Excerpt of the study "DQV - Data Quality Visualization"

Proposals for Visualizing Uncertainty of Bathymetric Data in S-101 ENCs

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This document is an excerpt of the study "DQV-Data Quality Visualization" and proposes three different approaches for visualizing uncertainty along with bathymetric data in future S-101 ENCs:

Proposal	Type of uncertainty	Ease of implementation
Texture overlay	Categorized uncertainty (QOBD)	Simple
Colored area as a replacement for the safety contour	Quantified uncertainty (potentially unsafe water)	medium
Additional depth profile plot	Quantified uncertainty	medium

For full understanding of the reasons behind these proposals, the reader is referred to the complete study.

4.1 Requirements

For proposing approaches for visualizing uncertainty of bathymetric data in ENCs, the large variety of existing techniques, as summarized in Chapter 3 of the full study, must be checked concerning their applicability and suitability. For this reason, application specific requirements are defined first.

- R1: It must be possible to visualize the uncertainty of bathymetric data along with all the other information incorporated in ENCs. This requires to consider properties, limitations and the interplay of data visualization, uncertainty visualization and representation of geo-spatial reference (map) [Röh14].
- R2: The addition of an uncertainty representation must not lead to visual clutter [NIP16; IHO10]. This requirement is especially challenging as ENCs already depict a multitude of information.
- R3: Information representation of any kind must be intuitive and unambiguous [NIP16; IHO10]. This implies a unique visual encoding of uncertainty.
- R4: Information should be represented with high contrast to each other [IHO10].
- R5: The visual encoding of uncertainty must be adapted according to the three ECDIS modes day, dusk and night [IHO10].
- R6: Important information should be encoded redundantly [IHO10].
- R7: There should be as little inaccuracy as possible when processing uncertainty information through the visualization pipeline [Röh14; BOL12].

- ▷ R8: The visual weighting between data, uncertainty and geo-spatial reference must be considered [Röh14]. For example, in coastal waters which are usually shallow, information concerning uncertainty of the depths play a more important role than in deep waters.

In addition to these requirements, a number of proposals concerning the visualization of uncertainty in ENCs have been made by different working groups of the IHO. These are summarized in the following.

- ▷ P1: The uncertainty visualization should include a legend for explanation [NIP16].
- ▷ P2: The uncertainty visualization should be configurable to meet the preferences of different mariners [HWG12].
- ▷ P3: Available details concerning uncertainty should be discoverable by interacting with the ECDIS [HWG12].
- ▷ P4: Increasing clarity of the depth representation in the chart should indicate increasing data quality (i.e., decreasing uncertainty) [DQW15].
- ▷ P5: To reduce visual clutter, the visualization of uncertainty should be restricted to a local area of interest [NIP16; DQW15].
- ▷ P6: Uncertainty concerning bathymetric data should be encoded via texture or color. However, a red / amber / green color scheme should not be applied as this is reserved for representation of under-keel clearance [DQW14].
- ▷ P7: Uncertainty should not be visualized via glyphs [DQW14].
- ▷ P8: Text should not be used to represent uncertainty as it is difficult to read and may lead to clutter [IHO10].
- ▷ P9: The categories *Unassessed* and *Quality_5* of the new composite quality indicator QOBD may be represented identically as they provide semantically similar information to mariners [DQW14].
- ▷ P10: The representation of numbers of selected depths may be adjusted to further represent uncertainty. This idea was mentioned by the *Bundesamt für Seeschifffahrt und Hydrographie* (BSH) within a kickoff-meeting concerning this study.

4.2 Proposals

Based on these requirements and recommendations, different options for visualizing uncertainty of bathymetric data have been examined within this study. This lead to proposals concerning what aspects of uncertainty should be visualized, where they should be visualized and how they should be visualized.

4.2.1 What aspects of uncertainty should be visualized?

The goal of visualizing uncertainty associated with bathymetric data in ENCs is to support mariners in deciding whether certain waters are deep enough for a safe passage. However, in order to avoid visual clutter and information overload, it is not possible to visualize all individual aspects of uncertainty (see Section 2.1 in the full study) at the same time. Even if this would be possible, it would be questionable whether mariners were able to extract useful information from this data. A better approach is to represent aggregated data, which are easy to interpret. These can either be quantitative or qualitative.

One option is to summarize and quantify all aspects of uncertainty contributing to deviations of the measurement position, the measured depths, and the depths over time. As discussed in Section 2.1 of the full study, those aspects include accuracy, precision and resolution of the positioning system, tides, wind and wave height at the time of depth measurement and dynamics of the seabed for example. Assuming that these information are available, it would be possible to calculate an interval describing the maximal impact of uncertainty to a charted depth (e.g., $[-5m, +5m]$) at a specific location and the estimated time of passage. This interval could be visualized either in combination with the depths themselves (a), or in form of adapted depths (b) (e.g., subtracting the quantified uncertainty from the charted depths).
Moreover, with this interval and the safety contour threshold, it would be possible classify waters into three categories instead of two (c): safe water (charted depths definitely deeper than safety contour threshold), potentially unsafe water (charted depth $+$ upper bound of uncertainty interval are shallower than safety contour threshold) and unsafe water (charted depth are definetly shallower than safety contour threshold). This opens up the possibility to visually highlight potentially unsafe waters instead of just displaying the safety contour as a rough border between safe and unsafe water.
All three variants would lead to a dynamic visualization and would enable mariners making more reliable decisions. A major difficulty of this approach is the quantification of potential changes over time. This requires suitable and complex models which might not exist yet. The visualization techniques recommended in Section 4.2.3.2 and 4.2.3.3 are based on (a) and (c).

A second option is to aggregate various aspects of uncertainty to a qualitative indicator like QOBD or CATZOC. Many possibilities of aggregating such data already exist and it is not entirely clear, which information should be included and how they should be weighted (i.e, what influence they have on the categorization's result). Although QOBD is more meaningful than CATZOC, there is still space for further improvements. This, however, requires dedicated in-depth research and additional domain knowledge.
Visualizing composite, qualitative indicators enables mariners to get a simple overview of existing uncertainty. This for instance allows to decide against a route through waters having high uncertainty and depths near the safety contour threshold. However, exact deviations of depths cannot be derived. The visualization techniques recommended in Section 4.2.3.1 are dedicated to the composite indicator QOBD.

4.2.2 Where should uncertainty be visualized?

Information concerning uncertainty of bathymetric data are typically required for certain areas of interest, not the entire map. This allows to restrict the uncertainty visualization locally (P5) which in turn helps to avoid visual clutter (R2). Which areas are of interest depends on the application scenario:

Route planning When planning a route one can distinguish between two situations: The mariner selects one of multiple predefined routes or a new route is defined. In the first case, the visualization of uncertainty can be restricted to a corridor along every predefined route. The widths of such corridors should have a meaningful default value which could be altered if necessary. In the second case, the visualization can be restricted to areas selected by the mariner though which the route in question might go. This allows to consider uncertainty of depths during route determination.

Monitoring As described in Section 2.2 of the full study, information concerning uncertainty of depths in monitoring scenarios are necessary for nearby areas when a planed route must be left, for example due to an emergency. As an interactive specification of areas of interest is not reasonable in such stressful situations, the uncertainty visualization should be provided for a circular area around the ship's position (all nearby area) automatically or during the entire voyage. The radius of this circular area should be calculated based on a reaction time set by the mariner and the current speed of the ship. Assuming a ship is traveling with 20 kn and the reaction time is set to 30 minutes, the radius of the circular area should be 10 nm. A similar strategy is already used in ECDIS to display warnings when a ship is going to enter restricted areas or areas with depths shallower than the safety contour threshold [IMO95].
In the unlikely situation that a mariner wants to review uncertainties concerning depths of future parts of the current route, the uncertainty visualization should be presented in a corridor along the remaining route.

4.2.3 How should uncertainty be visualized?

Within this study, novel concepts for visualizing the qualitative indicator QOBD as well as aggregated quantifications of uncertainty have been developed. These are introduced separately in the following sections. Presented figures are based on an ENC dataset from a part of the irish sea containing different depths and uncertainties classified according to CATZOC (see Figure 2.1 and Figure 2.4 in the full study). As a classification according to QOBD does not exist yet, areas with CATZOC class A1, A2, B, C, D, U are treated as QOBD classes Quality_1/Oceanic, Quality_2, Quality_3, Quality_4, Quality_5, Unassessed.

4.2.3.1 Recommendations for visualizing QOBD

Similar to the visualization of CATZOC, QOBD should be represented with an additional ENC layer, so that bathymetric data, geo-spatial reference and uncertainty can be viewed together. In [Nel00; Eva97] it is shown, that such an integrated representation is more efficient than a separate visualization of data and associated uncertainty, for example in individual views. In general, for representing QOBD, intrinsic visualization techniques are preferable (i.e., encoding uncertainty by adapting the representation of bathymetric data via depth zones, depth contours or numbers for selected depths), as they do not introduce new graphical objects which may lead to visual clutter (R2). However, for the main representation of bathymetric data as colored depth zones, a lot of possibilities for an intrinsic encoding are not applicable as discussed in the following.

- ▷ Color: Currently, color hue, saturation and brightness are used in combination to encode different depth zones. It would be possible to use one of these individual visual variables to additionally encode QOBD. The stepwise adaption of saturation for representing different QOBD categories would be an example. However, as the depth zone colors all have varying hue, saturation and brightness, a consistent encoding of QOBD cannot be realized and, thus, is not proposed.
- ▷ Noise: Another possibility for an intrinsic encoding of QOBD categories is to apply varying levels of noise to the representation of depth zones. However, the maximal amount of noise must be limited to a certain extent so that underlying depth zones can still be identified. This, however, leads to noise levels for QOBD categories which are difficult to distinguish (see Figure 6.1 in the annex of the full study). Consequently, such an encoding is not recommended.
- ▷ Transparency: Applying varying transparency to depth zones for encoding individual QOBD categories leads to mixed colors with the background which in turn hinders identifying depth zones. Thus, this kind of encoding is not suitable.
- ▷ Blur and fog: These visual variables cannot be used to encode QOBD as they do not have any effect on a single-colored background (depth zones).
- ▷ Water color simulation: As this kind of encoding is based on noise and blur, it is not applicable too.

Another possibility to represent QOBD in an intrinsic way is to adapt the representation of depth contours. But, as ENCs already incorporate a multitude of different contour encodings, the visibility of contours is not guaranteed and depth zones may include varying QOBD categories, this approach is not proposed.

A third option for an intrinsic visualization of QOBD is to adapt the representation of selected depths (soundings) as numbers (P10). However, as those numbers are colored in two different shades of gray based on the given safety depth (see Section 2.3 in the full study), adapting their transparency (or brightness) according to QOBD categories does not work. As shown in Figure 6.2 in the annex of the full study, different QOBD

categories cannot be distinguished this way. Similar problems would arise when adapting the size of numbers in a moderate way so that readability is maintained and visual clutter is avoided (P8).
In conclusion, although intrinsic visualization methods would have advantages, they are not suitable for this application. Thus, approaches for extrinsic visualization are recommend, as exemplified next.

Visualizing QOBD via texture/hierarchical structure overlay

Similar to the approach described in [VCL11], the idea is to represent QOBD with a texture overlay (P6, P7). The transparency of the texture is used to precisely encode the QOBD classes of the underlying survey areas as follows (R7):

- ▷ *Quality_1/Oceanic*: 100% transparency
- ▷ *Quality_2*: 75% transparency
- ▷ *Quality_3*: 50% transparency
- ▷ *Quality_4*: 25% transparency
- ▷ *Quality_5/Unassessed*: 0% transparency

As the texture becomes less visible with increasing quality of the underlying data, proposal P4 is fulfilled. In order to maximize the contrast between the representation of different QOBD categories (R4), the differences in transparency are made as large as possible and Quality_1/Oceanic as well as Quality_5/Unassessed are represented identically (P9). In addition, contours are added between areas with different QOBD class. The color of the texture is selected depending on the current ECDIS mode (R5). In day mode, black is used as texture color, whereas two different shades of gray are used in dusk or night mode. When selecting which kind of texture is used, requirement R1 must be taken into account. This means, that the texture must differ to textures, line patterns and symbol patterns which are already specified in S-52 for communicating other information. As grid- and hexagon textures can meet this requirement, they are proposed. It is important that the size and line thickness of such textures are selected appropriately so that differences in texture transparency can be recognized and underlying elements like depth zones can still be clearly identified (R3). This also defines the visual weighting between data and uncertainty (R8). To further increase the distinguishability of different QOBD classes, a redundant encoding via varying size of texture elements (i.e., squares or hexagons) is proposed (R6). As grid textures allow for a hierarchical subdivision of their elements into similar elements, they are especially well suited for this purpose. This approach for visualizing uncertainty is also known as *hierarchical structure overlay* [KMB03; Röh14]. To avoid introducing positional uncertainties by the visualization itself, the elements should be clipped at the precise borders of survey areas having different QOBD categories. In the light of P4, the size of texture elements should be decreased with increasing uncertainty. Thereby, a uniform line thickness must be maintained. Figures 4.1 and 4.2 show the resulting visualization for a fictitious route planning scenario in day mode. Figures 4.3 and 4.4 depict the respective visualization for a monitoring scenario in dusk mode. Additional figures for further combinations of ECDIS modes and application scenario are provided in the annex of the full study.

Independently from what kind of technique is used to visualize QOBD, the ECDIS should provide the option to display a legend for the uncertainty visualization as an aid for mariners to decode information. This follows proposal P10. Moreover, mariners should be enabled to view further detailed metadata concerning uncertainty by interacting with the ECDIS (i.e., attributes of the objects M_QUAL and M_SREL). One option would be to provide access to such information through a context menu, which can be opened interactively after selecting a position or area of interest with the mouse cursor (P3).

4.2.3.2 Highlighting potentially unsafe water

As described in Section 4.2.1, a quantification of the overall uncertainty can be used to visually highlight areas which might be unsafe for navigation. Such a visualization would outperform the safety contour in terms of precision and expressiveness. For representing potentially unsafe areas in an ENC (R1), an opaque color fill using the high contrast color of the safety contour is proposed (R3, R4, R5, P6, P7). Depending on the bathymetric data, the safety contour threshold set by the mariner and the given uncertainties, such potentially unsafe areas look differently. The thick gray line on the bottom part of Figure 4.1 gives an example. As the representation of such areas replace the representation of the safety contour and parts of adjacent depth zones, no additional visual clutter is introduced (R2).
The same approach would also be applicable for visualizing transition areas between depth zones based on other depth contour thresholds, for example the deep contour threshold. However, it is questionable whether this is needed, as such thresholds are usually less relevant for mariners.

4.2.3.3 Visualizing uncertainty in an additional depth profile plot

As an additional aid for mariners, a second view besides the main ECDIS view is proposed that visualizes a depth profile for the selected route. This way, the mariner is enabled to view the bathymetric data of interest and its associated uncertainty from another perspective, which may raise awareness and facilitate decision-making. As illustrated in Figure 4.5, the sections of the ship's route are presented on the x-axis whereas depths are encoded on the y-axis. The black dots on the upper line depict way points of the route. The depth contour thresholds selected by the mariner are marked as horizontal lines. The charted depth at a specific location is depicted with a black

contour. Solid material below this contour is visualized as a brown area. Water is depicted in different shades of blue depending on the depth, following the representation of the main ECDIS view.
In a monitoring scenario where nearby waters are of special interest, the plot is divided into 3 parts separated by two vertical lines. The left vertical line and a ship symbol depict the ship's current position. The right vertical line represents the border of a look-ahead zone specified by the mariner (e.g., based on a minimal reaction time set by the mariner, as described in Section 4.2.1). The part of the route between both vertical lines is automatically shown with a bigger scale, so that more details become visible. The grayed out part has already been traveled. In route planning scenarios where all waters along the route are of similar interest, this part of the visualization can be dropped.
A major feature of this visualization is the representation of quantified uncertainty as described in Section 4.2.1. The second, but less-emphasized contour in gray color denotes the maximal deviation of depths caused by all three aspects of uncertainty: positional uncertainty, uncertainty of depth and temporal uncertainty. This way, the different impact of uncertainty becomes clearly and intuitively visible (R3, R8). In Figure 4.5 for example, the ship has passed a route section with almost certain depths and now enters an area with higher overall uncertainty. If the depths plus their maximal deviations fall below the safety contour threshold, the mariner is warned through a highlighting of the respective part of the contour. For this purpose, the ECDIS warning color magenta is used. Solid material for depths, which is certainly above the safety contour threshold is highlighted similarly. If a route is crossing an area for which uncertainties have not been assessed yet, the respective parts of the line representing the safety contour are marked. This shall warn mariners of potentially unsafe water.
Another aspect of uncertainty explicitly represented here is the positional uncertainty of depth zones. As the visualization of clear borders between depth zones would not reflect reality, a blur with varying extension depending on the amount of positional uncertainty is applied (see center part of Figure 4.5). The visibility of the blur effect depends on the scale of the representation. This kind of intuitive visualization could also be applied in ENCs to represent positional uncertainty of depth zones.
Figure 4.6 shows a second depth profile visualization in dusk mode for the fictitious route used in Figure 4.1 to Figure 4.4. Further examples are provided in the annex.

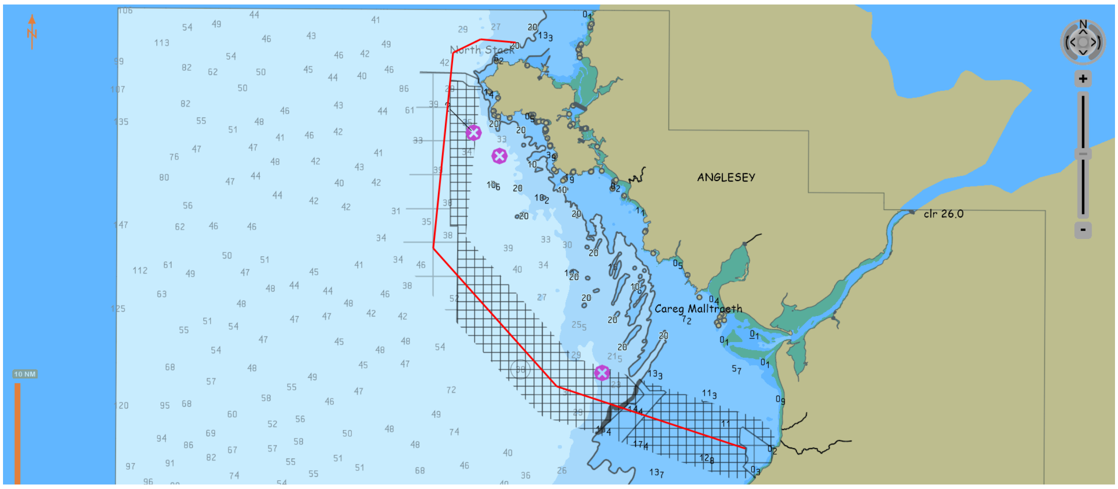

Figure 4.1: Visualizing QOBD with a hierarchical grid overlay in a fictitious route planning scenario. Different texture element sizes and transparencies encode different QOBD classes. The current ECDIS modes are day and base [1]. The visualization is restricted to a local area of interest (corridor along the route) to reduce display clutter.

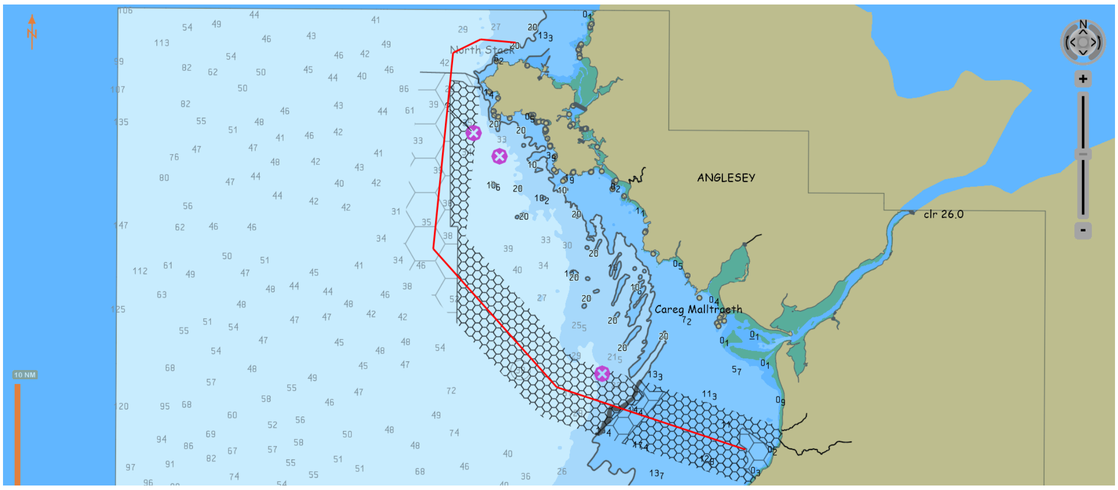

Figure 4.2: Visualizing QOBD with a hexagon texture overlay of varying size in a fictitious route planning scenario. Different texture element sizes and transparencies encode different QOBD classes. The current ECDIS modes are day and base. The visualization is restricted to a local area of interest (corridor along the route) to reduce display clutter.

[1] According to S-52, an ENC can be displayed in *base* or *standard* mode. While base mode displays all mandatory information, standard mode includes additional details.

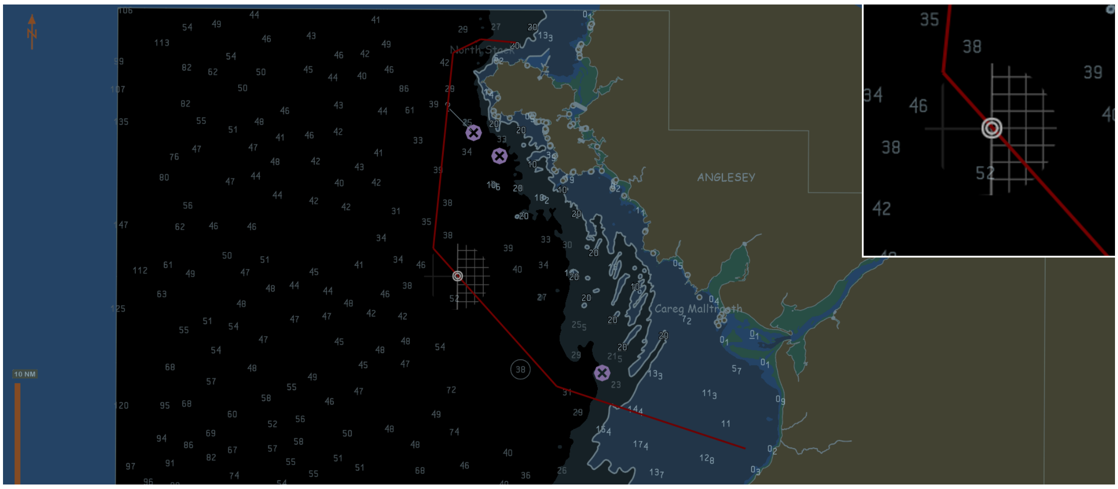

Figure 4.3: Visualizing QOBD with a hierarchical grid overlay in a fictitious monitoring scenario. Different texture element sizes and transparencies encode different QOBD classes. The current ECDIS modes are dusk and base. The visualization is restricted to a local area of interest (circular area around the ship's position) to reduce display clutter.

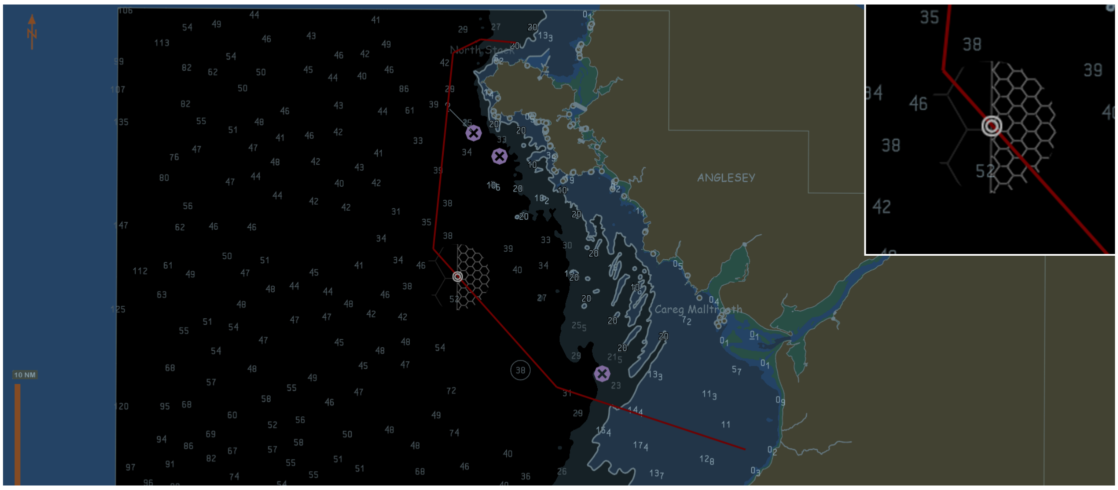

Figure 4.4: Visualizing QOBD with a hexagon texture overlay of varying size in a fictitious monitoring scenario. Different texture element sizes and transparencies encode different QOBD classes. The current ECDIS modes are dusk and base. The visualization is restricted to a local area of interest (circular area around the ship's position) to reduce display clutter.

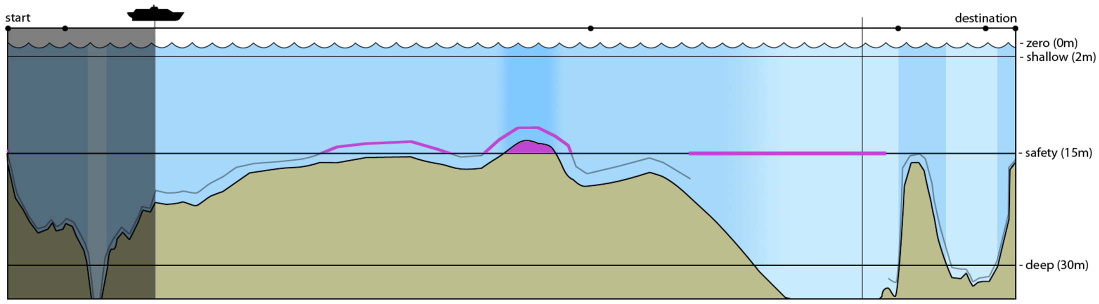

Figure 4.5: Visualizing the quantified uncertainty with a depth profile plot in ECDIS mode day in a monitoring scenario. The shown profile is not based on real data and serves for the purpose of illustration only.

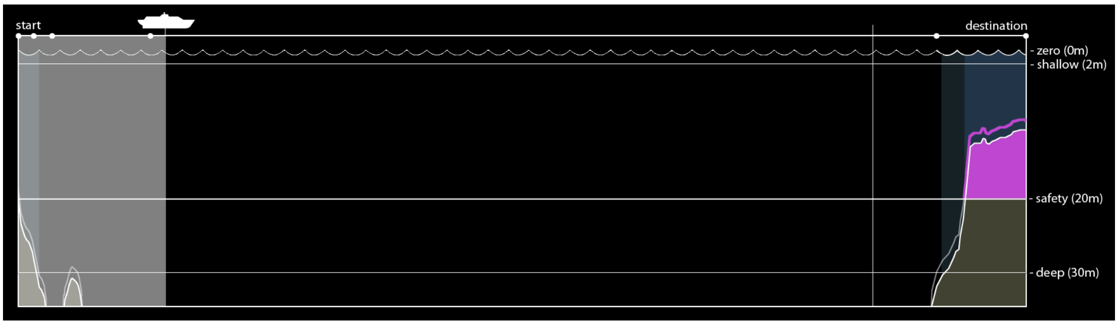

Figure 4.6: Visualizing the quantified uncertainty with a depth profile plot in ECDIS mode dusk in a monitoring scenario. The depth profile visualizes data from the route selected in Figures 4.1 to 4.4.

Summary

Nowadays, electronic nautical charts (ENCs) are common tools to support safe navigation at sea. An essential purpose of such charts is to provide information concerning measured depths of waters and their associated uncertainty, so that routes can be selected, which maintain under keel clearance. While the representation of depth information in ENCs according to S-52 is generally accepted, the visualization of associated uncertainties is not. A study by Harper et al. confirmed, that the current representation of uncertainty is difficult to understand for mariners and thus is rarely used [HWG12].
As the the new S-101 ENC standard is in development, the aim of this study was to propose solutions for standardization, which can visualize uncertainty in a more suitable way. This is a major difficulty as ENCs represent a multitude of information in a complex way and already utilize a large number of different visual variables. Based on an analysis of bathymetric data and their associated uncertainties, the mariners' tasks and literature on uncertainty visualization, proposals concerning what aspects of uncertainty should be visualized, where they should be visualized and how they should be

visualized were given. This led to three concrete visualization techniques which were described and illustrated for various scenarios:

1. A texture overlay for visualizing QOBD
2. An area coloring for highlighting potentially unsafe water
3. An additional depth profile plot for visualizing quantified uncertainty

For full understanding of the reasons behind these proposals, the reader is referred to the complete study. A formal evaluation of these approaches within a user study is a sensible next step for future work.

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