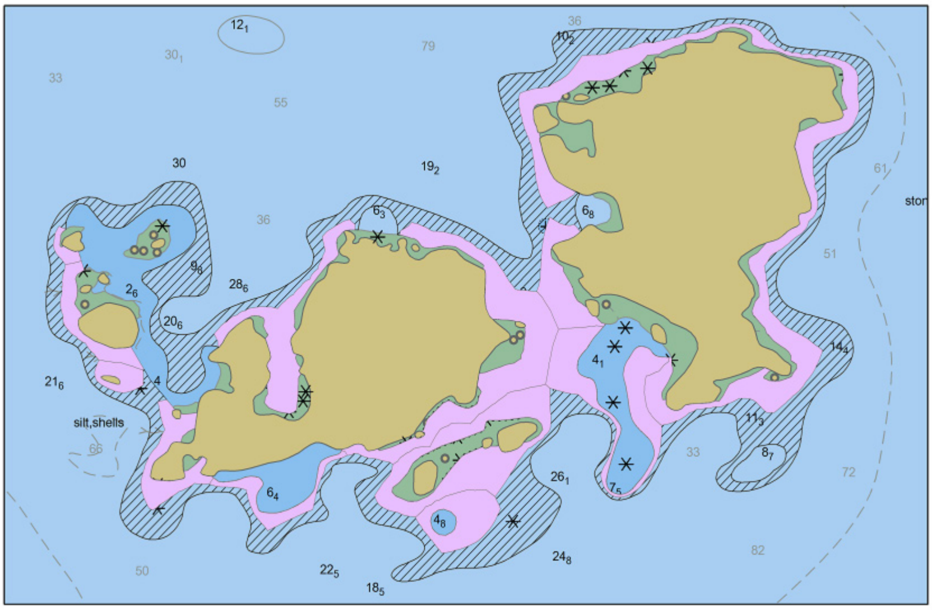

Figure 8: The recommended geometry changes to the depth area of Figure 4.

Lastly, Figure 9a shows an example of the dominating polygons of the edges with error (in yellow) and how they were utilized for splitting the depth area with errors into smaller areas (green and red shaded areas in Figure 9b). The automation of this process is under development.

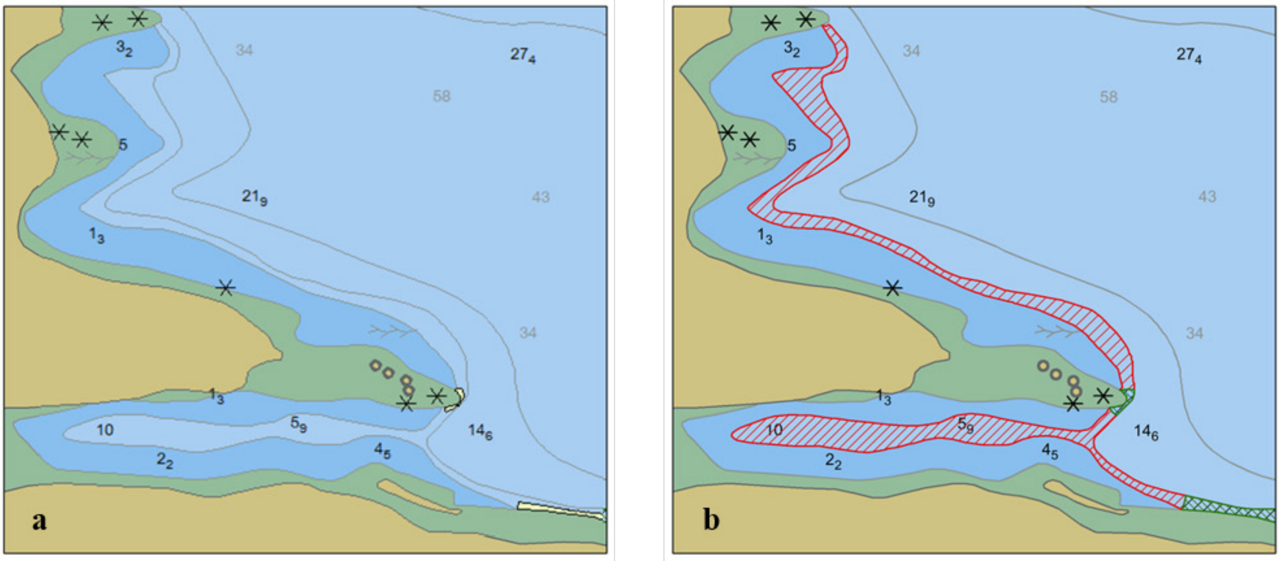

Figure 9: Recommended geometry changes are in yellow (a) and their incorporation as four new depth areas by the cartographer (b).

CONCLUSION

This paper presents the problem of depth discontinuities in ENCs and how they affect the ECDIS analysis in determining safe and unsafe navigation areas. It also presents the research work for the development of an algorithm to identify such discontinuities, and an iterative approach for error remediation. The approach begins with errors that may be fixed by making attribute changes, then proposes changes to the geometry of depth areas. The process is currently a mixed machine/human process, but a fully automated solution, pursuant to the limitations set by the cartographic constraints, is under investigation.

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BIOGRAPHIES

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 and represented his country at international committees and working groups. He holds a Pg.Dip. from the Hellenic Naval War College, a M.P.S. 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 maritime delimitation. He has worked as a part-time lecturer in GIS and Cartography at the HNA and NTUA. His research work at the Center focuses on data generalization, visualization, and topology on nautical charts.

Brian Calder graduated with a M.Eng (Merit) and Ph.D in Electrical and Electronic Engineering in 1994 and 1997 respectively, from Heriot-Watt University, Scotland. His doctoral research was in Bayesian statistical methods applied to processing of sidescan sonar and other data sources. He joined the Center for Coastal and Ocean Mapping & NOAA-UNH Joint Hydrographic Center at the University of New Hampshire as a founding member in 2000, where his research has focused mainly on understanding, utilizing and portraying the uncertainty inherent in bathymetric (and other) data, and in efficient semi-automatic processing of high density multibeam echosounder data, and associated technologies. He is a Research Professor, Associate Director of CCOM, the Chair of the Open Navigation Surface Working Group, and a past Associate Editor of IEEE Journal of Oceanic Engineering.

Megan Bartlett graduated with a B.Sc. and M.Sc. in GIS in 2017 and 2020 respectively, from the University of Maryland at College Park. She earned a FIG-IHO-ICA IBSC recognized Category B Certification in Nautical Cartography from NOAA in 2018. She first joined the Marine Chart Division (MCD) within the Office of Coast Survey at NOAA in 2012 as a nautical cartographer. During this time, she became an educator for IIC Technologies and instructed NOAA employees and students enrolled in the M.Sc. in Hydrographic Science program at the University of Southern Mississippi. Her current focus of work for MCD is production and modernization of NOAA's nautical charting suite, teaching courses in the Category B Certification program, and representing NOAA to the international community through working groups with the International Hydrographic Organization.