Study

DQV - Data Quality Visualization
Recommendations for Visualizing Uncertainty in Electronic Nautical Charts

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On behalf of
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– BSH –
Abstract

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 recent study confirmed, that the current representation of uncertainty is difficult to understand for mariners and thus is rarely used.

As the new S-101 ENC standard is in development, this study aims at proposing solutions for standardization, which can visualize uncertainty in a more suitable way. For doing so, a three step approach is applied. First, bathymetric data, associated uncertainties and mariners’ tasks are analyzed. Thereafter, existing approaches for visualizing uncertainty are examined. Finally, based on a compiled list of requirements, proposals for visualizing uncertainty of bathymetric data in ENCs are provided. This includes recommendations concerning what aspects of uncertainty should be visualized, where they should be visualized and how they should be visualized.
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1 Introduction

1.1 Motivation

Nowadays, electronic nautical charts (ENCs) are essential tools for safe navigation at sea. They depict a graphic representation of a maritime area with lots of important information like depths of water and height of land (topographic map), details of the coastline, navigational hazards, human-made aids to navigation and traffic routes. Based on these information, it is part of the navigation officers’ duty to do a ship’s passage planning and “ascertain that there is enough water under the keel during the entire voyage” [Por06]. This, however, is a difficult task, as the depth information in the chart are shown at normal water level. To determine realistic depths according to the current situation, potential deviations caused by uncertainty associated with the underlying bathymetric data must be considered. This includes measurement inaccuracy and environmental influences like tide, wind and wave height for example. To make mariners aware of this aspect and to increase the credibility and expressiveness of depth information depicted in the chart, it is useful to communicate the existence of uncertainty visually. If the uncertainty is quantifiable it is even better to visualize its extent, for instance by highlighting areas which might be to shallow for safe navigation. This can facilitate informed decision-making and thus avoid running aground in the worst case.

1.2 Problem description and goal

Despite the fact that visualization of data quality and uncertainty of data is a well-researched area within information visualization and cartography, visualizing uncertainty associated with bathymetric data in ENCs has not been addressed sufficiently yet [HWG12]. Although a standardized solution for visualizing the composite quality indicator Category of Zone of Confidence (CATZOC) exists in S-52\(^1\), a study by Harper et al. confirmed, that this kind of representation is difficult to understand for mariners and thus is rarely used [HWG12]. Moreover, it has been indicated that CATZOC itself has limited expressiveness. Consequently, the development of alternative visualization techniques for CATZOC as well as better quality indicators have been an issue for many years within the respective standardization committee (S-101 Carthographic

\(^1\)S-52 is a standard which provides specifications and guidance regarding the issuing and updating of ENCs and their display in Electronic Chart Display and Information Systems (ECDIS) [IHO15b; IHO10].
Standards Committee) and working groups of the International Hydrographic Organization (IHO) (Data Quality Working Group (DQWG), Nautical Cartography Working Group (NCWG)). After several iterations, the DQWG introduced a more comprehensive composite quality indicator called Quality of Bathymetric Data (QOBD), which is going to be standardized in the next generation ENC specification S-101\textsuperscript{2} [DQW15]. Furthermore, alternative techniques for visualizing composite quality indicators have been proposed [NIP16; DQW14a; HEA11]. While these solutions provide some useful ideas, they are only applicable to a limited extent. Hence, a suitable visualization approach is still to be found.

A major difficulty in this regard are ENCs themselves. These charts already represent a multitude of information in a complex way and utilize a large number of different visual variables. This does not only limit the possibilities of visualizing uncertainty, it also makes it difficult to meet representation requirements like intuitive readability, consistency of the visual encoding and prevention of visual clutter as well as ambiguities.

On the basis of a literature review on uncertainty visualization, this study’s objective is to propose suitable techniques for visualizing uncertainty associated with bathymetric data in ENCs, which can be considered for standardization in S-101.

1.3 Approach

The main approach of this study can be summarized in three steps:

1. **The basics of bathymetric data and its uncertainty are described and existing visualization techniques for ENCs are examined.** As a basis, the characteristics of bathymetric data are described at the beginning of Section 2.1. Afterwards, various aspects and sources of uncertainty are examined and existing composite quality indicators for bathymetric data uncertainty are analyzed (Section 2.1). Thereafter, mariners’ tasks concerning bathymetric data uncertainty are described for different scenarios in Section 2.2. As a final part of this step, the representation of bathymetric data and its uncertainty according to S-52 are reviewed and proposed alternatives are considered (Section 2.3).

2. **Existing approaches for visualizing uncertainty are reviewed.** As already mentioned, visualization of uncertainty is a well-researched topic within information visualization and cartography. In this step, existing categories of visualization approaches are reviewed and examples are given (Section 3). A special focus is set to approaches for visualizing uncertainty of geo-spatial data.

3. **Suitable techniques for visualizing uncertainty of bathymetric data in ENCs are compiled.** The presentation standard S-52 specifies a number of general

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\textsuperscript{2}S-101 is a new product specification standard for ENCs. It is currently under development by the IHO [IHO12].
1.3 Approach

presentation requirements for ENCs which must be taken into account when visualizing uncertainty. Moreover, specific recommendations concerning uncertainty visualization in ENCs can be found in reports published by the working groups of the IHO. These requirements and recommendations are summarized in Section 4.1 first. On the basis of the data, the tasks, existing visualization approaches as well as requirements and recommendations, novel techniques for visualizing uncertainty of bathymetric data in ENCs are derived and described in Section 4.2.
2 Analysis of the current situation

The basis of a suitable visualization are the data to be represented and the tasks to be facilitated. For this reason, this chapter examines bathymetric data and associated uncertainty, describes mariners’ tasks concerning both and reviews their current representation in ENCs according to S-52.

2.1 Bathymetric data and uncertainty

Bathymetric data

Bathymetric data are depth measurements (so-called soundings) of lake or ocean floors and can be seen as an underwater equivalent to topographic data. Within hydrographic surveys, such data is gathered for specific areas. While bathymetric data was originally collected by lowering a pre-measured rope or cable over a ship’s side, nowadays mainly echosounders (sonar systems) or laser scanning (LIDAR systems) are used.

Aspects of data uncertainty

The term uncertainty refers to imperfection of a dataset and associated analysis results. Usually, uncertainty is understood as a composition of different aspects [Röh14; Ske+08; GS06; Tho+05; Mac+05]:

- **Accuracy/error**: the difference between observation and reality, usually estimated based on knowledge of the measurement/estimation device and of phenomena in the work.
- **Resolution**: the difference between given and required resolution of a measurement.
- **Precision**: the exactness of measurement/estimate, i.e., the size of the interval in which the measurement/estimate can lie.
- **Completeness**: the extent to which information is comprehensive.
- **Consistency**: the extent to which information components agree.
- **Lineage**: the conduit through which information has passed, e.g., information at first or second hand.
2.1 Bathymetric data and uncertainty

- **Currency**: the time span between occurrence, information collection/processing and use.
- **Credibility**: the reliability of the information source.
- **Subjectivity**: the extent to which human interpretation or judgment is involved in information.
- **Interrelatedness**: the source’s independence from other information.

A study performed by Robert Roth emphasizes that these aspects can have varying influence on a dataset’s uncertainty [Rot09]. This is one reason why practical processing of uncertain data requires quantitative or qualitative descriptions of the aspects of uncertainty [Röh14]. Quantitative descriptions may be probabilities, error percentages, metrics and standard deviations. A possible alternative is to assign uncertain data to different uncertainty classes, value ranges or sets of potential values. For aspects that are difficult to quantify or cannot be quantified, qualitative descriptions can be used. An example would be "data at first-hand" concerning the data’s lineage. Such descriptions of uncertainty can be associated with the data in form of metadata.

### Sources of uncertainty of bathymetric data

As described by Hare et al. [HEA11], the basic sources of uncertainty of bathymetric data are quite well known. There are sources that contribute to uncertainty of depth measurements only (i.e., *vertical uncertainty*), like tides, wind, wave height, draft and heave, sources that contribute to uncertainty concerning the measurement position (i.e., *horizontal uncertainty*), such as horizontal positioning system and heading sensor, and sources that contribute to both, for example range and beam angle of echosounders. Moreover, there do exist sources that contribute to *temporal uncertainty* of bathymetric data, such as highly mobile or dynamic seabeds, changing amount of water and environmental influences as mentioned above (i.e., tides, wind, wave height).

According to [HEA11], sources of uncertainty can be classified as follows:

- **Platform**: e.g., static draft and changes in draft, vessel speed, location of sensors and dynamics of vessel such as amount of roll, pitch, heave and yaw
- **Sensor measurements**: e.g., sonar, roll, pitch, heading, heave and positioning
- **Environment**: e.g., tides, sound speed structure, sea state, state of seabed
- **Integration**: i.e, synchronization of all sensor measurements
- **Calibration**: e.g., misalignment angles of the sonar and the motion sensor

In case a suitable measurement uncertainty model is available, all contributing sources can be combined and the total horizontal and vertical uncertainty can be estimated. For the example of multibeam sonar systems, the methodology is documented in [Har95].

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1 Metadata is data that provides information about other data.
2 Analysis of the current situation

Further details concerning sources of uncertainty concerning bathymetric data can be found in the IHO standards for hydrographic surveys [IHB08].

Descriptions of bathymetric data’s uncertainty

The official transfer standard for ENC data (S-57) defines possibilities for storing quality information/information concerning uncertainty of bathymetric data from individual surveys. For this purpose, specific metadata objects and attributes of such objects are reserved. Mandatory information concerning quality, reliability and accuracy must be stored in the meta object $M\_QUAL$ [IHO14]. A requirement is that such information have been assessed in a uniform way for the respective area. One attribute of $M\_QUAL$ is $CATZOC$ (Category of zone of confidence). $CATZOC$ is a composite quality indicator which categorizes an area according to its state of assessment, horizontal uncertainty, vertical uncertainty, completeness of the survey and whether significant seafloor features have been detected. The categories are $A1, A2, B, C, D$ and describe the data’s quality in descending order. An additional category $U$ is used for areas where data quality is unassessed. More information concerning $CATZOC$ categories can be found in [IHO16].

Besides $M\_QUAL$, additional details about survey reliability can be stored optionally in the meta object $M\_SREL$. This includes information based on the source of the hydrographic survey as well as quality of soundings.

If further details regarding sounding accuracy, technique of sounding measurement and positional accuracy are required, they can be stored in additional attributes of $M\_QUAL$ and $M\_SREL$.

In 2011, IHO’s DQWG conducted a study with 574 participants concerning the suitability of $CATZOC$ and its current representation [HWG12]. As key results they found that more than 70% of all participants did not use the $CATZOC$ representation in ECDIS and that the majority would prefer an alternative solution. Moreover, the limited expressiveness of $CATZOC$ was criticized. As a consequence of these results, DQWG decided to replace the $CATZOC$ attribute with the more comprehensive composite quality indicator $Quality\ of\ Bathymetric\ Data$ (QOBD) [DQW15], which is going to be standardized in S-101. A big advantage of QOBD is, that it also takes temporal uncertainty into account for classification (i.e., if the seabed is changing over time). Moreover, it offers the possibility to “assess the quality as Oceanic in cases where the hydrographic office considers the waters in question being adequately safe for navigation because of location far offshore even if the positional uncertainty, completeness or temporal conditions for are not met” [DQW15]. Further quality categories of QOBD are $Quality\_1$ to $Quality\_5$, where data quality decreases with increasing number and $Unassessed\ (U)$ similar to $CATZOC$. The decision tree for classification is provided in [IHO15a].
2.2 Tasks

Several tasks demand the mariner’s consideration of information concerning uncertainty of the depths shown in a ENC. One can distinguish between tasks for two scenarios: route planning and monitoring [HWG12].

For route planning, the mariner must select a suitable route through safe water, where under keel clearance is assured during the entire voyage. This does not only require to perceive depth information depicted in the chart, but also information about their potential deviations caused by uncertainty and dynamic draught. If a certain route bears the risk of too shallow water, the mariner must be able to identify this situation.

In monitoring scenarios where a ship follows a specified route without significant deviations, information concerning uncertainty of depths are less relevant. However, in case of an emergency or any other situation where a planned route must be left, mariners must be able to navigate safely. This includes to decide whether certain waters are still deep enough when taking their uncertainty into account.

2.3 Current Representations in ENCs

In the following, the standardized representation of bathymetric data and its uncertainty in ENCs is summarized.

Visualization of bathymetric data

According to the ENC presentation standard S-52, bathymetric data is visualized in three different ways:

Colored areas depict depth zones  Depending on so-called depth contour thresholds specified by the mariner, marine areas are classified into depth zones, which are represented as differently colored areas in the ENC. Used colors vary depending on the current ECDIS mode. Available modes are day, dusk and night. A white to dark blue categorical color scheme is applied in day mode as illustrated in figure 2.1.

Contour lines represent depth contours  In addition to depth zones, depth contours (zero meter contour, shallow contour, deep contour) are visualized as thin contour lines. One exception is the representation of the safety contour\(^2\) that is highlighted with a thicker contour line and more conspicuous color (see Figure 2.1). As described above, applied colors depend on the current ECDIS mode.

\(^2\)The safety contour is an important depth threshold between safe water for navigation and unsafe water. It should be always set to the vessel safety draft which is defined as the sum of vessel draft, dynamic squat and a safety margin [DIP12]
2 Analysis of the current situation

**Numbers show selected depths**  Selected depths (soundings) which are representative for certain areas are depicted as numbers in ENCs. Their representation depends on the safety depth set by the mariner, which should equal the depth for the safety contour as recommended in [DIP12]. As shown in Figure 2.2, soundings deeper than the safety depth are displayed as gray numbers while soundings shallower than the safety depth are highlighted with black color in day mode.

![Figure 2.1: Visualization of depth zones and depth contours in ENCs. Depth zones are depicted as blue colored areas whereas depth contours are represented with grey/black contour lines. Land areas are colored in brown. In this exemplary ENC representing a part of the Irish sea in day mode, the following parameters for depth contours were used: zero meter contour: 0m, shallow contour: 2m, safety contour 20m, deep contour 30m.](image)

![Figure 2.2: Representation of selected depths in ENCs based on the safety depth threshold. In this example from [DIP12], the safety depth and the depth for the safety contour were both set to 20m. Depths deeper than 20m are colored in grey, while depths shallower than 20m are highlighted in black color.](image)
2.3 Current Representations in ENCs

Visualization of CATZOC

From the metadata objects and attributes used to store information concerning uncertainty of bathymetric data, only CATZOC can be visualized at the moment. This severely limits their usefulness [DH12]. According to S-52, the categories of CATZOC are represented as a symbol pattern (glyphs containing stars) with an optional ENC layer. Figure 2.3 shows the respective class-symbol mapping. An exemplary ENC where the CATZOC representation layer is currently activated is given in Figure 2.4.

![Figure 2.3: Mapping from CATZOC classes to symbols for representation in ENCs according to S-52.](image1)

![Figure 2.4: Day mode Visualization of CATZOC in an ENC. Numbers of selected depths have been removed to increase visibility of the CATZOC symbol pattern.](image2)

Further approaches for visualizing uncertainty in ENCs

Some techniques have already been developed to improve the visualization of uncertainty concerning bathymetric data in ENCs.
2 Analysis of the current situation

Encoding uncertainty with color

In 2011, Hare et al. proposed to encode an estimated quantification of the uncertainty for coastal areas with a continuous color scale in a juxtaposed ECDIS view (see Figure 2.5a) [HEA11]. A drawback of this approach is that it may conflict with the colors used to represent depth zones. Because the authors realized that encoding depth information and uncertainty in a single view would be even better, they also suggested a solution in this regard. This solution first calculates a correction of the charted depths in coastal regions based on an estimated quantification of the uncertainty, real-time information of tides and a vessel draft buffer set by the mariner. Afterwards, resulting depths are placed into three categories (safe-to-go-zone, cautionary zone, no-go zone) and visualized by using a green-yellow-red categorical color scale as shown in Figure 2.5b. However, this kind of traffic light visualization is not recommended for this purpose by the IHO, because it is reserved for the representation of under keel clearance [NIP16; DQW14b].

![Visualization of uncertainty by using a continuous color scale.](image1)

![Visualization of uncertainty by using a traffic light categorical color scale.](image2)

Figure 2.5: Techniques for visualizing uncertainty of bathymetric data proposed by Hare et al. [HEA11].

Encoding uncertainty with glyphs

In [NIP16], further visualization techniques were proposed considering the "general composition principles of the chart display as standardized by S-52, namely color tables for different light conditions (ECDIS modes day and night), contrast between fore- and background colours, symbol size and shape". However, as these techniques address a deprecated composite quality indicator with four classes, their applicability is limited. As illustrated in figure 2.6a, one technique uses a ring pattern overlay where circles are colored according to the underlying uncertainty class in either green, yellow, red or white. However, as described above, such a traffic light color scheme is already reserved for representing under keel clearance. A variation of this technique using
2.3 Current Representations in ENCs

A sequential color scale with varying saturation and brightness is also proposed, as can be seen in Figure 2.6b. A third proposal is to visualize uncertainty classes with a pie chart pattern overlay of varying transparency. An example is given in Figure 2.6c. As drawbacks of this approach, ambiguity and severe display clutter are mentioned in [DQW15].

Because visual clutter is recognized as a growing problem in ENCs, the authors further suggested to optionally restrict the uncertainty visualization to a local region of interest, for example a corridor along the ship’s route.

Figure 2.6: Techniques for visualizing uncertainty of bathymetric data recently proposed in [NIP16]. (a) uses a ring pattern overlay with a traffic light color scheme, (b) uses a ring pattern overlay with varying saturation and brightness of a selected color and (c) uses a pie chart pattern overlay of varying transparency.

Encoding uncertainty with texture

Another suggestion of how uncertainty might be visualized in ENCs is given in [DQW14b]. As illustrated in Figure 2.7, the idea is to encode uncertainty classes with varying transparency of a texture overlay. In contrast to the solutions described above, this approach could be applied to visualize the new S-101 composite quality indicator QOBD.
2 Analysis of the current situation

Figure 2.7: Using transparency of a texture overlay to encode different classes of uncertainty in ENCs as proposed in [DQW14b].
3 Visualization of uncertainty in Information Visualization and Cartography

The goal of visualizing uncertainty is to communicate its existence and its influence on the data. This facilitates a sound analysis of the data and enables users to make more accurate and reliable decisions [Tho+05; Har02]. However, visualizing uncertainty in addition to the data is challenging as the amount of information to be represented increases considerably while the human perception and possibilities for encoding information via visual variables remain limited [PRJ12].

Visual variables are graphic dimensions across which a graphical object can be varied to encode information [Ber83].

For this reason it is often not possible to visualize all aspects of the data and its uncertainty at once. One strategy to deal with this problem is to represent subsets of interest or abstractions only, for example composite quality indicators like CATZOC or QOBD. In some situations, it is even not sensible to visualize all data. When working with critical data where wrong decisions caused by uncertainty can have fatal consequences (e.g., affecting a large number of people), it is common to discard any data for visualization exceeding a specific uncertainty threshold, which is defined according to the given application and tasks [Hol+12].

An additional challenge when visualizing uncertainty is to meet general requirements like distinguishability between data and uncertainty, avoidance of mutual interference between the visual representation of data and uncertainty, intuitive interpretability, and efficient perception via suitable visual variables [Mac+05; Ger98].

In the last two decades, more than 100 papers addressing uncertainty visualization have been published within the fields of information visualization and cartography. A lot of this research focused on the fundamental problem of deciding how to depict the data and its uncertainty [Mac+05]. The variety of existing approaches can be classified in different ways [BOL12; PRJ12; Mac+05; PWL97]. One possibility is to differentiate approaches according to the combination of visual data representation and uncertainty representation as proposed by MacEachren [Mac92]:

1. **Visualizing data and uncertainty side-by-side**: These approaches use the visualization concept of multiple coordinated views and separate the representation of data and uncertainty across views [San+10; Slo+09; Pot+10; JCL04; Mac92].
3 Visualization of uncertainty in Information Visualization and Cartography

Figure 3.1: Visualizing minimum temperature (data) and error (uncertainty) in juxtaposed maps [GD16].

Figure 3.2: Visualizing minimum temperature (data) and error (uncertainty) in an integrated way. Different levels of transparency are used to represent different levels of error. "Areas with a larger error are more difficult to see through" [GD16].

When following this approach, the user has to mentally overlay both representations or to compare specific areas to determine how reliable the data is [GD16]. An example is the pair of maps presented in Figure 3.1.

2. **Sequential visualization of data and uncertainty:** Data or uncertainty are presented in the same view but not at the same time. A toggled map display as presented in [GD16], where the user has to interact with the system to switch between data representations or uncertainty representation, would be an example for this category of approaches. Further possibilities are to toggle the representation switch automatically similar to the *blinking regions* approach [KMG06], or to use an animated change of the representation over time indicating uncertainty (e.g., potential value alternatives) [BFW02; DK97; ESG97].

3. **Combined visualization of data and uncertainty:** These approaches have in common, that the data of interest and its uncertainty are both represented in one view at the same time. An example is depicted in Figure 3.2. One advantage of such integrated representations is that it is virtually impossible for users to ignore the uncertainty information [GD16]. However, it is important to carefully choose combinations of visual variables so that the uncertainty representation clarifies the data rather than clutters it [LB00]. Researchers have tested various combinations of visual variables to determine which ones are most effective. They have generally found that visually separable variable combinations are better than visually integral combinations [GD16; Mun14].
Another possibility to categorize existing approaches for uncertainty visualization is to distinguish how uncertainty is encoded. A simple but general categorization in this regard is introduced by Gershon [Ger98]: intrinsic and extrinsic visualization of uncertainty. Both categories are described in the following two sections and examples are given. In doing so, it is assumed that data is encoded by color as it is done with bathymetric data in ENCs (i.e. depth zones).

### 3.1 Intrinsic uncertainty visualization

An intrinsic or integrated visualization of uncertainty means, that uncertainty is encoded via additional, unused visual variables (e.g., fuzziness, noise, transparency) of graphical objects used to represent the data via basic visual variables (e.g., color, position, shape, size etc. [Mun14; Ber83]). As obvious, the applicability of such approaches depends largely on the data representation itself.

A large number of visual variables have been proposed as valid means to represent uncertainty, but only few techniques were actually developed and even less have been evaluated [Dre09]. The following paragraphs provide selected examples.

**Color** A typical approach is to encode uncertainty by varying color [Mac+05]. Color is a composite visual variable and can be further divided into three separate variables: hue, saturation and brightness. If the data is for instance visualized by color hue, saturation and brightness can be used to depict uncertainty. In [Hen03] for example, saturation and brightness (i.e., "whiteness") are incremented proportionally with increasing data uncertainty. This leads to an image where the representation of uncertain data becomes pale or white as illustrated in figure 3.3. Another option for representing data and uncertainty simultaneously is to utilize a bi-variate color scale [TSS11] as shown in Figure 3.4.

**Noise, blur, fog and transparency** To support the user in distinguishing color coded data and representation of uncertainty, it makes sense to visualize uncertainty with different visual variables. Noise, blur, fog and transparency are considered as intuitive candidates for this purpose. However, when using these visual variables, it is difficult to decode exact values. Thus, they should be rather used for visualizing qualitative aspects of uncertainty [Röh14].

In literature, transparency has been used to encode uncertainties of spatial structures and time reference of historical architecture [ZCG05; SS02] (see Figure 3.5d). A general drawback of transparency is, that it leads to mixed colors with the background, which may be interpreted in the wrong way.

As exemplified in Figures 3.5a – 3.5c, varying levels of noise, fog and blur have been used to encode uncertainty of volume, flow, and geo-spatial data [Röh14; Con+11; BWE05; Dju+02]. Blur and fog, however, usually affects the entire content of an image
3 Visualization of uncertainty in Information Visualization and Cartography

Figure 3.3: Color encoding of data (left) where saturation and brightness are set proportionally to uncertainty of the data (right) [Hen03].

Figure 3.4: Using a bi-variate color scale for encoding data and uncertainty at the same time (right). For comparison, an individual encoding of data and uncertainty is shown on the left and center [Röh14].

area. This might include a spatial reference in the background (e.g., a map when dealing with geo-spatial data), which leads to reduced visibility. A requirement for using blur is a visually structured background. While blur can be seen easily on edges of objects, it is difficult, sometimes even impossible, to recognize on uniform image areas or areas with color gradients.

Illustrative methods Another option to represent uncertainty is to apply illustrative methods from the field on non-photo-realistic rendering. These include differently styled polylines and the simulation of water colors as discussed in [Lub14; LRS10]. When using polylines, various variables can be used to encode uncertainty, for example width, end-caps, dash-pattern, blur or the level of sketchiness as depicted in Figure 3.6a.

With a water color simulation as exemplified in Figure 3.6b, uncertainty can be encoded by varying grain (i.e., capacity of the virtual medium) and blur (i.e., absorbability of the
3.1 Intrinsic uncertainty visualization

Figure 3.5: Visualizing uncertainty by using noise (a) [Con+11], blur (b) [Röh14], fog (c) [Röh14] and transparency (d) [ZCG05].

medium) in addition to the color-coded data.

Figure 3.6: Visualizing uncertainty by using illustrative methods. In (a), the uncertainty of a building’s structure is visualized with sketched lines [Sch+96]. (b) shows a visualization of uncertainty via water color simulation [Lub14; LRS10].
3 Visualization of uncertainty in Information Visualization and Cartography

3.2 Extrinsic uncertainty visualization

Approaches for extrinsic visualization of uncertainty have in common, that they use separate graphical objects with their own visual variables for encoding either data or uncertainty. Thus, the visualization of uncertainty does not fully depend on the visualization of data. However, to enable users to set both in relation, respective visual cues must be used. This may be spatial proximity, a similar color encoding, or visual links (e.g., lines connecting related objects). A general drawback of extrinsic approaches is, that added graphical objects may lead to occlusion and visual clutter. In the following, selected approaches are briefly described.

**Glyphs** A common approach which is capable of visualizing multiple aspects of uncertainty concerning a data point or a local area of interest is to superimpose the data representation with glyphs. Various solutions have been developed which fall into this category [San+10; ZWK10; Mil+03; CR00; Pan01; WPL96]. One example is the representation of CATZOC with star-glyphs according to S-52 (see Figures 2.3 and 2.4 on page 9). Further approaches include line glyphs to represent uncertainty of vector fields [Zuk08], circular glyphs to communicate uncertainty of geo-spatial data [Röh14] and complex glyphs for representing spatial, temporal as well as attribute uncertainty, as shown in Figure 3.7.

![Figure 3.7: Visualizing spatial, temporal and attribute uncertainty with a complex glyph. Attribute uncertainty in this case refers to the uncertain dosage of a release of a toxic substance. [GD16].](image-url)
3.2 Extrinsic uncertainty visualization

**Isolines**  Another common approach is to define specific uncertainty thresholds being represented by isolines [Röh14; San+10; PH11; Pot+10; AB08]. To ensure that users can distinguish between the thresholds of different isolines, a different line color, line thickness or line style should be applied. Figure 3.8a presents an example of visualizing the uncertainty of geo-spatial data with isolines.

**Hierarchical Structure**  As presented in [KMB03] and [Röh14], uncertainty concerning data with spatial reference can also be represented by superimposing a mesh or structure which is hierarchically subdivided. The level of subdivision is utilized to indicate the extent of the underlying data’s uncertainty. Various types of hierarchical structures can be used for this purpose, for example triangle meshes as illustrated in Figure 3.8b.

![Figure 3.8: Visualizing uncertainty associated with geo-spatial data via additional isolines or superimposed hierarchical structure.](image)

(a) (b)

In summary, a large variety of approaches for visualizing uncertainty along with different types of data have been proposed. Additionally, there is a growing body of empirical
Figure 3.9: Encoding uncertainty of geo-spatial data by using a texture overlay with varying transparency (a) [VCL11] and a superimposed hatching with varying number, alignment and opacity of strokes (b) [Röh14].

research that is providing insights concerning which methods are effective in different application contexts and for which types of tasks [Mac+05]. However, there is little agreement in the literature about when and why one uncertainty visualization strategy should be used over others, or in other words, what is the best way to represent uncertainty [Mac+12]. "[..] Most methods for depicting uncertainty visually have been tested in only a single narrow study, if at all" [Mac+05; Dre09]. Consequently, selecting an approach for visualizing uncertainty associated with bathymetric data is difficult.
4 New ways of visualizing uncertainty of bathymetric data in S-101 ENCs

In this chapter, approaches for visualizing uncertainty along with bathymetric data in future S-101 ENCs are proposed. To be able to do so, the large variety of existing visualization approaches, as summarized in the previous chapter, must be checked concerning their applicability for this specific use case. For this reason, application dependent requirements are defined.

4.1 Requirements

- **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.
4 New ways of visualizing uncertainty of bathymetric data in S-101 ENCs

- 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 [DQW14b].
- P7: Uncertainty should not be visualized via glyphs [DQW14b].
- 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 [DQW14b].
- 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) 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.
4.2 Proposals

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, 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 definitly 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, information concerning uncertainty of depths in monitoring scenarios are necessary for nearby areas when a planned 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 on page 8 and Figure 2.4 on page 9). 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
4.2 Proposals

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). 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), adapting their transparency (or brightness) according to QOBD categories does not work. As shown in Figure 6.2 in the annex, 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. Another important texture requirement is, that the size and line thickness 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). 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. Figures of this kind of visualization concerning further combinations of ECDIS mode and application scenario are provided in the annex (see page 33).

Although the described approach visualizes QOBD quite well, there is still room for improvement by using a redundant encoding (R6). One proposed option in this regard is to communicate different QOBD classes additionally by varying size of texture elements (i.e., squares or hexagons). In the light of P4, the size of texture elements should be decreased with increasing uncertainty. Thereby, a uniform line thickness must be maintained. Textures well suited for this purpose allow for a hierarchical subdivision of their elements into similar elements. One example is a regular grid consisting of squares as illustrated in Figure 4.5 and 4.6. 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 with different QOBD category.
4.2 Proposals

Figure 4.1: Visualizing QOBD with a grid texture overlay in a fictitious route planning scenario. The current ECDIS modes are day and base mode \(^1\).

Figure 4.2: Visualizing QOBD with a hexagon texture overlay in a fictitious route planning scenario. The current ECDIS modes are day and base.

Independently from the technique 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).

\(^1\)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.
4 New ways of visualizing uncertainty of bathymetric data in S-101 ENCs

Figure 4.3: Visualizing QOBD with a grid texture overlay in a fictitious monitoring scenario. The current ECDIS modes are dusk and base.

Figure 4.4: Visualizing QOBD with a hexagon texture overlay in a fictitious monitoring scenario. The current ECDIS modes are dusk and base.

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
4.2 Proposals

Figure 4.5: Visualizing QOBD with a hierarchical grid overlay in a fictitious route planning scenario. The current ECDIS modes are day and base.

Figure 4.6: Visualizing QOBD with a hierarchical grid overlay in a fictitious monitoring scenario. The current ECDIS modes are dusk and base.

The bottom part of Figure 4.5 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 4.7, 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 4.7 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 4.7). 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 4.8 shows a second depth profile visualization in dusk mode for the fictitious route used in Figure 4.1 to Figure 4.6. Further examples are provided in the annex.
Figure 4.7: 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 4.8: 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 4.6.
5 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 ENC.s 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 ENC.s represent a multitude of information in a complex way and already utilize a large number of different visual variables. To be able to propose suitable visualization solutions, the first step was to analyze bathymetric data and their associated uncertainties as well as the mariners’ tasks. Afterwards, the literature on uncertainty visualization was reviewed and existing approaches were investigated. This led to specific requirements for visualizing uncertainty associated with bathymetric data in ENC.s. On this basis, recommendations concerning what aspects of uncertainty should be visualized, where they should be visualized and how they should be visualized were given. This included an approach for visualizing the new compound quality indicator QOBD with a texture overlay, a solution for visualizing potentially unsafe waters based on a quantification of the overall uncertainty and a novel approach for visualizing a depth profile in an additional ECDIS view. A formal evaluation of these approaches within a user study is a sensible next step for future work.
6 Annex

The following Figures 6.1 and 6.2 underline that an intrinsic visualization of QOBD via noise applied to the representation of depth zones, or transparency applied to numbers of selected depths should not be used. As can be seen, QOBD categories are difficult to distinguish.

Figure 6.1: Visualizing QOBD with varying noise applied to depth zones for a route planning scenario. The current ECDIS modes are day and base. This approach is not recommended as QOBD categories are difficult to distinguish.

Figure 6.2: Visualizing QOBD with varying transparency applied to numbers of selected depths for a route planning scenario. The current ECDIS modes are day and base. This approach is not recommended as QOBD categories are difficult to distinguish.
The following figures refer to the visualization approach described in Section 4.2.3.1 (and 4.2.3.2) and illustrate different combinations of textures, ECDIS modes and application scenario (i.e., route planning or monitoring). The texture consisting of hierarchically subdivided squares is assessed as the most efficient variant and presented first.

**Visualizing QOBD via hierarchical grid texture overlay**

Figure 6.3: Visualizing QOBD via hierarchical grid texture overlay for a route planning scenario in ECDIS modes day and base. QOBD categories are encoded by varying texture transparency and hierarchy level.

Figure 6.4: Visualizing QOBD via hierarchical grid texture overlay for a route planning scenario in ECDIS modes dusk and base. QOBD categories are encoded by varying texture transparency and hierarchy level.
Figure 6.5: Visualizing QOBD via hierarchical grid texture overlay for a route planning scenario in ECDIS modes night and base. QOBD categories are encoded by varying texture transparency and hierarchy level.

Figure 6.6: Visualizing QOBD via hierarchical grid texture overlay for a monitoring scenario in ECDIS modes day and base. QOBD categories are encoded by varying texture transparency and hierarchy level.
Figure 6.7: Visualizing QOBD via hierarchical grid texture overlay for a monitoring scenario in ECDIS modes dusk and base. QOBD categories are encoded by varying texture transparency and hierarchy level.

Figure 6.8: Visualizing QOBD via hierarchical grid texture overlay for a monitoring scenario in ECDIS modes night and base. QOBD categories are encoded by varying texture transparency and hierarchy level.
Figure 6.9: Visualizing QOBD via hierarchical grid texture overlay for a route planning scenario in ECDIS modes day and standard. QOBD categories are encoded by varying texture transparency and hierarchy level.

Figure 6.10: Visualizing QOBD via hierarchical grid texture overlay for a route planning scenario in ECDIS modes dusk and standard. QOBD categories are encoded by varying texture transparency and hierarchy level.
Figure 6.11: Visualizing QOBD via hierarchical grid texture overlay for a route planning scenario in ECDIS modes night and standard. QOBD categories are encoded by varying texture transparency and hierarchy level.

Figure 6.12: Visualizing QOBD via hierarchical grid texture overlay for a monitoring scenario in ECDIS modes day and standard. QOBD categories are encoded by varying texture transparency and hierarchy level.
Figure 6.13: Visualizing QOBD via hierarchical grid texture overlay for a monitoring scenario in ECDIS modes dusk and standard. QOBD categories are encoded by varying texture transparency and hierarchy level.

Figure 6.14: Visualizing QOBD via hierarchical grid texture overlay for a monitoring scenario in ECDIS modes night and standard. QOBD categories are encoded by varying texture transparency and hierarchy level.
Visualizing QOBD via hexagon texture overlay with varying scale

Figure 6.15: Visualizing QOBD via hexagon texture overlay with varying scale for a route planning scenario in ECDIS modes day and base. QOBD categories are encoded by varying texture transparency and scale.

Figure 6.16: Visualizing QOBD via hexagon texture overlay with varying scale for a route planning scenario in ECDIS modes dusk and base. QOBD categories are encoded by varying texture transparency and scale.
Figure 6.17: Visualizing QOBD via hexagon texture overlay with varying scale for a route planning scenario in ECDIS modes night and base. QOBD categories are encoded by varying texture transparency and scale.

Figure 6.18: Visualizing QOBD via hexagon texture overlay with varying scale for a monitoring scenario in ECDIS modes day and base. QOBD categories are encoded by varying texture transparency and scale.
Figure 6.19: Visualizing QOBD via hexagon texture overlay with varying scale for a monitoring scenario in ECDIS modes dusk and base. QOBD categories are encoded by varying texture transparency and scale.

Figure 6.20: Visualizing QOBD via hexagon texture overlay with varying scale for a monitoring scenario in ECDIS modes night and base. QOBD categories are encoded by varying texture transparency and scale.
Figure 6.21: Visualizing QOBD via hexagon texture overlay with varying scale for a route planning scenario in ECDIS modes day and standard. QOBD categories are encoded by varying texture transparency and scale.

Figure 6.22: Visualizing QOBD via hexagon texture overlay with varying scale for a route planning scenario in ECDIS modes dusk and standard. QOBD categories are encoded by varying texture transparency and scale.
Figure 6.23: Visualizing QOBD via hexagon texture overlay with varying scale for a route planning scenario in ECDIS modes night and standard. QOBD categories are encoded by varying texture transparency and scale.

Figure 6.24: Visualizing QOBD via hexagon texture overlay with varying scale for a monitoring scenario in ECDIS modes day and standard. QOBD categories are encoded by varying texture transparency and scale.
Figure 6.25: Visualizing QOBD via hexagon texture overlay with varying scale for a monitoring scenario in ECDIS modes dusk and standard. QOBD categories are encoded by varying texture transparency and scale.

Figure 6.26: Visualizing QOBD via hexagon texture overlay with varying scale for a monitoring scenario in ECDIS modes night and standard. QOBD categories are encoded by varying texture transparency and scale.
Visualizing QOBD via grid texture overlay

Figure 6.27: Visualizing QOBD via grid texture overlay for a route planning scenario in ECDIS modes day and base. QOBD categories are encoded by varying texture transparency.

Figure 6.28: Visualizing QOBD via grid texture overlay for a route planning scenario in ECDIS modes dusk and base. QOBD categories are encoded by varying texture transparency.
Figure 6.29: Visualizing QOBD via grid texture overlay for a route planning scenario in ECDIS modes night and base. QOBD categories are encoded by varying texture transparency.

Figure 6.30: Visualizing QOBD via grid texture overlay for a monitoring scenario in ECDIS modes day and base. QOBD categories are encoded by varying texture transparency.
Figure 6.31: Visualizing QOBD via grid texture overlay for a monitoring scenario in ECDIS modes dusk and base. QOBD categories are encoded by varying texture transparency.

Figure 6.32: Visualizing QOBD via grid texture overlay for a monitoring scenario in ECDIS modes night and base. QOBD categories are encoded by varying texture transparency.
Figure 6.33: Visualizing QOBD via grid texture overlay for a route planning scenario in ECDIS modes day and standard. QOBD categories are encoded by varying texture transparency.

Figure 6.34: Visualizing QOBD via grid texture overlay for a route planning scenario in ECDIS modes dusk and standard. QOBD categories are encoded by varying texture transparency.
Figure 6.35: Visualizing QOBD via grid texture overlay for a route planning scenario in ECDIS modes night and standard. QOBD categories are encoded by varying texture transparency.

Figure 6.36: Visualizing QOBD via grid texture overlay for a monitoring scenario in ECDIS modes day and standard. QOBD categories are encoded by varying texture transparency.
Figure 6.37: Visualizing QOBD via grid texture overlay for a monitoring scenario in ECDIS modes dusk and standard. QOBD categories are encoded by varying texture transparency.

Figure 6.38: Visualizing QOBD via grid texture overlay for a monitoring scenario in ECDIS modes night and standard. QOBD categories are encoded by varying texture transparency.
Visualizing QOBD via hexagon texture overlay

Figure 6.39: Visualizing QOBD via hexagon texture overlay for a route planning scenario in ECDIS modes day and base. QOBD categories are encoded by varying texture transparency.

Figure 6.40: Visualizing QOBD via hexagon texture overlay for a route planning scenario in ECDIS modes dusk and base. QOBD categories are encoded by varying texture transparency.

The following figures illustrate the visualization approach described in Section 4.2.3.3 for the ECIDS modes day, dusk and night in two exemplary monitoring scenarios.
Figure 6.41: Visualizing QOBD via hexagon texture overlay for a route planning scenario in ECDIS modes night and base. QOBD categories are encoded by varying texture transparency.

Figure 6.42: Visualizing QOBD via hexagon texture overlay for a monitoring scenario in ECDIS modes day and base. QOBD categories are encoded by varying texture transparency.
Figure 6.43: Visualizing QOBD via hexagon texture overlay for a monitoring scenario in ECDIS modes dusk and base. QOBD categories are encoded by varying texture transparency.

Figure 6.44: Visualizing QOBD via hexagon texture overlay for a monitoring scenario in ECDIS modes night and base. QOBD categories are encoded by varying texture transparency.
Figure 6.45: Visualizing QOBD via hexagon texture overlay for a route planning scenario in ECDIS modes day and standard. QOBD categories are encoded by varying texture transparency.

Figure 6.46: Visualizing QOBD via hexagon texture overlay for a route planning scenario in ECDIS modes dusk and standard. QOBD categories are encoded by varying texture transparency.
Figure 6.47: Visualizing QOBD via hexagon texture overlay for a route planning scenario in ECDIS modes night and standard. QOBD categories are encoded by varying texture transparency.

Figure 6.48: Visualizing QOBD via hexagon texture overlay for a monitoring scenario in ECDIS modes day and standard. QOBD categories are encoded by varying texture transparency.
Figure 6.49: Visualizing QOBD via hexagon texture overlay for a monitoring scenario in ECDIS modes dusk and standard. QOBD categories are encoded by varying texture transparency.

Figure 6.50: Visualizing QOBD via hexagon texture overlay for a monitoring scenario in ECDIS modes night and standard. QOBD categories are encoded by varying texture transparency.
Figure 6.51: Visualizing the quantified uncertainty with a depth profile plot in ECDIS mode day in a monitoring scenario. The depth profile visualizes data from the route selected figures above.

Figure 6.52: 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 figures above.

Figure 6.53: Visualizing the quantified uncertainty with a depth profile plot in ECDIS mode night in a monitoring scenario. The depth profile visualizes data from the route selected figures above.
Figure 6.54: Visualizing the quantified uncertainty with a depth profile plot in ECDIS mode day in a second monitoring scenario. The shown profile is not based on real data and serves for the purpose of illustration only.

Figure 6.55: Visualizing the quantified uncertainty with a depth profile plot in ECDIS mode dusk in a second monitoring scenario. The shown profile is not based on real data and serves for the purpose of illustration only.

Figure 6.56: Visualizing the quantified uncertainty with a depth profile plot in ECDIS mode night in a second monitoring scenario. The shown profile is not based on real data and serves for the purpose of illustration only.
Bibliography


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