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Preliminary Study on Data Consistency of S-100-based Product Specifications for Ensuring S-98 Interoperability: Focusing on S-101 and S-102 Empirical Data

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The International Maritime Organization (IMO) has adopted revised Electronic Chart Display and Information System (ECDIS) performance standards that support the operational use of S-100-based hydrographic products, with optional implementation beginning in 2026 and mandatory implementation from 2029. During this digital transformation, interoperability issues among S-100 product specifications, including Electronic Navigational Charts (S-101) and Bathymetric Surface (S-102), have become critical concerns. S-101 represents charted soundings through selected point-based depth information edited for nautical chart production, whereas S-102 provides gridded bathymetric information in which the shallowest depth within each cell is used as the representative value. Although both product specifications are intended to support consistent portrayal and safe navigation, differences in data structure and depth representation may result in discrepancies in displayed depth information, potentially causing ambiguity in navigational interpretation and reducing safety. Therefore, semantic consistency and data reliability between S-100-based products must be ensured beyond formal compliance with individual product specifications. In this study, a comprehensive data governance framework is proposed as a fundamental approach to addressing these interoperability issues. The proposed framework covers policy and technical management across the entire data lifecycle, including data generation, validation, distribution, and updating. By establishing consistent governance mechanisms, the proposed approach is expected to improve data quality, enhance reliability among S-100 product specifications, and contribute to the successful implementation and operational use of the S-100 framework in digital hydrographic information services.

1. Introduction

With the revision of the Universal Hydrographic Data Model (S-100), spearheaded by the International Hydrographic Organization (IHO), to version 5.2.0,[1,2] the paradigm of marine

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geospatial information is shifting from a legacy single ENC (S-57)-centric system to a multidimensional information fusion system. Consequently, the future Electronic Chart Display and Information System (ECDIS) will omit display multiple product specifications in an integrated manner on a single screen.(3,4) These include not only the S-101 ENC for navigation but also the S-102 Bathymetric Surface for high-resolution seabed topography, S-111 (Surface Currents), and S-104 (Water Level).

The key challenge in this multidata environment is ensuring interoperability to prevent conflicts between differing standards and to ensure seamless integration.(5) To address this, the IHO established the S-98 Interoperability Specification, which defines the layer ordering and processing rules for data displayed on the screen.(5) According to the current S-98 Interoperability Catalogue, when an S-101 ENC and an S-102 Bathymetric Surface overlap in the same area, the system assumes that S-102 provides more precise information and grants it display priority.(5) Accordingly, the sounding objects of S-101 are suppressed on the screen, and the grid depths of S-102 replace them.(5,6)

Previous studies have encompassed several technical aspects related to S-100-based hydrographic data and marine spatial information. Lee *et al.* proposed a data model for the marine information industry based on the S-100 standard,(7) while Kang *et al.* examined S-100 interoperability for the application of multiple S-100 products.(8) Other research groups have evaluated the usability of S-100-based marine GIS software,(9) assessed the accuracy and reliability of S-101 ENCs through validation procedures,(10) and examined S-100 ECDIS implementation based on S-10X digital maritime safety information.(11) Additional studies have also contributed to the development and application of marine spatial and geographic information systems.(12,13) However, those studies were focused mainly on data modeling, system implementation, usability, the validation of individual products, or general spatial information applications. Relatively little attention has been paid to the quantitative consistency between S-101 and S-102 depth information when both products are integrated under the S-98 interoperability framework.

However, the critical issue is that this prioritization is applied mechanically without verifying the consistency between the datasets. Since S-101 and S-102 differ in their generation sources, survey times, and levels of generalization, numerical discrepancies are inevitable. If the system blindly prioritizes S-102 despite the existence of significant errors between the two datasets that could threaten navigational safety, mariners may place undue confidence in incorrect depth information, thereby increasing the risk of marine accidents such as grounding.

Therefore, in this study, we aim to analyze the quantitative differences between S-101 and S-102 data constructed for actual coastal waters in Korea by performing a one-to-one matching of depth information between the two standards. Beyond a simple comparison of mean errors, in this research, we intend to identify the spatial distribution characteristics of errors by sea area (East, West, and South Seas) and depth zone. Ultimately, our purpose is to propose data quality verification mechanisms and safety criteria that should be incorporated into the future S-158 validation process.(14)

2. Overview of S-100 Standard and S-100-based Product Specifications

2.1 IHO S-100 universal hydrographic data model

S-100 is a universal data model based on the ISO 19100 series of geographic information standards.[1,2] It provides a platform for modeling various types of marine information in an object-oriented manner and ensuring interoperability.[1] This model is designed to break away from the rigid structure of the legacy S-57 standard, allowing the flexible integration (plug-and-play) of new data types.[1,4]

2.2 S-101 ENC

S-101 is a product specification that comprehensively defines the structure, representation, and metadata of official ENC datasets for next-generation ECDIS.[15] To overcome the rigidity of S-57, it introduces the concept of managed change based on machine-readable Feature and Portrayal Catalogues. This design ensures consistency between data production by hydrographic offices and the display and alarm functions of navigation systems. Furthermore, it allows for flexible adaptation to operational changes solely through catalogue updates, without requiring core software updates.

In particular, S-101 reinforces vertical reference information directly related to navigational safety. It explicitly specifies the Vertical Datum and Sounding Datum at the dataset level.[15] Precision is enhanced through the use of the VDAT field within the ISO 8211 structure and the application of the Vertical Datum of Data metafeature to express local variations.[15]

2.3 S-102 bathymetric surface

S-102 standardizes the bathymetric surface based on a regular grid to support navigational safety.[16] It is intended to be used either as an independent data product or as a core depth information source for S-100-based ECDIS. This standard integrally defines the data's spatial structure, metadata, encoding structure, portrayal, and exchange format.

The product catalogue is structured around two key coverage types: Bathymetry Coverage and Quality of Bathymetry Coverage. Notably, the quality coverage is interpreted within the same grid system as the bathymetry coverage, ensuring data reliability by including the "uncertainty" attribute for each grid point.

The coordinate system primarily applies EPSG:4326 (WGS84) for global interoperability. However, the use of UTM (32601–32660/32701–32760) and UPS (5041/5042) coordinate systems is permitted depending on regional characteristics or projection needs.

Currently, S-102 Edition 3.0.0 has been officially released for operational use and has been listed in the standards registry.[16] The introduction of S-102 overcomes the limitations of restricted depth information provided by existing ENCs (S-57/S-101). It is emerging as a core element of next-generation navigation support systems by enabling the generation of dynamic

Safety Contours—combining vessel draft and tidal levels—and precise Under Keel Clearance (UKC) management.

2.4 S-98 interoperability specification

S-98 defines the processing rules when multiple S-100 products are superimposed on an ECDIS screen. The current S-98 Interoperability Catalogue stipulates that when S-101 and S-102 overlap, the system must prioritize the display of the higher-precision S-102 data over S-101 depths.

3. Research Methodology

3.1 Definitions and comparative methodology of S-101 and S-102 depth data

To verify the depth consistency between S-101 and S-102, which possess distinct data models, we examined the conceptual characteristics of "depth" defined by each standard and established the validity of the comparative analysis on that basis.

3.1.1 Characteristics of S-101 depth data

In the S-101 ENC, depth information is primarily represented through "sounding" objects. Geometrically, these consist of single-point or multipoint coordinates (x, y) and their corresponding depth values (z). However, from the perspective of navigational safety, the S-101 depth is not merely a physical measurement of a specific point. Within the S-101 data model, a sounding object exists within a depth area partitioned by contours and possesses attributes that represent the depth information of that specific area. In other words, the S-101 depth can be interpreted as the representative depth of an area representing the safe depth of the local area to which the point belongs.

3.1.2 Characteristics of S-102 depth data

The S-102 Bathymetric Surface is composed of a uniform grid with a defined resolution. In this model, depth is defined as a single representative value for each cell, which serves as a two-dimensional areal unit. The S-102 Product Specification defines rules for processing source data during grid generation; typically, to ensure navigational safety, the shoalest depth or a statistical representative value derived from the cell area is assigned as the cell's depth. Consequently, the S-102 depth is also defined as a value representing a spatial unit of a specific size.

3.1.3 Validity and methodology of comparison

From a geometric perspective, a direct one-to-one comparison between the zero-dimensional point data of S-101 and the two-dimensional cell data of S-102 is theoretically impossible owing to spatial mismatch. This is because the spatial scope and the level of generalization represented by the two datasets differ. However, the definitions in the IHO S-100 data model and the principles of navigational safety advocate that a comparison between the two datasets is valid.

- Shoalest Depth Principle: S-100-based navigational data follows the common principle of adopting the minimum value (shoalest depth) within a specific area as the representative depth to prevent vessel grounding.
- Premise of Comparison: Therefore, in this study, we operate under the premise that both the S-101 sounding point and the S-102 grid cell value share the same semantic meaning as the representative shoalest depth that ensures navigational safety at that location.

Accordingly, this study was conducted by identifying and matching the S-102 grid cell that contains the S-101 point coordinates, and then quantitatively comparing the differences between the representative depth values presented by the two datasets.

Figure 1 shows the overall workflow used to extract, spatially match, compare, and statistically analyze S-101 sounding points and S-102 grid cells.

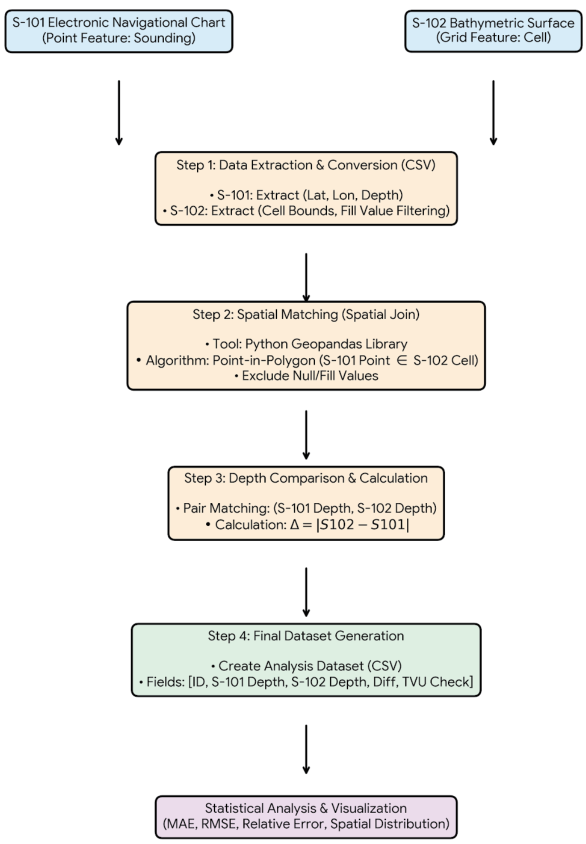

Fig. 1. (Color online) Workflow for S-101 and S-102 depth consistency analyses.

3.2 Data acquisition

To enhance the generalizability of the consistency assessment between S-100-based Product Specifications—so that it is not limited to specific sea areas or datasets—we used datasets with diverse sources and characteristics.

3.2.1 International reference datasets

The S-100 test datasets produced by the United Kingdom Hydrographic Office (UKHO) and the Canadian Hydrographic Service (CHS) were utilized to verify the technical feasibility of the IHO S-100 standard. Generated in a controlled environment, these datasets serve as a baseline for determining standard compliance. For the UKHO datasets, the latest 2023 standard versions were applied for both S-101 and S-102. For the CHS field data distributed via its official portal, the latest 2025 editions were used for both S-101 and S-102.

3.2.2 Domestic field datasets

To reflect the complexities of the actual marine environment, the S-101 and S-102 field datasets covering the East, West, and South Seas of Korea, produced by the Korea Hydrographic and Oceanographic Agency (KHOA), were collected. These datasets differ from foreign reference datasets in that they are operational datasets characterized by rapid changes in seabed topography and a mixture of various survey sources, rather than datasets generated in a controlled environment. Table 1 shows the production years, standard editions, and total numbers of S-101 points and S-102 cells used in the experiment.

3.3 Data preprocessing and null value control

To compare S-101 (vector) and S-102 (grid), which have distinct data structures, the following preprocessing algorithms were applied.

3.3.1 Feature extraction and standardization

From the S-101 ENC, the 3D coordinates (latitude, longitude, depth) of sounding objects were extracted. From the S-102 Bathymetric Surface, the center point coordinates and representative

Table 1
Overview of experimental datasets (S-101 & S-102).

Country (Agency)	Production year		Standard edition		Total count	
	S-101	S-102	S-101	S-102	S-101 points	S-102 cells
South Korea (KHOA)	2025	2025	2.0.0	3.0.0	575578	41427647
Canada (CHS)	2025	2025	2.0.0	3.0.0	439	1001000
UK (UKHO)	2023	2023	1.1.0	2.2.0	14094	30391779

depth values of each cell were extracted. Both datasets were subsequently converted into data tables sharing an identical schema.

3.3.2 S-102 fill value filtering

According to the S-102 Product Specification (Edition 2.0.0), a specific fill value of 1,000,000 is defined for areas where valid depth data does not exist or where transparency processing is required. Interpreting this value as a physical depth during calculation would lead to critical statistical errors. Therefore, in this study, we ensured analysis reliability by applying a filtering rule that regarded cells with a value of 1,000,000 as “no data” and excluded them entirely from the comparison.

3.4 Spatial matching and analysis metrics

For valid matched data pairs, the following quantitative metrics were calculated. In particular, we focused on identifying the magnitude of physical discrepancy between the two datasets rather than the direction of the depth differences (i.e., which is deeper). Consequently, the depth error (E_d) was defined as an absolute value.

$$E_d = |Depth_{S\text{-}102} - Depth_{S\text{-}101}| \tag{1}$$

The analysis includes mean bias, standard deviation (*Std*), and root mean square error (*RMSE*). The total vertical uncertainty (TVU) formula corresponding to the S-44 Order 1a grade—the IHO standard for hydrographic surveys—was applied to determine the compliance status (pass/fail) within the allowable tolerance for each matching point.

4. Results

In this section, we analyze the depth consistency of the preprocessed domestic and international S-100 test datasets. The analysis was divided into overall valid data analysis, by which the overall quality of the data is examined, and valid range analysis (within 20 m), by which substantial precision is evaluated by excluding abnormal outliers.

4.1 Comparative analysis of consistency by country (overall comparison)

4.1.1 Overall data analysis

First, after removing the fill values (1000000) defined in the S-102 standard, depth consistency was calculated for all statistically valid samples. The results are presented in Table 2.

The analysis results indicated that the Canadian and UK datasets exhibited high precision with mean absolute errors (*MAE*s) of 0.12 and 0.37 m, respectively, which were close to zero. Notably, the Canadian data reached a 95.61% compliance rate with IHO S-44 standards,

Table 2
Depth consistency for overall data.

Category	Sample size (*N*)	*MAE* (*m*)	*RMSE* (*m*)	S-44 pass rate (%)
Korea	324038	4.59	7.05	31.02
Canada	433	0.12	0.24	95.61
UK	11144	0.37	0.62	79.14

confirming that almost no discrepancies exist between S-101 and S-102. This can be attributed to the fact that these datasets were produced in a precisely controlled environment for the purpose of standard verification.

In contrast, the Korean field data showed a very large deviation, with an *MAE* of 4.59 m and an *RMSE* of 7.05 m. This appears to result from the existence of cases in which the depth itself is counted as a large absolute error when partial missing data or matching errors occur in the S-102 data in the deep waters (*Depth* > 1,000 m) of the East Sea.

4.1.2 Valid range analysis (within 10 m)

The previous overall analysis may distort the representativeness of the owing due to the presence of extreme outliers. Therefore, to assess practical precision, a reanalysis was performed by regarding depth errors (E_d) exceeding 10 m as abnormal errors and excluding them.

After the 10 m filtering, the UK and Canada datasets showed no change in sample size or results. This implies that outliers exceeding 10 m did not exist in the first place, suggesting highly homogeneous data quality.

The change in Korean data is noteworthy. Upon removing outliers of 10 m or more, the *MAE* significantly decreased (an improvement of approximately 46.4%) from 4.59 to 2.46 m. However, this figure (2.46 m) is still more than 10 times higher than that of the foreign datasets (0.1–0.3 m). This empirically demonstrates that the domestic datasets contain structural inconsistencies (*e.g.*, differences in survey time, and sources) between S-101 and S-102, which arise in actual operational environments, beyond simple outlier issues.

4.2 Spatial distributions of errors by domestic sea area

To identify the causes of errors appearing in the domestic data, the spatial distributions of errors by sea area (East Sea, West/South Seas) were analyzed.

Figure 2 shows the spatial distribution of depth difference between S-101 and S-102 in Korean waters.

4.2.1 East Sea (predominance of absolute error)

In the deep waters of the East Sea, the magnitude of errors tended to be extremely large. This was identified as the primary factor behind the stark difference between Tables 2 and 3 (*MAE*

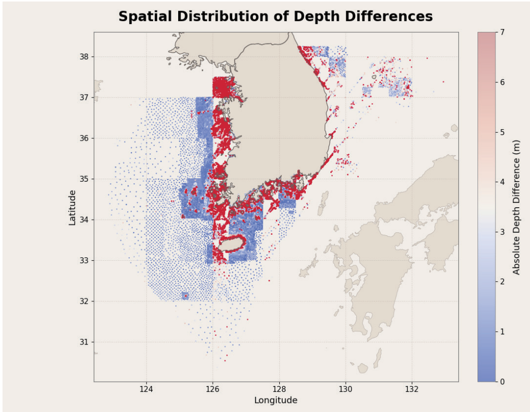

Fig. 2. (Color online) Depth difference between S-101 and S-102 in Korea.

Table 3
Depth consistency for valid range (within 10 m).

Category	Sample size (*N*)	*MAE* (*m*)	*RMSE* (*m*)	S-44 pass rate (%)	Improvement rate (*MAE*)
Korea	267188	2.46	3.67	37.50	46.4%
Canada	433	0.12	0.24	95.61	—
UK	11144	0.37	0.62	79.14	—

4.59 m → 2.46 m), confirming that large errors on the order of hundreds of meters occurring in deep-sea areas were distorting the overall statistics.

4.2.2 West and South Seas (predominance of relative error)

In contrast, the coastal areas of the West and South Seas, which are shallow, were dominated by errors within 10 m, yet they posed more serious navigational risks from the perspective of navigational safety. The analysis of low-depth zones (under 40 m) revealed that about 30–40% of the total sample showed errors exceeding 10 m. For instance, a 5 m error in a 15 m depth zone can critically threaten a vessel's under-keel clearance (UKC). In other words, while the absolute magnitude of errors in the West and South Seas is small, the "relative error" (error-to-depth ratio) is large, making the actual risk of marine accidents higher than that in the East Sea.

4.3 Subconclusion

The findings of this study suggest that the S-98 Interoperability Specification must be designed on the basis of real-world data rather than idealized data. While the S-102 priority rule may be valid in controlled environments such as those of the UK and Canada, even a 2.46 m error in shallow coastal zones can threaten navigational safety in operational environments such as Korea. Therefore, it is imperative to introduce not only a filtering mechanism to screen out outliers of 10 m or more but also a rigorous verification system for low-depth zones.

5. Conclusions

5.1 Summary

The introduction of the IHO S-100 data model is shifting the paradigm of marine geospatial information from a legacy single ENC-centric system to a multidimensional information fusion environment. Accordingly, the current S-98 Interoperability Specification functions as a key mechanism to prevent conflicts between heterogeneous data. However, when an S-101 ENC and an S-102 Bathymetric Surface overlap, the current S-98 grants unilateral "display priority" to S-102 without verifying data consistency.

This study was conducted to verify whether such priority rules can ensure navigational safety in actual operational environments. To this end, the depth consistency between S-101 and S-102 was quantitatively compared and analyzed using standard test datasets from the UK (UKHO) and Canada (CHS), as well as field datasets from South Korea (KHOA).

5.2 Key research findings

The key conclusions derived from this study are as follows.

First, the discrepancy between the ideal and actual operational environments was confirmed. The datasets from the UK and Canada, produced for standard verification, showed very high consistency with an *MAE* of 0.1–0.3 m. In contrast, Korea's field data, which contains various survey sources and temporal differences, showed an *MAE* of 2.46 m even after removing outliers exceeding 10 m. This indicates a 10- to 30-fold difference compared with foreign test sets. This suggests that S-98 interoperability should be designed on the basis of real-world data, where errors coexist, rather than ideal data.

Second, a dual pattern of errors depending on sea area characteristics was identified. In the deep waters of the East Sea, massive absolute errors due to missing data and matching errors were dominant. Conversely, in the coastal waters of the West and South Seas, relative errors—a high ratio of error to depth—were prominent. In particular, the finding that errors exceeding 10 m occurred in about 30% of low-depth zones (under 40 m) in the West and South Seas was identified as a critical safety threat directly linked to grounding risks when S-102 is prioritized.

Third, the necessity of data-quality-based filtering was demonstrated. The analysis of S-102 fill values identified in the Canadian data and outliers in the domestic data showed that simple data merging without preprocessing can cause not only statistical distortion but also ECDIS malfunctions.

5.3 Policy suggestions and implications

The results of this study suggest directions for improving the current IHO S-158. Currently, S-158 focuses on individual validation checks that independently verify data structure and format for each product specification. However, as confirmed in this study, even if each dataset maintains its own integrity, physical discrepancies can occur in an operational environment where heterogeneous data are merged, posing a fatal threat to navigational safety.

Therefore, future S-158 must go beyond the simple verification of individual products and include cross-validation items to verify data consistency between related product specifications, such as an S-101 ENC and an S-102 Bathymetric Surface.

Specifically, logic should be added to the S-158 validation process to determine whether the depth difference between the two datasets exceeds a threshold, such as the IHO S-44 TVU. Through this, a safety mechanism that detects in advance when inconsistent and potentially unsafe data are loaded into ECDIS and automatically displays a warning on the system should be introduced, thereby prompting mariners to cross-check S-101 depths.

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