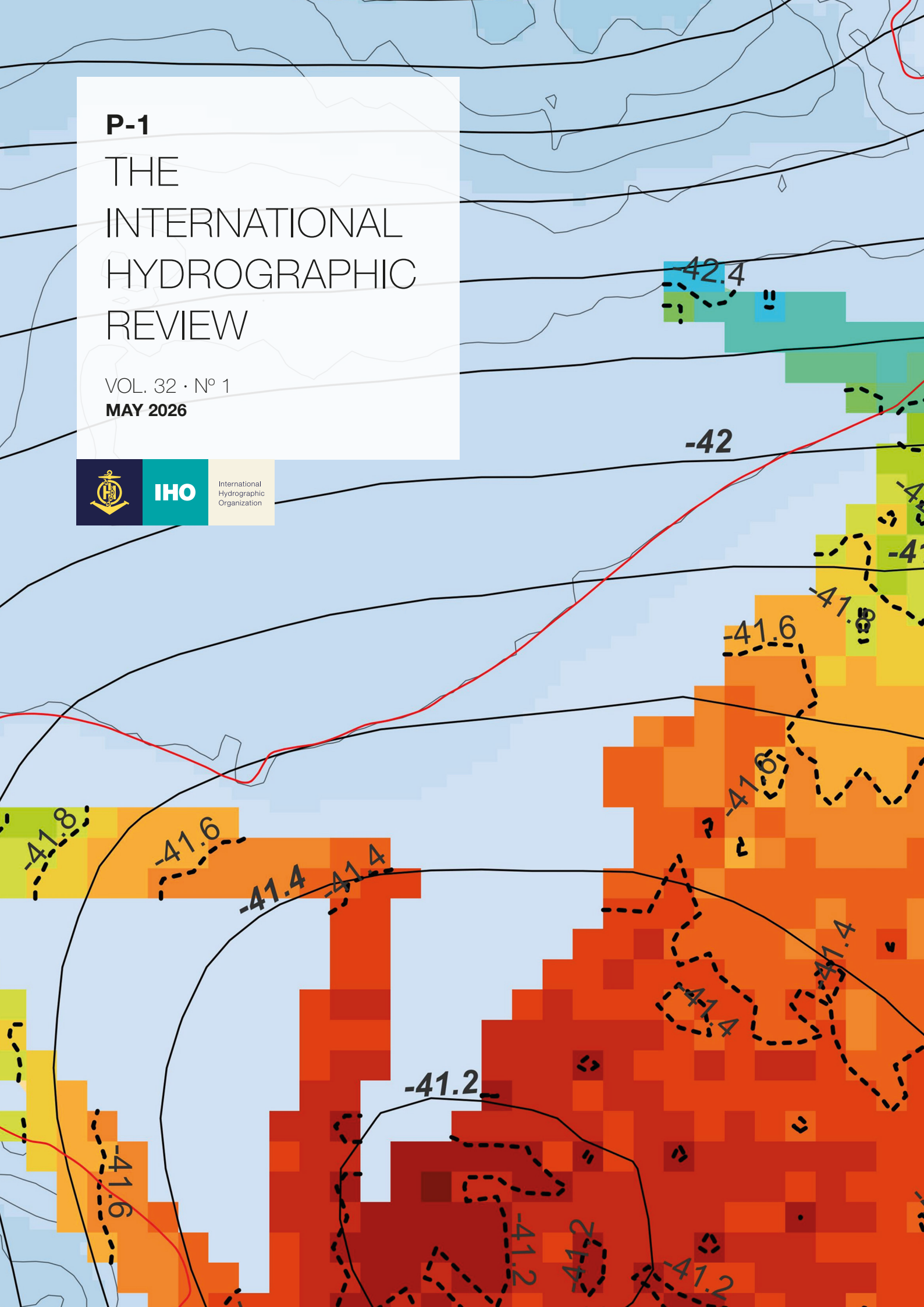


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Cover image

The cover image presents vessel-derived Mean Sea Level–ellipsoid separation values in the waters surrounding Saba and the Saba Bank in the Dutch Caribbean. It illustrates the spatial variability of the vertical reference surface and highlights the capability of shipborne GNSS measurements to provide reliable vertical control in data-sparse offshore environments. Further details on the methodology and findings are provided in the article by Merte P. J. Peeters in this issue (pp. 9–21).

Open Access Policy

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About the Journal

The International Hydrographic Review (IHR) is an international scientific journal publishing peer-reviewed papers on all aspects of hydrography and associated subjects, ranging from the latest technical developments and significant events to book reviews and historical recollections. The IHR was first published in 1923 and since then has been published regularly.

Editorial



Patrick Westfeld

Welcome to the first issue of the 32nd volume of The International Hydrographic Review (IHR).

This issue once again brings together a diverse set of contributions that reflect the evolving challenges and opportunities in hydrography and ocean governance.

Hydrography today operates at the intersection of rapid technological innovation, increasing societal expectations, and urgent environmental change. From satellite-based observation to community-led surveying and new legal frameworks for ocean governance, the discipline continues to expand its scope and relevance. The contributions in this issue highlight how hydrography responds to these dynamics – providing critical data, methods, and perspectives to support safe navigation, sustainable ocean use, and informed decision-making.

This issue of the IHR also features a series of conference papers from the 12th Conference of the IHO–IAG Advisory Board on the Law of the Sea (ABLOS), introduced by a foreword from Luigi Sinapi, Director and Secretary-General Elect of the International Hydrographic Organization (IHO), setting the stage for insightful discussions at the interface of hydrography, law, and policy.

The invited article is authored by Merte P. J. Peeters of MLA College (Plymouth, United Kingdom), who was awarded second prize in the International Federation of Hydrographic Societies (IFHS) Student Award 2025 for his Master's thesis. His contribution, *Towards an accurate mean sea level to ellipsoid separation model for the Dutch Caribbean: an operational vessel based GNSS approach* (pp. 9–21), presents a concise overview of his award-winning research. The paper demonstrates how vessel-based GNSS measurements can be used to derive accurate regional models for mean sea level separation, offering a practical solution for data-sparse coastal environments and supporting hydrographic surveying and climate adaptation efforts. In this context, it is also worth noting that the first prize of the IFHS Student Award 2025 was awarded to Isabella Metz (Julius-Maximilians-Universität Würzburg, Germany) for her outstanding Master's thesis titled *Analysis of uncertainties for error detection and quantification of bathymetry data from multispectral Sentinel-2 imagery*. While her work cannot be included in this issue, it nevertheless stands as an excellent example of the high quality and relevance of emerging research within the hydrographic community. The entire IHR Editorial Board warmly congratulates both early-career scientists on their achievements. The dedication of such young professionals gives us confidence that the future of hydrography is in very capable hands.

The peer-reviewed section opens with a study by Anand Hiroji & Olaoluwa Oderinde on standardizing hydrographic vessel offset surveys (pp. 23–39). Their work highlights how methodological choices such as baseline length and station configuration influence accuracy, contributing to improved survey reliability. René Chénier and colleagues explore the operational use of satellite-derived bathymetry within the Canadian Hydrographic Service (pp. 41–55). Their contribution illustrates how iterative processing can enhance model performance while underlining the importance of careful accuracy assessment. Mathieu Rondeau and co-authors present an innovative approach to Arctic hydrography by engaging Inuit communities in nearshore mapping (pp. 57-67). Their findings demonstrate how community-sourced bathymetry can complement traditional surveying and contribute to improved safety and knowledge integration.

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The conference section is introduced by Luigi Sinapi, who provides a foreword to the selected contributions (pp. 69–71). Ayo Olugbode examines Nigeria's blue economy and ocean governance, identifying institutional and legal challenges and proposing pathways for more effective implementation of international frameworks (pp. 73–79). Tullio Scovazzi discusses the protection of underwater cultural heritage, highlighting gaps and ambiguities in the current international legal regime (pp. 81–87). Tihao Zeng addresses the ocean observation paradox in the context of marine plastics governance, emphasizing the tension between legal frameworks and the need for continuous environmental monitoring (pp. 89–97). Eva van Heukelom investigates the balance between fisheries data protection and international obligations, particularly in the context of increasing use of artificial intelligence (pp. 99–105). Andrey Chernov focuses on evidence requirements for alternative fuel bunkering under decarbonisation rules, emphasizing the growing importance of robust data and verification processes (pp. 107–110). Laura Meyer and co-authors explore opportunities for mobilizing private sector ocean data under emerging frameworks such as the BBNJ Agreement (pp. 111–116). Emily Charry Tissier highlights the role of integrated observation systems and data governance in protecting marine megafauna, pointing to the need for improved interoperability and standards (pp. 117–122).

Within the technical reports section, an open-source perspective is introduced with *SidescanTools,* presented by Mia Schumacher and collaborators (pp. 123–131). The software provides a comprehensive and flexible solution for processing common sidescan sonar data formats, including functionalities such as bottom detection, geometric and radiometric corrections, and gain normalisation. By enabling the export of georeferenced raster products and enhancing overall data quality, the tool supports more efficient workflows in hydrographic practice. As an open-source development arising from the Ghostnetbusters project, it also exemplifies the growing importance of accessible, community-driven tools for advancing innovation and collaboration in the field.

This issue of the IHR also includes an update on Malaysia's hydrographic leadership, with the appointment of Rear Admiral Dr Najhan bin Md Said as Chief Hydrographer, marking a new phase in the country's hydrographic development (pp. 133–134). Additionally, an information on the *Third Portuguese-Spanish Hydrography Conference* highlights continued regional cooperation and knowledge exchange in the field (pp. 135–138).

On behalf of the Editorial Board, I hope that this issue provides valuable insights and inspiration to the hydrographic community and beyond.



Dr Patrick Westfeld
Chief Editor, IHR

https://doi.org/10.58440/ihr-32-1-e01

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INVITED ARTICLE

Towards an accurate mean sea level to ellipsoid separation model for the Dutch Caribbean: an operational vessel based GNSS approach

Author
Merte P. J. Peeters[1]

Preamble

Merte P. J. Peeters from MLA College (Plymouth, United Kingdom) has been awarded second prize in the IFHS Student Award 2025 for his Master's thesis titled "Establishing an Accurate Mean Sea Level Model in the Dutch Caribbean Using Vessel-Based PPP-GNSS Measurements". The following article presents a concise overview of his award-winning research.

Abstract

This contribution demonstrates the applicability of vessel-based GNSS measurements for deriving a regional Mean Sea Level (MSL)-ellipsoidal separation model in the Dutch Caribbean. Legacy hydrographic survey data from the 2019 Caribbean survey campaign is combined with tidal observations, predicted tides, and satellite altimetry to address limitations of global satellite-derived MSL models in complex coastal environments. Vessel-derived separation values show close agreement with shore-based benchmarks after correction for Sea Level Rise, Vertical Land Movement, and seasonal variability, with residuals typically within a few centimetres. The results confirm vessel-based separation measurements as a practical solution for establishing vertical control in data-sparse coastal regions, supporting hydrographic surveying, coastal management, and sea-level adaptation in Small Island Developing States.

Keywords
vessel-based GNSS · Mean Sea Level (MSL)-ellipsoid separation · Dutch Caribbean · vertical datum · tide models

Resumé

Cet article démontre la pertinence des mesures GNSS effectuées à partir de navires pour l'élaboration d'un modèle régional de séparation entre le niveau moyen de la mer (MSL) et l'ellipsoïde dans les Caraïbes néerlandaises. Les données hydrographiques historiques issues de la campagne de levés menée en 2019 dans les Caraïbes sont combinées à des observations des marées, à des prévisions de marées et à des données d'altimétrie satellitaire afin de pallier les limites des modèles globaux de MSL dérivés des satellites dans les environnements côtiers complexes. Les valeurs de séparation dérivées à partir des navires concordent étroitement avec les repères terrestres après correction pour tenir compte de l'élévation du niveau de la mer, des mouvements verticaux du sol et de la variabilité saisonnière, avec des écarts résiduels généralement de l'ordre de quelques centimètres. Les résultats confirment que les mesures de séparation à partir de navires constituent une solution pratique pour établir un contrôle vertical dans les régions côtières où les données sont rares, ce qui facilite les levés hydrographiques, la gestion côtière et l'adaptation au changement du niveau de la mer dans les petits États insulaires en développement.

✉ Merte P. J. Peeters · mpj.peeters@mindef.nl
[1] Royal Netherlands Navy, Netherlands

Resumen

Esta contribución demuestra la aplicabilidad de las mediciones GNSS desde buques para derivar un modelo regional de separación entre el Nivel Medio del Mar (MSL) y el elipsoide en el Caribe Neerlandés. Los datos hidrográficos históricos de la campaña de levantamientos en el Caribe de 2019 se combinan con observaciones de mareas, mareas previstas y altimetría por satélite para abordar las limitaciones de los modelos globales de MSL por satélite en entornos costeros complejos. Los valores de separación derivados en buques muestran una estrecha concordancia con los puntos de referencia terrestres después de su corrección por Aumento del Nivel del Mar, Movimiento Vertical del Terreno y variabilidad estacional, con residuos normalmente de pocos centímetros. Los resultados confirman que las mediciones de separación desde buques son una solución práctica para establecer el control vertical en regiones costeras con escasez de datos, lo que apoya a los levantamientos hidrográficos, la gestión costera y la adaptación al nivel del mar en los Pequeños Estados Insulares en Desarrollo.

1 Introduction

Accurate vertical reference systems are fundamental to hydrographic surveying, nautical charting, coastal engineering, and long-term sea-level monitoring. Mean Sea Level (MSL) serves as a key vertical datum for reducing hydrographic measurements and linking marine observations to terrestrial reference frames. In many coastal regions, however, reliable local MSL-ellipsoidal separation models are lacking, forcing hydrographic operations to rely on global geoid or Mean Sea Surface (MSS) models. While these global models perform well offshore, their accuracy often degrades in nearshore and island environments with complex coastlines and steep bathymetry.

In the Dutch Caribbean, the absence of a regionally validated MSL-ellipsoidal separation model has been shown to negatively affect vertical referencing. Hydrographic surveys conducted by the Royal Netherlands Navy Hydrographic Service revealed vertical discrepancies of up to 0.7 metres when using the EGM08 geoid as an ad-hoc alternative for MSL, particularly in coastal zones near Saint Martin and during harbour development works on Sint Eustatius in 2019. Similar inconsistencies were later observed in airborne LiDAR surveys and coastal infrastructure projects, highlighting the limitations of global reference models in this region.

These challenges are exacerbated by the Dutch Caribbean's geographical and environmental characteristics. The islands are characterised by irregular coastlines, narrow continental shelves, and steep seabed gradients, which complicate the installation and maintenance of conventional tide gauge networks. At the same time, the region is highly vulnerable to the impacts of climate change (Maitland et al., 2023). Small Island Developing States (SIDS) in the Caribbean are particularly exposed to Sea Level Rise (SLR) and increased coastal flooding (Intergovernmental Panel on Climate Change, 2022), making reliable vertical control increasingly critical for safe navigation, coastal development, and environmental management.

Recent advances in Global Navigation Satellite System (GNSS) positioning now enable operational alternatives to conventional tide gauges in the form of Ellipsoidally Referenced Surveying (ERS) (Ligteringen et al., 2014). By combining Precise Point Positioning (PPP-GNSS) with vessel motion sensors and tidal information, it is possible to calculate sea surface heights directly from survey vessels. This method offers greater spatial coverage than shore-based tide gauges and allows the use of legacy survey data collected during routine hydrographic operations. However, vessel-based measurements are affected by environmental and vessel-specific factors, such as tides, draught, squat, vessel motion, and atmospheric pressure, which must be carefully modelled to ensure reliable results.

This study explores the use of vessel-based PPP-GNSS data to develop a regional MSL-ellipsoidal separation model for the Dutch Caribbean. Focusing on the Leeward Islands (Aruba and Curaçao) and the Windward Islands (Saba and Saba Bank), the research combines existing data from a previous survey campaign with tide gauge observations, predicted tides, and satellite altimetry. The aims are to assess the accuracy and uncertainty of vessel-derived separation values, verify their consistency with shore-based benchmarks and global MSS models, and evaluate their suitability for hydrographic and coastal applications in these data-sparse island regions. This work seeks to improve vertical referencing in the Dutch Caribbean and to support the development of a more robust regional geodetic and tidal infrastructure.

2 Research objectives

The objectives of this study are to evaluate the potential of vessel based GNSS measurements for establishing a reliable Mean Sea Level (MSL)-ellipsoidal separation model in the Dutch Caribbean and to assess its suitability for operational hydrographic surveying. Specifically, the study aims to:

- Assess the applicability of existing data from previous survey campaigns for deriving MSL separation values;
- Assess current vertical reference levels and tidal infrastructure in the region, including their limitations.

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in complex island environments;
- Develop a statistical model that links vessel-based sea-surface height measurements to environmental and vessel-specific parameters such as tides, motion, squat, draught, and atmospheric pressure.
- Validate vessel-derived separation values against independent observations, including shore-based tide gauges and satellite altimetry, and quantify associated uncertainties

Examine the implications of the results for vertical control in data-sparse coastal regions and develop recommendations for future geodetic and tidal infrastructure in the Dutch Caribbean.

3 Materials and methods

3.1 Study sites

The study was conducted in two distinct regions of the Dutch Caribbean, deliberately selected to represent contrasting coastal, geodetic, and operational conditions. Together, these sites allow evaluation of the vessel-based Mean Sea Level (MSL)-ellipsoidal separation in both well-instrumented coastal settings and data-sparse offshore environments.

3.1.1 Site 1: Leeward Islands (Aruba and Curaçao)

The Leeward Islands (Site 1) comprise the coastal waters surrounding Aruba and Curaçao. This area is characterised by accessible shorelines, developed coastal infrastructure, and the availability of shore based tide gauge (TG) installations, making it suitable for direct validation of vessel derived MSL-ellipsoidal separation values. Both islands exhibit steep nearshore bathymetry, with the continental shelf narrowing rapidly away from the coastline.

The EGM08 geoidal height varies substantially across Site 1, reflecting complex regional gravity field behaviour. Along the Curaçao coastline, geoidal heights show a pronounced east-west gradient of approximately -23.3 m to -26.7 m, while Aruba exhibits a smaller but still notable north-south variation ranging from approximately -24.7 m to -25.5 m. These spatial gradients make the region particularly sensitive to vertical referencing errors when global geoid or MSS models are used without local validation.

The presence of permanent and temporary tide gauges at multiple locations around Aruba and Curaçao enables the derivation of coastal MSL-ellipsoidal separation values based on static GNSS observations combined with long term tidal records. As such, Site 1 provides a benchmark environment in which vessel based GNSS results can be directly compared with shore based references.

3.1.2 Site 2: Windward Islands (Saba and Saba Bank)

In contrast, the Windward Islands (Site 2) cover the coastal and offshore waters around Saba and the Saba Bank. This area presents a significantly different operational environment, marked by limited coastal access, rugged island terrain, and a lack of extensive shore-based tidal infrastructure. Water depths in the survey zone generally range from 20 m to 40 m, gradually increasing over the Saba Bank.

The geoidal height across Site 2 exhibits a relatively smooth but distinct gradient, ranging from approximately -41.6 m to -43.5 m. Unlike Site 1, the lack of accessible coastline and permanent tide gauges necessitated the use of predicted tidal levels derived from harmonic constituents. Consequently, Site 2 serves as a test case for assessing the performance of vessel based separation measurements in areas where conventional tide gauge based vertical control is not feasible.

Together, the two sites provide complementary test environments. Site 1 represents a coastal setting where vessel based separation measurements can be rigorously validated against shore derived MSL references, while Site 2 represents a data sparse offshore environment that relies heavily on predicted tides and vessel based observations. This contrast allows assessment of how environmental conditions, geoidal variability, and data availability influence the accuracy and reliability of vessel derived MSL-ellipsoidal separation.

For both sites, the research area extends from the coastline to the 200 m isobath, aligning with the maximum depth range for tidal reduction as defined by IHO S44 Order 1/2 survey requirements (IHO, 2020). This depth range reflects typical hydrographic survey operations in the Dutch Caribbean and ensures that the derived separation values are applicable for practical charting and coastal purposes.

Fig. 1 provides an overview of the spatial extent of both study sites and highlights the contrasting coastal accessibility, bathymetric gradients, and geographical distribution that underpin the comparative

3.2 Vessel setup

Data was collected aboard HNLMS Snellius (Fig. 2), an 82-metre hydrographic survey vessel. Positioning

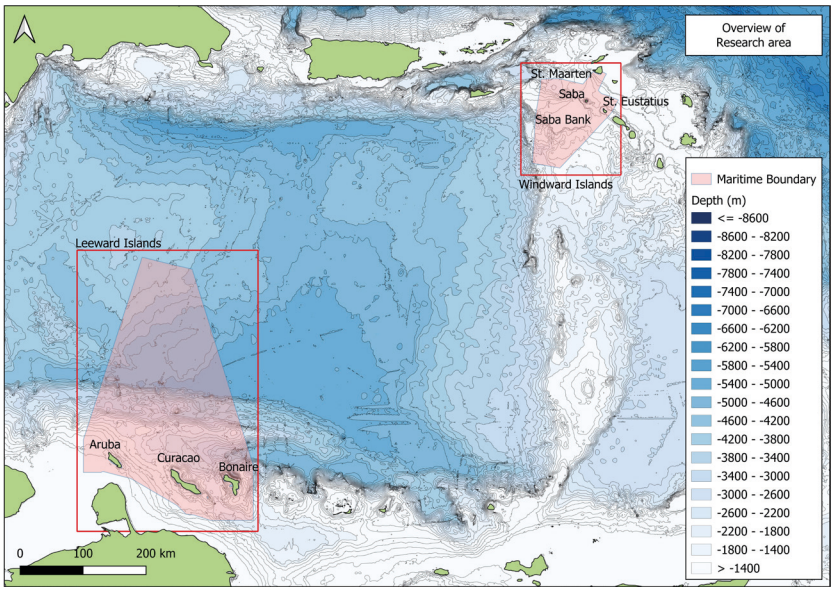


Fig. 1 Overview of the research sites in the Dutch Caribbean.

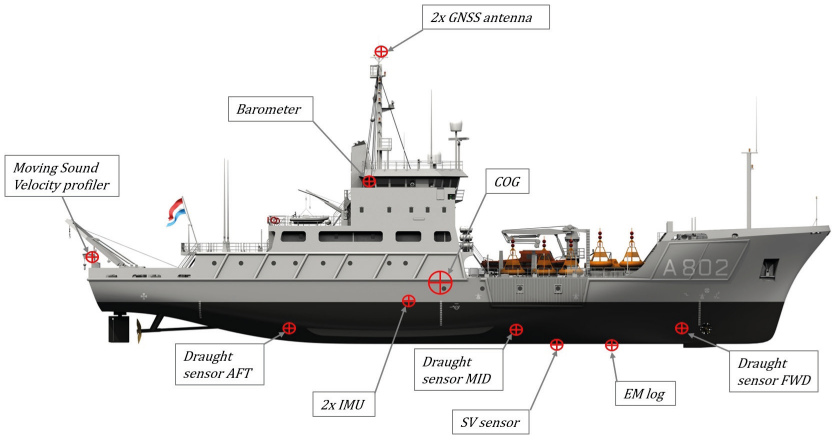


Fig. 2 Sensor geometry HNLMS Snellius.

relied on Trimble SPS855 and Septentrio AsteRx GNSS receivers, with real-time PPP augmentation provided by Fugro Marinestar G4+ (Ligteringen et al., 2014; Tegedor et al., 2017). Two IXSEA OCTANS MkIII MRUs measured vessel attitude and heave, while draught was recorded using a VegaBar 52 pressure system, corrected for atmospheric pressure and density (Chen & Millero, 1977). Squat effects were estimated through a polynomial function based on previous sea trials. All GNSS, draught, and speed measurements were logged at 1 Hz using QINSy data acquisition software.

3.3 Data processing

Data processing was conducted through the following steps:

1. Satellite-derived MSS models (DTU21, CNES2022) and VORF-global were selected as offshore reference levels (Andersen et al., 2023; Schaeffer et al., 2023; EMODnet, 2017).
2. For coastal separation values, MSL-ellipsoidal separation at five shore stations in Site 1 was determined using static GNSS measurements and processed via Trimble RTX, combined with a 30-day tide series, corrected for barometric variation.
3. Tidal validation of the permanent TG at Bullenbaai (University of Hawaii, UHSLC) on Site 1 was conducted by comparing its readings to temporary stations (ARUB, ANNA, WEST, BULL, NEWP). Fort Bay TG on Site 2 served solely as a reference.
4. Tidal values at Site 2 were calculated for each vessel measurement using harmonic constituents from DELTARES (2009–2010) and FES2014 (AVISO+), employing the Admiralty calculation method (Glen, 1977).
5. Offshore MSL values were calculated for Sites 1 and 2, accounting for vessel motion, draught, and squat. A 60-second moving average filter was used to reduce noise and residual vessel motion artefacts.
6. Separation was calculated at each datapoint using the following formula

$$SEP_{MSL\text{-}ITRF} = h_{cog} - h_{adr} + h_{draught} + h_{squat} - h_{tide} \quad (1)$$

where:

$SEP_{MSL\text{-}ITRF}$: separation between MSL and ITRF ellipsoid (GRS80)

h_{cog}: measured ellipsoidal centre of gravity (COG) height

h_{adr}: fixed COG to draught reference offset

$h_{draught}$: draught

h_{squat}: dynamic settlement of the vessel as a function of vessel speed

h_{tide}: tidal level i.r.t. MSL

7. The instrument and methodological uncertainties were modelled to establish a priori confidence intervals for the established separation.
8. For comparative analysis, the derived MSL values were compared with satellite MSS and VORF models to assess the a-posteriori accuracy of vessel-based GNSS-tide methods.

4 Results

4.1 MSS model comparison

Across Site 1 (Aruba and Curaçao), the DTU21 and CNES2022 Mean Sea Surface models generally show consistent offshore behaviour, although increasing discrepancies are seen in nearshore zones and over land. Along the south-west coast of Curaçao, as well as in terrestrial areas, the model contours diverge, indicating reduced reliability of global reference surfaces in complex coastal environments. In contrast to DTU21, CNES2022 displays a noticeable local deviation near the NEWP location, similar to the contour pattern observed at ARUB. Over the land areas of Aruba and Curaçao, VORF global shows prominent artefacts, highlighting its limitations for coastal island applications. The absence of similar artefacts in the VORF global model near Saba is probably due to the limited land surface, which lessens its impact on satellite altimetry processing (Andersen et al., 2023).

At Site 2 (Saba and Saba Bank), all evaluated

Table 1 Overview of tide/GNSS locations on Site 1.

Island	Location	Designation	Description
Aruba	Savaneta	ARUB	Savaneta Military Barracks jetty
Curacao	Westpunt	WEST	GoWest Diving resort jetty
Curacao	Bullenbaai	BULL	Bullenbaai oil terminal jetty
Curacao	Annabaai	ANNA	Annabaai Port authority
Curacao	Nieuwpoort	NEWP	Nieuwpoort jetty

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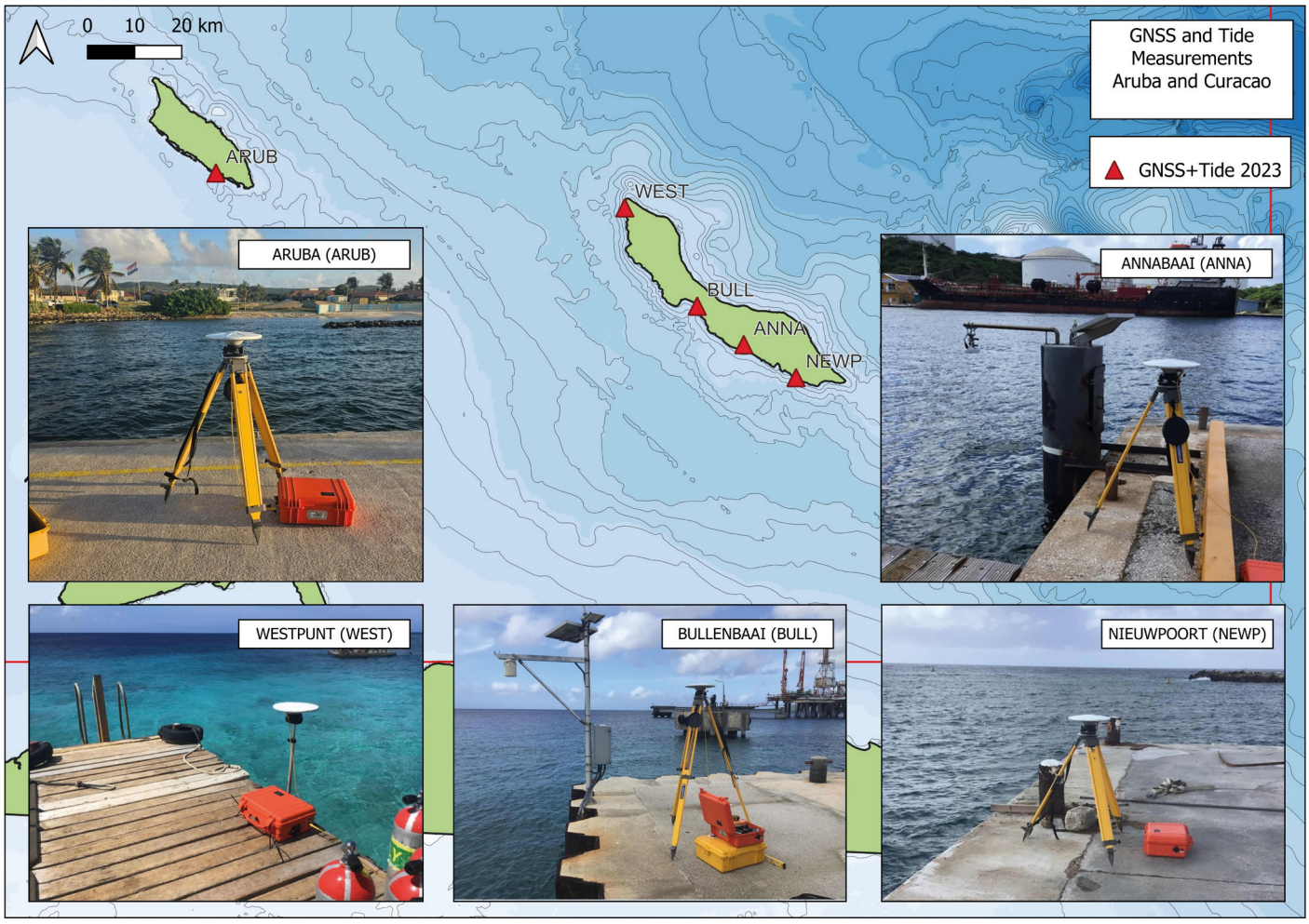


Fig. 3 Tide/GNSS measurements on Site 1.

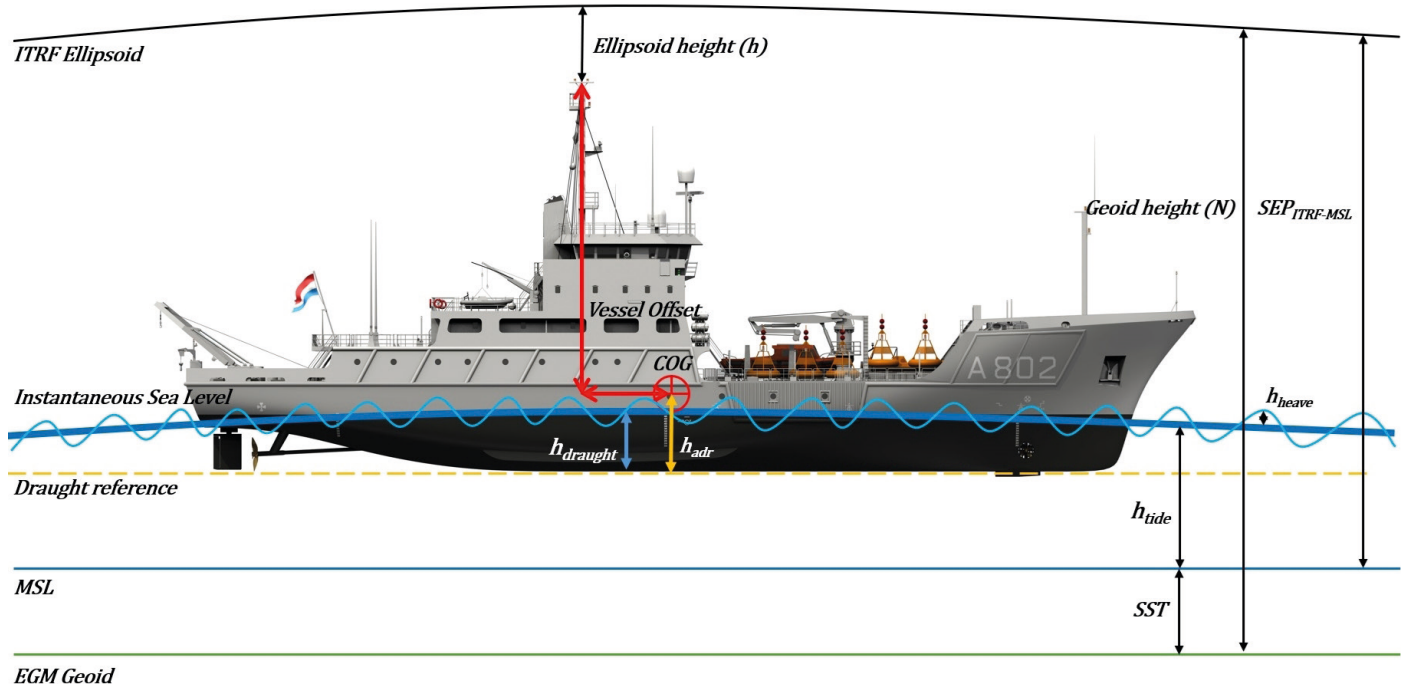


Fig. 4 Relation between vessel COG height and MSL.

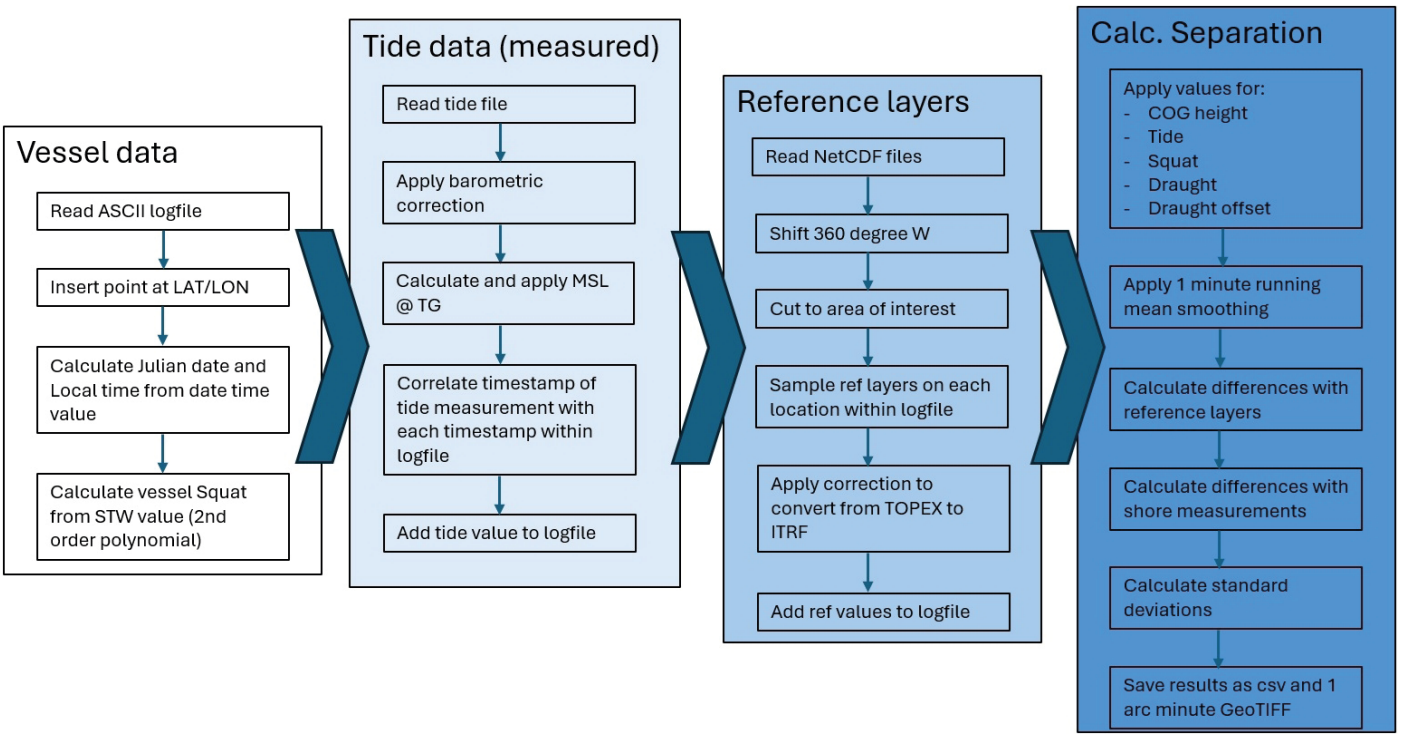


Fig. 5 Data processing workflow for Site 1.

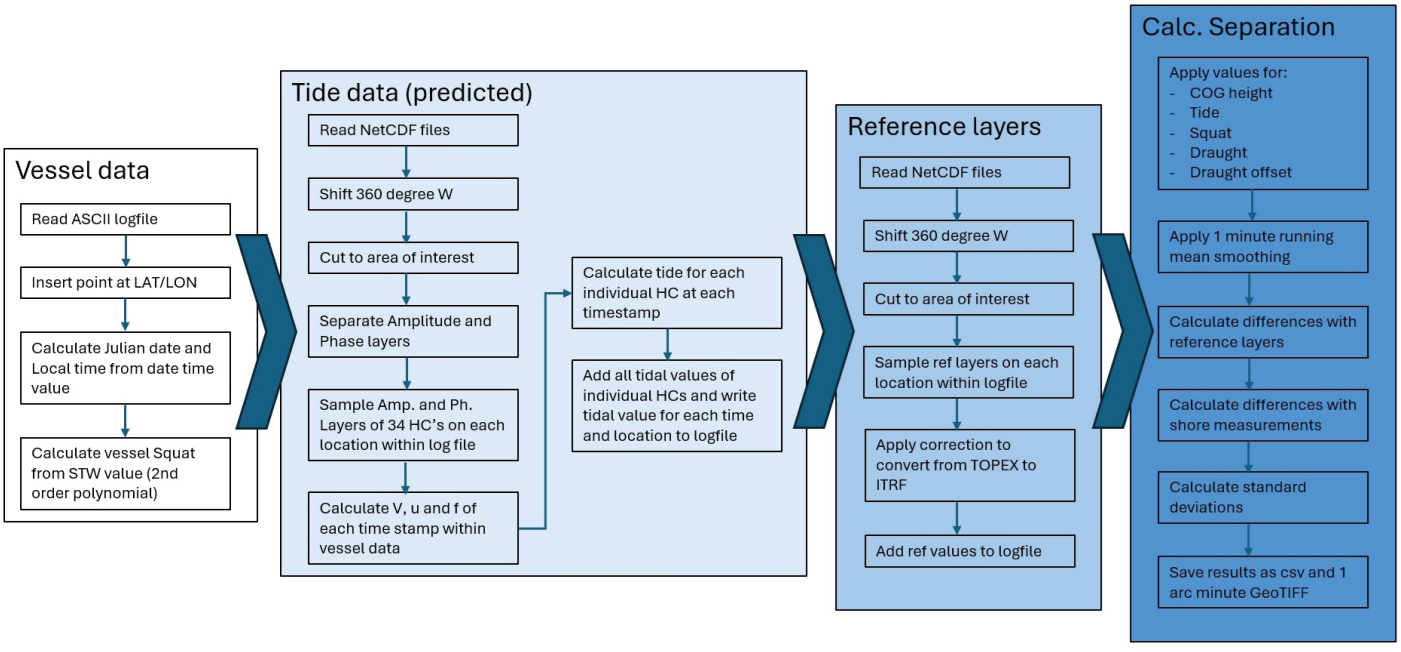


Fig. 6 Data processing workflow for Site 2.

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reference models exhibit more uniform spatial behaviour, but with consistently larger vertical offsets compared to Site 1. The difference between DTU21 and both EGM08 and VORF global is approximately 35–40 cm, significantly exceeding the inter-model differences observed in the Leeward Islands. Differences between VORF global and the MSS models at Site 2 are comparable to those observed near Aruba, but slightly smaller than those near Curaçao.

Overall, the MSS comparison reveals a clear site contrast: Site 1 is dominated by nearshore and land-related artefacts, while Site 2 exhibits smoother spatial patterns but larger systematic offsets between global models.

4.2 Shore-based separation values

At Site 1, coastal Mean Sea Level-ellipsoidal separation values were calculated at five shore stations using static GNSS measurements processed with Trimble RTX, combined with a 30-day tide series corrected for barometric variation. These shore-based values offer a well-constrained local reference for validating vessel-derived separation values in the Leeward Islands.

At Site 2, the ellipsoidal height of the Fort Bay tide gauge was established using ITRF to Saba Datum transformation parameters (Lesparre et al., 2023), with an approximate uncertainty of 10 cm due to limited benchmark availability. Therefore, shore-based validation at Site 2 relies on a single reference point, which has a higher associated uncertainty than those at Site 1.

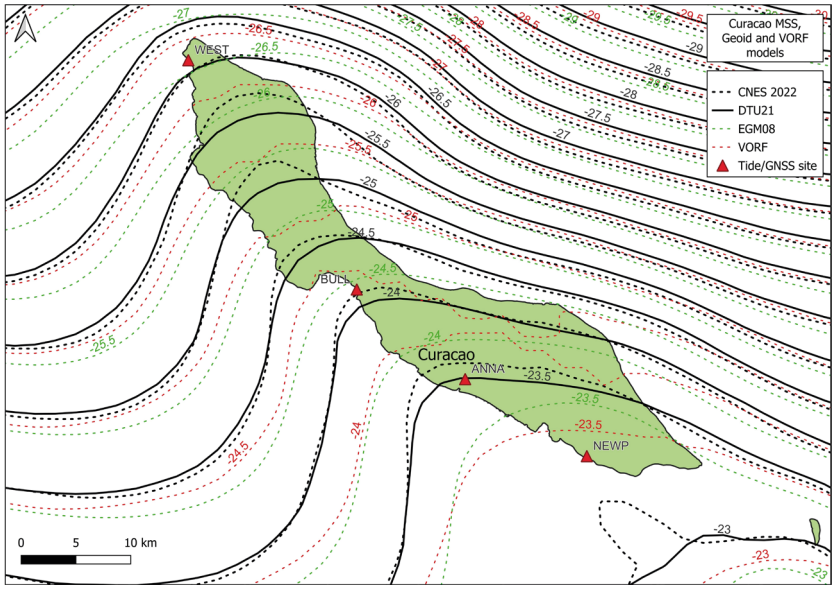


Fig. 7 Reference models Curaçao (Site 1).

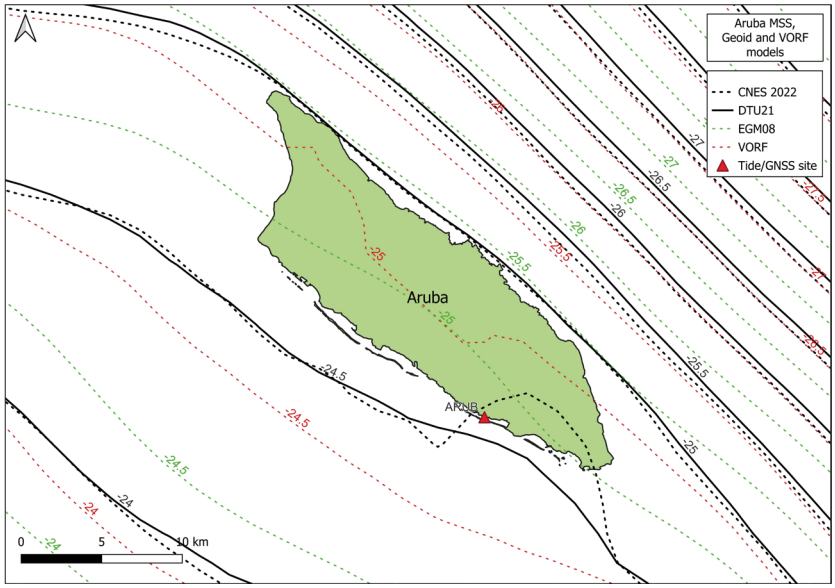


Fig. 8 Reference models Aruba (Site 1).

4.3 Tide prediction and validation

At Site 1, the permanent tide gauge at Bullenbaai was validated by comparison with multiple temporary stations (ARUB, ANNA, WEST, BULL, and NEWP), providing confidence in the shore-based tidal reference used for separation analysis.

At Site 2, where predicted tides are required, comparison of measured and predicted tides at Fort Bay shows only minor differences between the DELTARES and FES2014 harmonic constituents, with the largest discrepancies occurring in long-period components. Despite limitations in resolving long-period variability, FES2014 exhibits slightly better agreement with observed tidal records. Application of Glen's Admiralty method (Glen, 1977) presented computational challenges, which were mitigated through a simplified polygon-based sampling approach applied to the vessel measurement locations.

These results indicate that tidal prediction constitutes a more significant source of uncertainty at Site 2 than at Site 1, where direct gauge-based validation is possible.

4.4 Uncertainty and data quality

The total vertical uncertainty of offshore separation measurements is estimated at 9.2 cm, including GNSS positioning accuracy, MRU performance, tidal zoning, and draught effects. This level of uncertainty aligns with hydrographic survey standards (NOAA, 2021) and matches the performance of existing separation models (Abd Rahman & Md Din, 2020).

Data quality varied within Site 1, with MRU settling artefacts more prominent in the Curaçao dataset due to frequent vessel manoeuvres and variable survey speeds. Applying a 1-minute moving average filter effectively reduced noise and residual motion artefacts, enhancing the stability of the separation time series, while acknowledging a trade-off between noise suppression and spatial resolution (Liibusk et al., 2022).

4.5 Regional and model-based variability

Comparison of vessel-derived separation values with shore-based references shows differences from 1 to 14 cm before geophysical correction. After accounting for Vertical Land Movement (Cadastral authority), Sea Level Rise (Maitland et al., 2024), and

Table 2 Measured MSL-ellipsoidal separation values.

Site ID	BM height (m)	TG MSL (m)	Offset (m)	Separation (m)	Remarks
ARUB	-23.416	0.525	1.729	-24.620	
WEST	-25.568	0.596	1.136	-26.108	
BULL	-23.262	0.840	1.660	-24.082	
ANNA	-22.512	0.373	1.196	-23.335	
NEWP	-20.345	0.979	3.559	-22.925	
SABA	-42.220	0.000	0.088	-42.308	Offset with Saba datum calculated using BESTRANS parameters

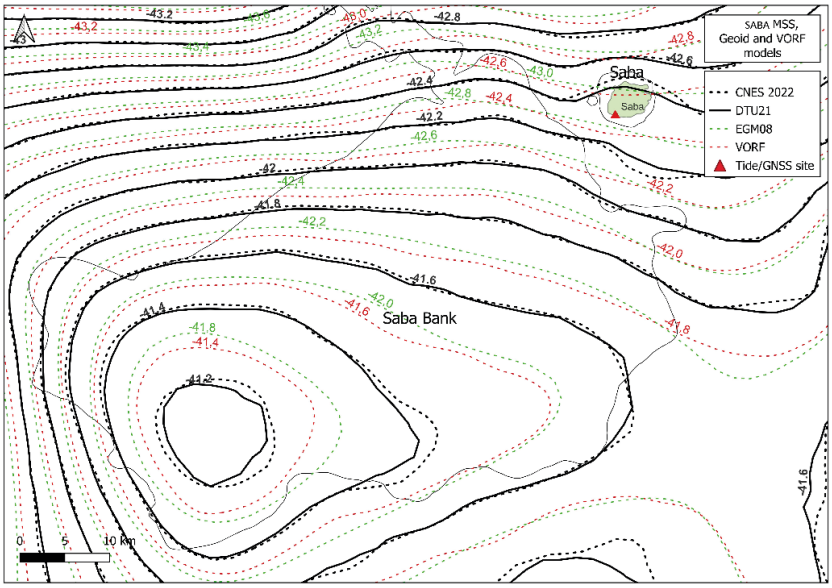


Fig. 9 Reference models Saba and Saba Bank (Site 2).

seasonal sea level variability (Maitland et al., 2024), residual differences decrease to 0–3 cm at ARUB, BULL, ANNA, and SABA, indicating strong agreement between vessel-based and shore-derived separation values at these locations. Higher residuals at WEST and NEWP remain, suggesting the presence of local systematic effects.

When vessel-derived offshore separation values are compared with global reference models, the closest agreement is observed with DTU21, while CNES2022 shows larger average differences, particularly near Curaçao. In all cases, the global models exhibit higher separation values than those derived from vessel-based observations. Differences between the epochs of MSS model development and the present study, especially regarding the assumed yearly Sea Level Rise, may contribute to these discrepancies (Schaeffer et al., 2023; Andersen et al., 2023). VORF global and EGM08 show significantly larger deviations from both vessel-based and shore-based separation values, highlighting their limitations as vertical reference levels in the Dutch Caribbean.

5 Discussion and limitations

The results show that vessel-based GNSS positioning provides a reliable foundation for determining the Mean Sea Level (MSL)-ellipsoidal separation in the Dutch Caribbean, even in areas with limited geodetic infrastructure. The close agreement between vessel-derived and shore-based separation values, especially after adjustments for Vertical Land Movement (VLM), Sea Level Rise (SLR), and seasonal variations, confirms the methodology's validity and supports its application in operational hydrographic tasks.

A key outcome of this study is the strong site-dependent contrast observed between the Leeward and Windward Islands. At Site 1 (Aruba and Curaçao), the availability of multiple shore-based tide gauges enabled rigorous validation of vessel-derived separation values. After geophysical corrections, residual differences were reduced to within a few centimetres at most reference locations, demonstrating that vessel-based GNSS can reproduce coastal MSL references with high internal consistency. The remaining higher residuals at specific stations (WEST and NEWP) suggest the presence of local systematic effects, potentially related to site-specific sensor configuration, benchmark stability, or local hydrodynamic influences.

In contrast, Site 2 (Saba and Saba Bank) presents a more challenging operational environment, where validation depends on a single tide gauge reference with higher transformation uncertainty and where predicted tides are necessary. Despite these limitations, the vessel-derived separation values at Site 2 demonstrate comparable agreement with the available shore reference after correction, indicating that vessel-based GNSS remains a feasible approach even in data-scarce offshore settings. This finding is especially relevant for remote island regions where installing and maintaining conventional tide gauge networks is impractical.

The comparison with global reference surfaces further emphasises the benefits of the vessel-based approach. Among the evaluated global models, DTU21 aligns most closely with vessel-derived offshore separation values across both study sites, while CNES2022 shows larger deviations in nearshore zones, especially near Curaçao. The significant differences observed for VORF global and EGM08 highlight their limitations as vertical reference proxies in complex island environments. These discrepancies are consistent with the known sensitivity of global models to coastal altimetry artefacts and variations in model epoch, particularly

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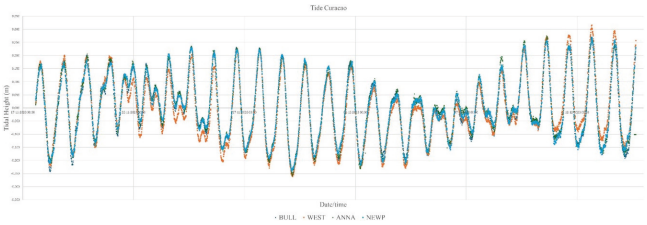


Fig. 10 Comparison of tidal measurements on Curaçao (Site 1

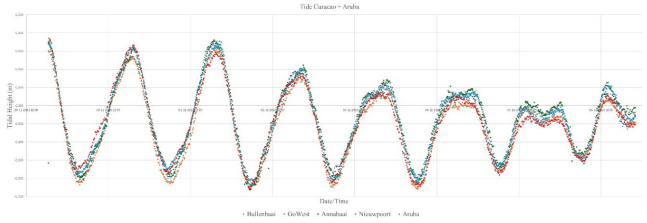


Fig. 11 Comparison of tidal measurements on Aruba and Curaçao (Site 1).

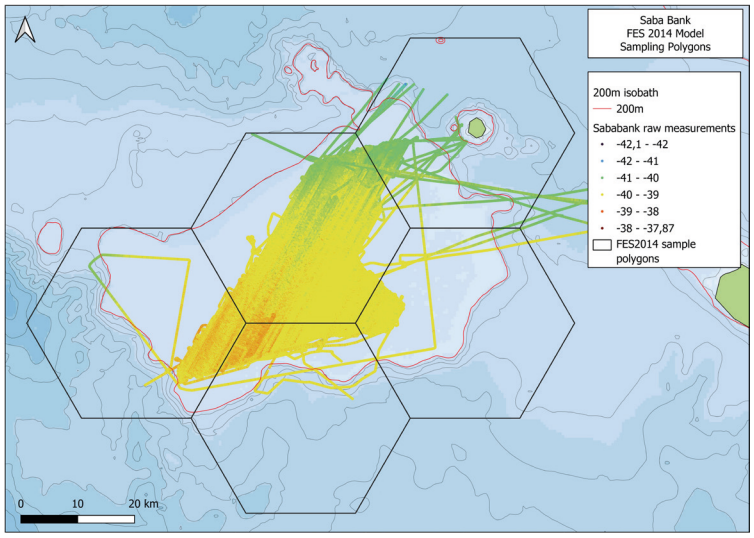


Fig. 12 FES2014 Sampling polygons Site 2.

Table 3 Comparison of predicted and measured tide at SABA (Site 2).

Comparison	Average difference (m)	Standard deviation (m)
Gauge – DELTARES	-0.011	0.031
Gauge – FES2014	-0.004	0.024
FES2014 – DELTARES	0.007	0.021

Table 4 Overview of a priori and a posteriori accuracy compared to the survey standard.

Dataset	Number of data points	Survey standard (m)	A-priori SD (m)	A-posteriori SD (m)
Aruba (vessel)	309,905	0.100	0.092	0.095
Curacao (vessel)	94,385	0.100	0.092	0.118
Sababank (vessel)	1,680,809	0.100	0.092	0.065

Table 5 Achieved residuals of vessel-derived separation values compared to shore sites. The colored markings indicate the presence of a systematic error.

Dataset	ARUB	WEST	BULL	ANNA	NEWP	SABA
Aruba (vessel) (m)	0.040	-	-	-	-	-
ΔCuracao (vessel) (m)	-	0.139	0.026	0.061	-	0.120
ΔSababank (vessel)	-	-	-	-	-	0.012
VLM/year (m)	0.0007	0.0006	0.0006	0.0006	0.0006	0.0017
SLR/year (m)	0.00615	0.00615	0.00615	0.00615	0.00615	0.00615
ΔTime (year)	4	4	4	4	4	4
Seasonal effect (m)	0.02	0.00	0.00	0.00	0.02	0.01
Cumulative change (m)	0.0474	0.0270	0.0270	0.0270	0.0270	0.010
Residual difference (m)	-0.0074	0.112	-0.001	0.034	0.093	0.002

Table 6 Differences between vessel-derived separation values and global reference models.

Dataset	ΔDTU21	ΔCNES22	ΔVORF	ΔEGM08
Aruba (vessel) (m)	-0.010	-0.030	0.130	0.350
Curacao (vessel) (m)	-0.050	-0.110	0.180	0.210
Sababank (vessel) (m)	-0.031	-0.039	0.090	0.459

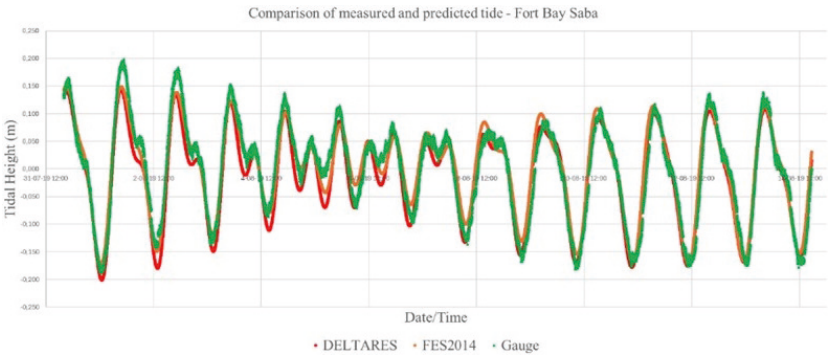


Fig. 13 Comparison of measured and predicted tide at SABA (Site 2).

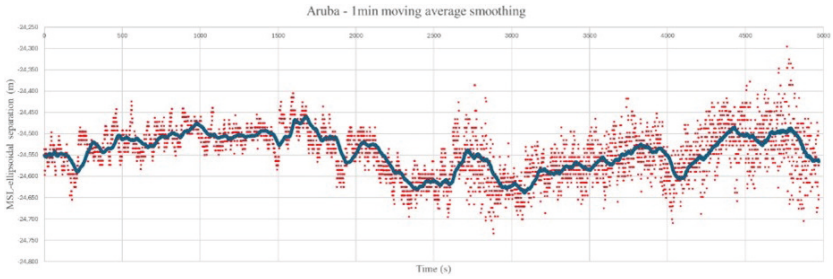


Fig. 14 Noise reduction by 1-minute moving averaging.

concerning assumed rates of Sea Level Rise.

Uncertainty analysis shows that the overall vertical uncertainty of about 9.2 cm matches that of current separation models and meets hydrographic survey standards. However, the results also highlight how vessel-based separation estimates depend on vessel dynamics and motion sensor performance. Increased noise and settling artefacts observed during manoeuvring, especially in the Curaçao dataset, emphasise the need for high-quality motion reference units and consistent survey speeds. While temporal filtering effectively reduces noise, it also lowers spatial resolution and cannot entirely counteract sensor limitations in highly dynamic conditions.

Several limitations of the present study should be acknowledged. The reliance on real-time PPP solutions limited access to raw GNSS observations for post-processing, which could otherwise enhance positioning accuracy and consistency. At Site 2, dependence on predicted tides introduces additional uncertainty, especially in long-period tidal components that are not fully captured by existing harmonic models. Moreover, the limited availability of long-term GNSS and tide gauge records restricts the ability to fully characterise local VLM and SLR trends, which are crucial for long-term vertical datum maintenance.

Despite these limitations, the findings demonstrate that vessel-based GNSS measurements offer a flexible and scalable alternative to traditional tide gauge-based vertical referencing. When combined with appropriate environmental corrections and uncertainty assessment, this approach enables the generation of reliable MSL-ellipsoidal separation values in regions where conventional geodetic infrastructure is limited or absent. The results, therefore, support the establishment of a regional network of permanent tide gauges and GNSS stations in the Dutch Caribbean, which would further enhance separation accuracy, improve monitoring of VLM and SLR, and strengthen the link between marine and terrestrial reference frames.

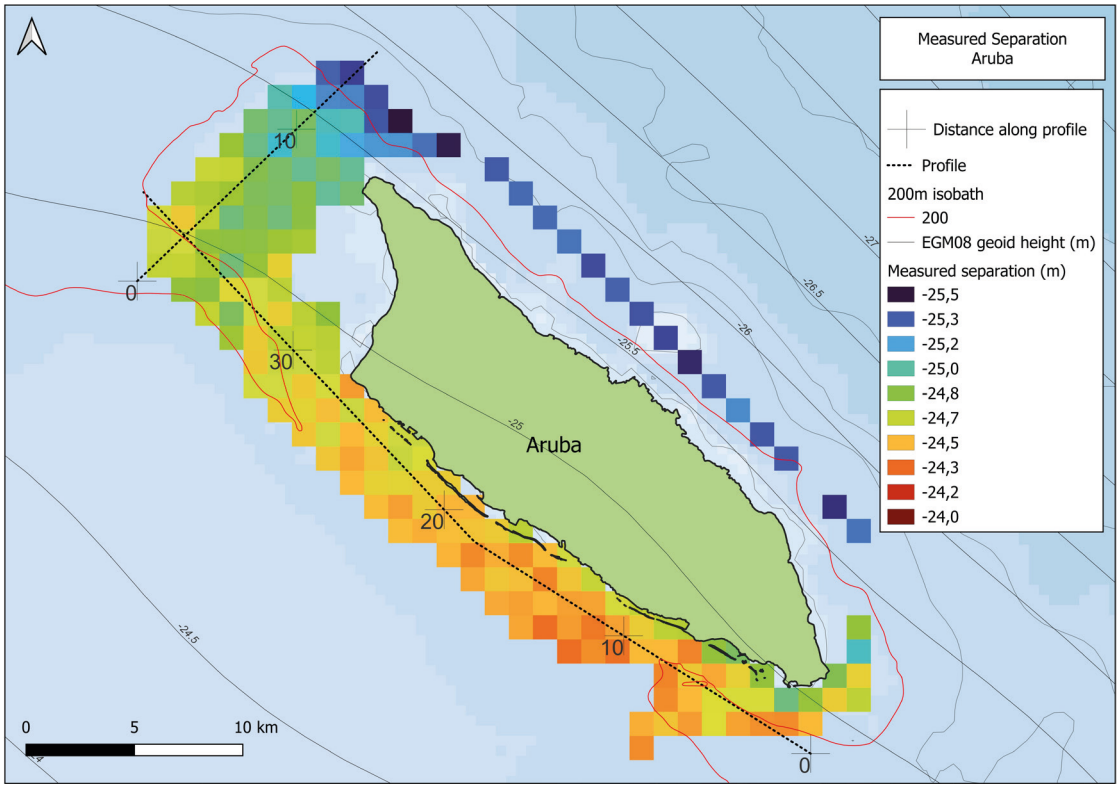


Fig. 15 Measured separation values near Aruba (Site 1).

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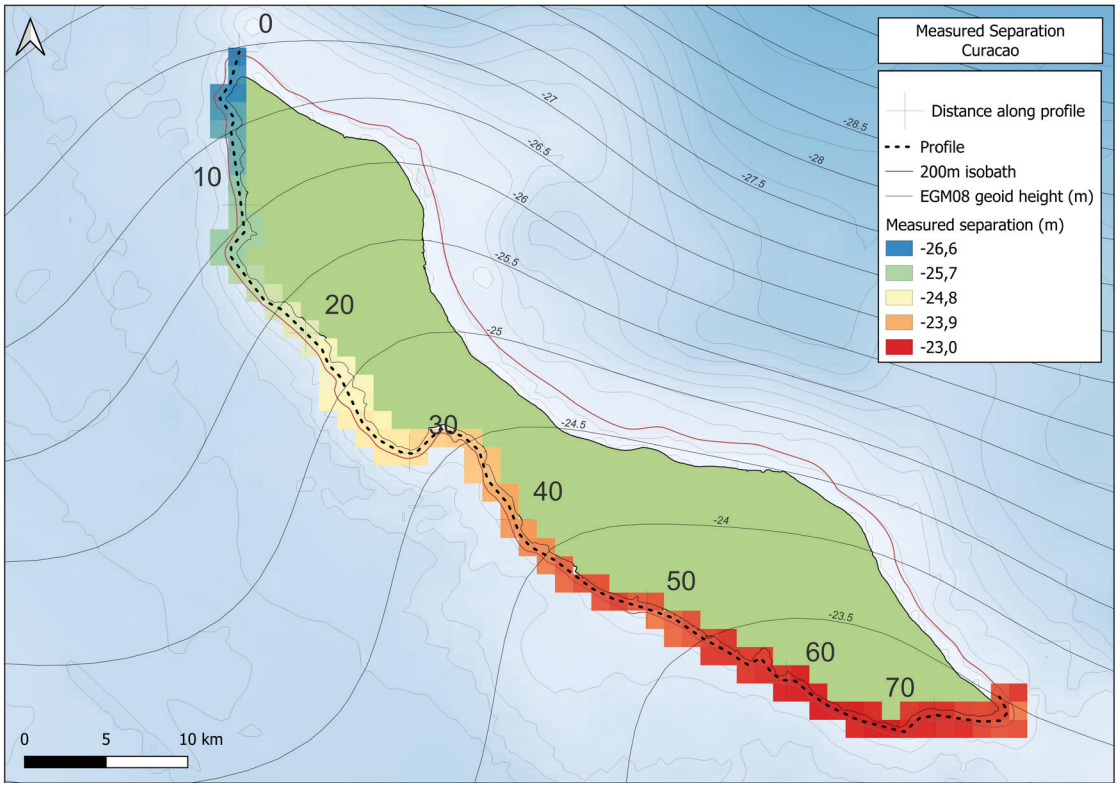


Fig. 16 Measured separation values near Curaçao (Site 1).

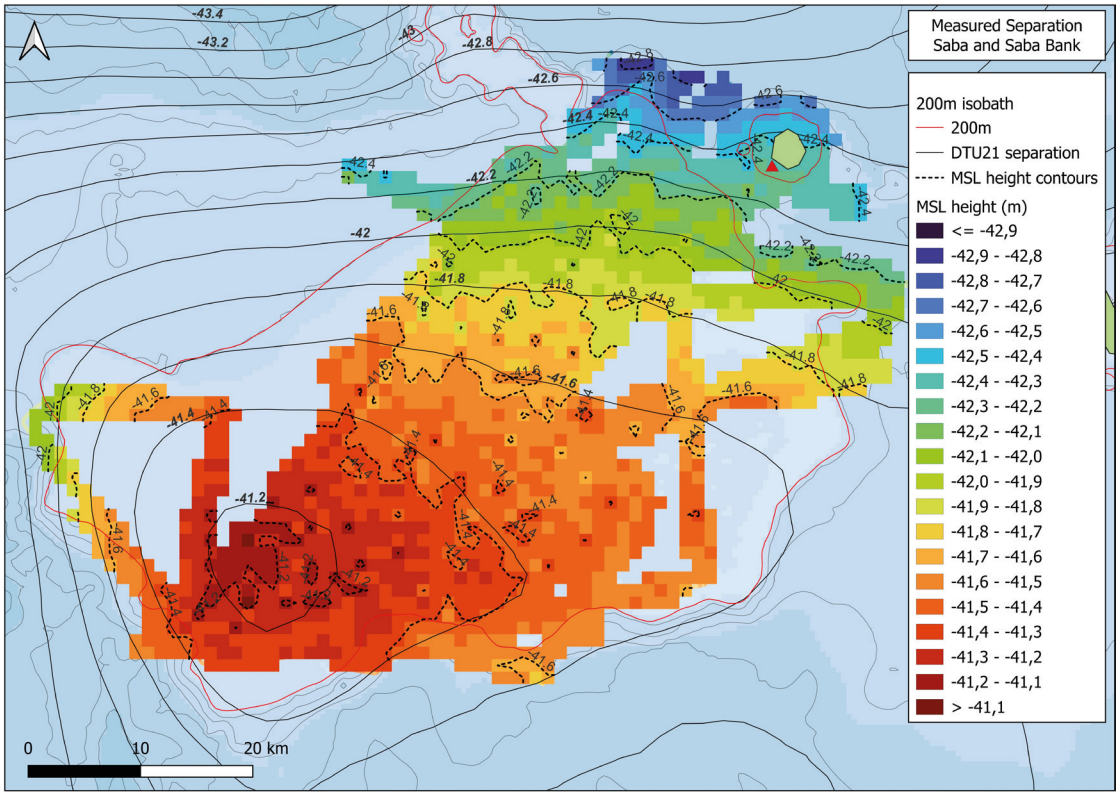


Fig. 17 Measured separation values near Saba and Saba Bank (Site 2).

6 Conclusion

This study shows that vessel-based Global Navigation Satellite System (GNSS) positioning offers a practical and reliable method for determining the Mean Sea Level (MSL)-ellipsoidal separation in the Dutch Caribbean, even in areas with limited geodetic infrastructure. By combining legacy vessel-based PPP GNSS data with tidal observations, predicted tides, and satellite altimetry, the approach effectively connects offshore measurements with coastal vertical reference systems.

The results indicate that vessel-derived separation values can match shore-based MSL references within a few centimetres after adjustments for Vertical Land Movement (VLM), Sea Level Rise (SLR), and seasonal variability. This agreement is strongest in the Leeward Islands (Aruba and Curaçao), where multiple shore-based tide gauges enable rigorous validation. At the Windward Islands (Saba and Saba Bank), where validation depends on predicted tides and a single tide gauge reference, the vessel-based method remains consistent within the achievable uncertainty range, confirming its suitability in environments with limited data and operational challenges.

Comparison with global reference surfaces shows that DTU21 aligns most closely with vessel-derived offshore separation values across both study sites. Conversely, CNES2022 exhibits larger nearshore deviations, while VORF global and EGM08 display significant inconsistencies, especially in complex island environments. These results underline the limitations of relying solely on global models for vertical referencing in the Dutch Caribbean and highlight the importance of empirical, region-specific separation estimates.

The total vertical uncertainty of about 9.2 cm meets hydrographic survey standards and aligns with existing separation models. However, the analysis also shows sensitivity to vessel movement, sensor performance, and tidal modelling, especially during manoeuvres and in areas without permanent tide gauges. These issues highlight the need for high-quality motion sensors, stable survey operations, and better access to post-processed GNSS data.

Overall, this contribution demonstrates that vessel based GNSS positioning provides a robust and operationally viable approach for vertical referencing in coastal and island environments where traditional tide gauge networks are sparse or absent. To further improve accuracy and long-term consistency, establishing a permanent regional network of tide gauges and GNSS stations in the Dutch Caribbean is highly recommended. Such infrastructure would enhance monitoring of VLM and SLR, strengthen connections between marine and terrestrial reference frames, and support future hydrographic surveying, coastal development, and climate change impact assessments.

By demonstrating the practical potential of vessel based GNSS for achieving consistent vertical control, this study contributes to improved coastal decision making and supports the development of informed sea level adaptation strategies in the Dutch Caribbean.

References

Abd Rahman, M. F. and Md Din, A. H. (2020). The Development of Continuous Hydrographic Datum Using Geodetic-Based Approaches: A Review. *IOP Conf. Ser: Earth Environ. Sci., 540*, 012062. https://doi.org/10.1088/1755-1315/540/1/012062

Andersen, O. B., Rose, S. K., Abulaitijiang, A., Zhang, S. and Fleury, S. (2023). The DTU21 global mean sea surface and first evaluation. E*arth Syst. Sci. Data, 15*, 4065–4075. https://doi.org/10.5194/essd-15-4065-2023

Chen, C.-T. and Millero, F. J. (1977). Speed of sound in seawater at high pressures. *The Journal of the Acoustical Society of America, 62*, 1129–1135. https://doi.org/10.1121/1.381646

EMODnet (2017). WP2.1: Assess consistency of the existing vertical datum Vertical datums in the European coastal zone. In *EMODnet Coastal Mapping – Final Report* (Phase 2, version 1.1).

Glen, N. C. (1977). The Admiralty Method of Tidal Prediction. *The International Hydrographic Review, 54*(1), 14. https://journals.lib.unb.ca/index.php/ihr/article/view/23705 (last accessed 3 April 2026).

Ligteringen, T., Loog, J. and Dorst, L. (2014). *GNSS-Based Hydrographic Surveying: clear advantages and hidden obstacles* [Conference presentation]. European Navigation Conference on GNSS 2014, Rotterdam, p. 11.

Liibusk, A., Varbla, S., Ellmann, A., Vahter, K., Uiboupin, R. and Delpeche-Ellmann, N. (2022). Shipborne GNSS acquisition of sea surface heights in the Baltic Sea. J*ournal of Geodetic Science, 12*, 1–21. https://doi.org/10.1515/jogs-2022-0131

Maitland, D. O., Taylor, M. A. and Stephenson, T. S. (2023). Investigation of Multi-Timescale Sea Level Variability near Jamaica in the Caribbean Using Satellite Altimetry Records. *JMSE, 11*, 1499. https://doi.org/10.3390/jmse11081499

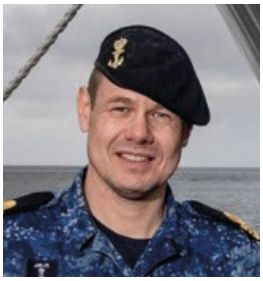
Schaeffer, P., Pujol, M.-I., Veillard, P., Faugere, Y., Dagneaux, Q., Dibarboure, G. and Picot, N. (2023). The CNES CLS 2022 Mean Sea Surface: Short Wavelength Improvements from CryoSat-2 and SARAL/AltiKa High-Sampled Altimeter Data. *Remote Sensing, 15*, 2910. https://doi.org/10.3390/rs15112910

Tegedor, J., Ørpen, O., Melgard, T., Lapucha, D. and Visser, H. (2017). G4 Multi-constellation Precise Point Positioning Service for High Accuracy Offshore Navigation. *TransNav, 11*, 425–429. https://doi.org/10.12716/1001.11.03.05

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Author's biography

Merte P. J. Peeters is a Commanding Officer of a hydrographic survey vessel in the Royal Netherlands Navy and has been an IHO Category A certified hydrographic surveyor since 2010. His professional experience spans navigation, hydrographic operations, offshore surveying, and geospatial analysis, including roles as a survey party chief and GIS specialist with Boskalis Westminster. He holds a Master's degree in Advanced Hydrography from MLA College (2025), where his thesis was recognised with the University of Plymouth Academic Partnerships Prize, THS-UKI Alan Ingham award, and second place in the IFHS Student Award. His work focuses on vessel-based GNSS positioning, vertical reference systems, and their application to hydrographic surveying in data-sparse and climate-vulnerable coastal regions.



Merte P. J. Peeters

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PEER-REVIEWED ARTICLE

Toward standardizing hydrographic vessel offset surveys: angular offset determination of hydrographic sensors at short-range using total station observations

Authors

Anand Hiroji[1] and Olaoluwa Oderinde[1]

Abstract

Vessel offset surveys (VOS) are essential for accurately integrating hydrographic systems, ensuring correct positioning and mounting angles for sonars, and positioning and orientation systems within specified manufacturer accuracies, which are necessary to meet the expected hydrographic survey standards summarized in the International Hydrographic Organization's publication S-44. This study examines factors affecting VOS accuracy, such as the number of station setups, baseline lengths, least square plane fitting, and instrument accuracies. Results indicate that multiple setups are required to achieve accurate mounting angles. Longer baselines improve accuracy, particularly for small sensors like an inertial measurement unit, while circular transducers benefit from fitting a plane with multiple points. This analysis supports standardizing VOS procedures to enhance VOS reliability and accuracy.

Keywords

vessel offset surveys · hydrographic system integration · sonar mounting angles

Resumé

Les levés des déports du navire (VOS) sont essentiels pour intégrer avec précision les systèmes hydrographiques, garantir le positionnement et les angles de montage adéquats des sonars, ainsi que le positionnement et l'orientation des systèmes dans les limites de précision spécifiées par les fabricants, ce qui est nécessaire pour respecter les normes de levés hydrographiques attendues, résumées dans la publication S-44 de l'Organisation hydrographique internationale. Cette étude examine les facteurs qui affectent la précision des VOS, tels que le nombre de configurations de stations, les longueurs de base, l'ajustement d'un plan par la méthode des moindres carrés et la précision des instruments. Les résultats indiquent que plusieurs configurations sont nécessaires pour obtenir des angles de montage précis. Des lignes de base plus longues améliorent la précision, en particulier pour les petits capteurs comme les unités de mesure inertielle, tandis que les transducteurs circulaires tirent avantage de l'ajustement d'un plan à partir de plusieurs points. Cette analyse plaide en faveur de la normalisation des procédures VOS afin d'améliorer leur fiabilité et leur précision.

✉ Anand Hiroji · anand.hiroji@usm.edu

[1] School of Ocean Science and Engineering, University of Southern Mississippi, USA.

Resumen

Los levantamientos de calibración del buque (VOS) son esenciales para integrar con precisión los sistemas hidrográficos, asegurar la corrección del posicionamiento y ángulos de montaje de los sonares, y el posicionamiento y orientación de los sistemas dentro de los márgenes de precisión especificados por los fabricantes, lo que es necesario para cumplir con las normas de levantamientos hidrográficos resumidas en la publicación S-44 de la Organización Hidrográfica Internacional. Este estudio examina los factores que afectan a la precisión de los VOS, como el número de configuraciones de estación, las longitudes de las líneas de base, el ajuste de planos por mínimos cuadrados y la precisión de los instrumentos. Los resultados indican que se requieren múltiples configuraciones para conseguir ángulos de montaje precisos. Las líneas de base más largas mejoran la precisión, particularmente para sensores pequeños como las unidades de medición inercial, mientras que los transductores circulares se benefician del ajuste de un plano con múltiples puntos. Este análisis respalda la normalización de los procedimientos de VOS para mejorar su fiabilidad y precisión.

1 Introduction

The hydrographic survey ships use positioning and orientation systems (POS) in conjunction with sonar systems to determine seafloor positions and depths. Modern surface POS consists of two subsystems: a global navigation satellite system (GNSS) unit with two antennas and an inertial measurement unit (IMU) (Kongsberg, 2024; SBG, 2025; Applanix, 2025). On the multibeam side, high-frequency, shallow water sonars may have transmit and receive arrays mounted on machined frames and generally enclosed in a single casing, while low-frequency sonars (e.g., 100 kHz or lower, such as EM 304 (Kongsberg, 2021), SeaBeam 3050 (ELAC Sonar, 2021), and HydroSweep DS (Teledyne Marine, 2022)) have separate transmit (Tx) and receiver (Rx) arrays mounted on the ship. To integrate these systems properly, it is crucial to understand the spatial and angular relationship of all physical components, including GNSS antennas, IMU, multibeam Tx and Rx arrays, with respect to a common reference frame, typically referred to as the vessel reference frame (VRF).

A coordinate reference system (CRS) defines the rules for measuring coordinates within a specific framework (Vaníček & Krakiwsky, 2015). In the context of a vessel reference system, these rules include defining:

1. the location of the origin of the coordinate system, which can be a physical or virtual point on the vessel (e.g., a center of gravity, IMU reference mark or phase center, sonar acoustic center, or a granite reference block (IMTEC Group, 2021; Westlake Consultant, 2021)) or a fictitious point anywhere in or outside the vessel (Hiroji & Oderinde, 2022);
2. the orientation of three orthogonal axes, which typically follows the POS or sonar coordinate system's convention;
3. the linear scale, which is one for VOS given the small distances involved (a few hundred meters); and
4. the unit of measure, which is usually consistent with the hydrographic data collection software.

The VRF is the physical realization of the vessel's CRS, requiring the identification of specific points on the vessel relative to the defined origin and orientation of axes. Establishing the VRF is one of the objectives of any VOS, followed by measuring the spatial and angular offsets of onboard systems relative to the realized VRF. VOS are referred to by various terms, including Dimensional Control Survey, Alignment Survey, Vessel Configuration Survey, or Vessel Geometry Survey. In some cases, they are even called Land Surveys as these surveys are often conducted on land in a dry dock. These different names reflect the same underlying objective: to precisely measure and define the spatial and angular relationships of various system components to ensure accurate integration and performance of the hydrographic and positioning systems.

1.1 Accuracy requirement of VOS

The deviations of spatial and angular offsets of various system components critically influence system performance (Applanix, 2017; Kongsberg, 2021). For instance, any error in the spatial relationship of GNSS antennas directly impacts the accuracy of position and heading. Similarly, any error in the IMU's angular alignment with the VRF directly affects the orientation accuracy. Given the three-dimensional spatial relationships among system components and the three degrees of freedom in orientation, errors in spatial and angular offsets measured during VOS introduce non-linear effects on final bathymetry (Hughes Clarke, 2003). In general, larger spatial offsets between system components and increased vessel motion exacerbate the impact of errors in VOS on the position and motion outputs from POS, multibeam and other system performance, ultimately affecting the accuracy of seafloor position and depths. In some cases, the manufacturers of hydrographic systems provide the minimum accuracy with which various offsets must be obtained during VOS. An example of such a requirement is shown in Table 1.

In all multibeam systems with separate Tx and Rx arrays, the angular relationship between Tx and Rx is crucial to sonar performance (90° ± 2°). The most

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Table 1 Summary of accuracy requirements for VOS extracted from Kongsberg EM 304 installation manual (Kongsberg, 2021).

Parameter	Sensor	Accuracy
Pitch	Tx, IMU	±0.05°
Roll	Rx, IMU	±0.02°
Pitch	Rx	±0.2°
Roll	Tx	±0.2°
Heading	Tx, Rx, IMU	±0.1°
Relative heading between Rx and Tx transducer	Tx, Rx	±0.1°
Position (*x, y, z*)	Tx, Rx, IMU	±0.05 m

stringent linear accuracy requirement during VOS is for the flatness of different modules of the Tx and Rx units; for example, for Kongsberg systems, this is 0.6 mm (Kongsberg, 2021). Similarly, the most stringent angular requirement can be for Applanix POS MV Ocean Master IMU at ±0.008° at its highest performance level (Applanix, 2017).

1.2 Patch test and VOS

Before delving into the experiments and analysis, it is essential to clarify why a multibeam patch test cannot replace VOS. When the first multibeam systems were deployed, it was found that residual angular offsets, the remaining angular offset after applying offsets computed during VOS, and latency between positioning and sonar system could introduce significant systematic errors in seafloor positioning (Hughes Clarke, 2018). To address this, a field calibration process, commonly known as the multibeam patch test, was developed to estimate these residual angular offsets. The patch test, now a standard procedure following new sonar installations, derives residual roll and pitch offsets between the IMU and the multibeam system (combined Tx and Rx), along with the residual heading offset between the heading device and the multibeam system (combined Tx and Rx). The patch test results are applied in addition to the angular offsets obtained from VOS. Typically, a patch test provides roll offsets with an angular resolution on the order of 0.001° and pitch and yaw offsets on the order of 0.01°, as demonstrated in published technical reports from the U.S. academic research fleet (MAC, 2024).

However, the patch test estimates only the residual angular offsets and does not replace the need for the initial angular and spatial offsets derived through VOS. The patch test provides three residual angular misalignments: roll, pitch, and yaw. However, it is important to acknowledge the limitations of the patch test. First, it cannot estimate the angular misalignment between a system's reference frame and the VRF. The patch test only addresses the residual misalignment between the sonar and other systems (Hughes Clarke, 2003). For instance, if an IMU has a roll mounting angular error of -0.05° with VRF and the combined transmit (Tx) and receive (Rx) multibeam system has a mounting angle error of +0.05° with VRF, the patch test will theoretically show a residual roll offset with a magnitude of 0.10° to be applied to the IMU or Tx and Rx, with the sign depending on the adopted coordinate-system convention and the correction definition.

Additionally, the patch test cannot detect the angular misalignment between the separate multibeam Tx and Rx units in low-frequency sonar systems. Residual errors in this alignment remain undetectable, but significant unaccounted misalignment degrades the performance of the sonar system, especially in the mathematical beamforming process where the Tx and Rx cone intersections are computed.

Moreover, the patch test does not account for the heading misalignment between the IMU forward axis and the VRF forward axis. Since the heading in the POS system is primarily derived from the GNSS vector, the residual heading value from the patch test does not reflect the IMU's heading misalignment with the VRF. Any misalignment left uncorrected will distort the IMU's roll and pitch readings, with the error increasing in magnitude as higher roll and pitch motion are experienced.

Because of the above reasons, while the patch test can reduce systematic errors in bathymetric data, it cannot fully eliminate the effects of residual angular misalignments and their cross-talk. The only way to minimize these errors effectively is through a high-accuracy VOS.

1.3 Motivation for this study

Typically, a sonar manufacturer or a shipyard contracts a survey company to conduct a VOS. The survey company is usually provided with the minimum requirements set by the equipment manufacturers. The resulting reports detail the computed offsets, aiming to present the information in a user-friendly format and to prevent misunderstandings in sign conventions. In some cases, a national advisory committee provides guidelines for standardizing these reports across different survey companies and vessels for a national fleet (MAC, 2024). However, a review of several reports, along with discussions with survey companies and contractors, reveals that while minimum accuracy requirements and report guidelines are provided, there are no publicly available formal standards or guidelines outlining how the survey itself should be designed and executed. In addition, IHO S-44 (IHO, 2022) does not provide

Table 2 Different total stations and their corresponding linear and angular accuracies. Generally, total stations with an accuracy of 0.5", 0.5 mm to 1", and 1 mm are utilized for VOS (LEICA, 2014, 2020; TOPCON, 2016, 2018, 2019, 2025; Trimble, 2015, 2023).

Total station	Angular accuracy (")	Linear accuracy
Sokkia Net05AXII	0.5	0.5 mm + 1 ppm
Topcon MS05AX	0.5	0.5 mm + 1 ppm
Leica Nova MS60	1	1 mm + 1.5 ppm
Trimble SX12 Robotic	1	1 mm + 1.5 ppm
Topcon GT1201	1	1 mm + 2 ppm
Trimble S9 Robotic	0.5	1 mm + 2 ppm
Topcon GM-55	5	1.5 mm + 2 ppm
Leica TS07	5	1 mm + 1.5 ppm

specific guidance on minimum accuracy or uncertainty requirements for vessel offset surveys, either in general or by survey order. We hope that this study represents a step toward the development of a more standardized, traceable, and technically defensible approach for conducting VOS.

The methodology for performing a VOS is typically left to the discretion of the surveyors and is not required to be detailed in the final report. In the absence of standardized procedures, key variables, such as the accuracy of the instrumentation, the number of redundant observations, the methods for computing angular offsets, and the overall observed uncertainties, can vary significantly between survey companies. A review of recent VOS reports for the U.S. academic fleet (IMTEC Group, 2021) indicates that general estimates for both linear and angular accuracies are provided. Linear accuracies are typically reported between 1 mm to 2 mm, which is generally twice the distance measurement accuracy of the instrument used. Angular accuracies are reported between 30" and 60", corresponding to approximately 60 times the angular accuracies of the instrument used. Mostly, the instrument used for VOS is a total station, an electro-optical instrument measuring slope distance, vertical angles, and horizontal angles in an instrument-related relative frame (Ghilani & Wolf, 2012). In certain cases, particularly for short-range measurements conducted in stable environments, a laser tracker may also be utilized. The methods described in this document apply equally to all such instruments. Table 2 outlines some of the available total stations with different accuracies.

Due to varying geometries and distances involved during field measurements, several parameters associated with the VOS method can likely cause different angular offsets to have different observed errors. Several key parameters that may influence the final observed accuracies have been identified. These include the accuracy of the instruments used, the geometry and orientation of the station setups, the baseline length, the number of points used for generating a line or plane, the orientation and number of reference points, and the number of station setups performed. This research aims to compute more reliable observed uncertainties in angular misalignments and identify parameters that critically affect those uncertainties, ultimately contributing to the standardization of VOS procedures to achieve specific required thresholds.

The findings presented are based on two experimental setups. The first focused on the IMU's mounting angles, conducted in a controlled laboratory environment at the Stennis Space Center, Mississippi, USA. The second setup, targeting a circular transducer, collected data during the VOS of EV Nautilus in Hawaii, USA. These experiments allowed for a detailed analysis of the factors influencing angular and linear offset accuracies, providing a foundation for establishing a more standardized and reliable VOS methodology.

2 Methodology

VOS is typically conducted using survey-grade total stations, either in dry docks or on floating dry docks. Fig. 1 illustrates a typical survey network for a 29-foot survey launch secured on a trailer, covering all hydrographic systems. For the purposes of this study, only one sensor was analyzed to ensure efficiency and allow sufficient time for the multiple sets of observations required for the analysis.

In the first experimental setup, the IMU was selected as the sensor for observation. Generally, the IMU has the smallest physical footprint but the most stringent angular accuracy requirements, with a particular focus on roll, which demands an uncertainty of ±0.02°; for example, in the case of the Applanix POS MV WaveMaster with RTK (Applanix, 2015). In the second experimental setup, a circular transducer (Simrad EC150) was chosen, which similarly requires a VOS uncertainty of ±0.02° in both roll and pitch (Simrad, 2019).

The following sections detail the general setup and methodology used for both experiments, focusing on ensuring the required angular accuracy and facilitating reliable comparisons between the sensor setups.

2.1 Experimental setup 1: IMU

In the first experimental setup, an IMU was placed in

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a stable, quiet storage room to ensure no movement during the one-week data collection period. Eight reference targets were positioned approximately two meters above the IMU at four corners around it (Sokkia 30 mm reflective tape) (Fig. 2). Fig. 3 shows the photograph of the experimental setup. The setup involved observing all eight reference targets and then collecting measurements from specific points on the IMU, including a level placed flush to the IMU base plate, to calculate roll, pitch, and yaw angles.

A Sokkia Net05AXII industrial total station was used for the experiment. The manufacturer-specified accuracy of the total station is 0.5 mm + 1 ppm for distance measurements and 0.5" for angular measurements (SOKKIA, 2022). The total station was calibrated by a Sokkia certified servicing center eight months prior to this study. The total station measures three basic observables: slope distance, vertical angle, and horizontal angle from the phase center of the instrument to the back of a reflective target. Using trigonometric calculations and applying corrections for environmental factors, these observed quantities were converted by the algorithm inside the total station processor into 3D Cartesian coordinates relative to the origin of the defined local coordinate system.

When doing measurements to compute coordinates of a single point, direct and indirect observations were conducted to minimize residual systematic errors, once with the vertical circle of the total station on the left side of the telescope (known as "face-left" or direct observation) and once with the telescope rotated 180° and the vertical circle on the right (known as "face-right" or indirect observation) (Ghilani & Wolf, 2012). One distance measurement was taken in both face-left and face-right positions, and the average distance was used in the computation. These direct and indirect observations were mathematically adjusted to correct for any residual systematic errors caused by instrument inaccuracies, and the final 3D coordinates of the measured points were calculated. In this context, one observation refers to the combined, adjusted results from both face-left and face-right observations.

For each total station setup, a unique coordinate system was defined using a fixed offset (100 m North, 100 m East, and 10 m up) from the point of occupation and setting the azimuth to 0° while pointing roughly towards North. This approach avoided using the real-time resection method for station setup and ensured that each setup remained independent, reflecting real-world VOS scenarios where resection or coordinate transformation is typically handled in post-processing. A custom Python script using the singular value decomposition method was developed to compute the six parameters required for coordinate transformation between systems, with flexibility in considering a variable number of common points between the two coordinate systems. The script also performed the coordinate transformation and produced the transformed coordinates of subsequent

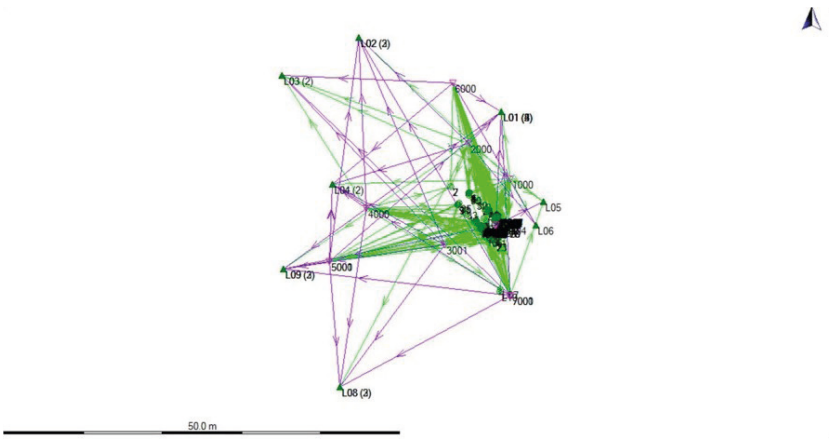


Fig. 1 A network of measurements performed during a VOS for a 29-foot survey vessel (Class of 2023, 2023).

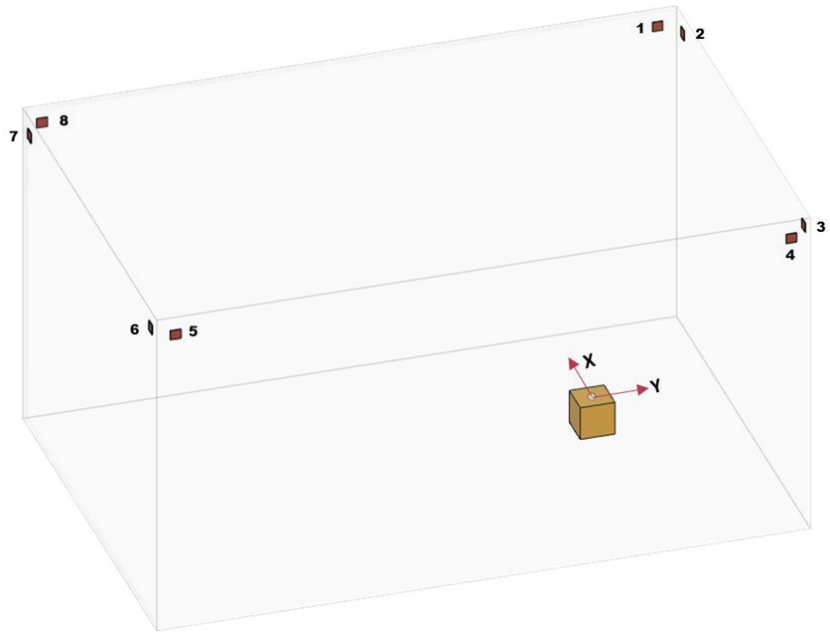


Fig. 2 General overview of the experimental setup, showing the location of eight reference points and IMU along with its X and Y orientation axis. The Z axis is orthogonal to the *X* and *Y* axis and points down, completing the right-handed coordinate system.



Fig. 3 A picture taken during field measurements.

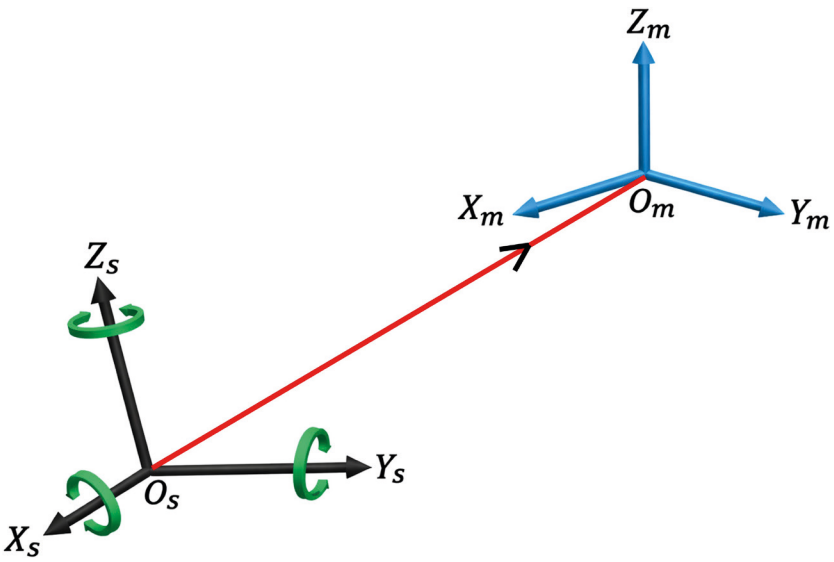


Fig. 4 Conceptual example of coordinate transformation: A slave coordinate system (subscript s) is transformed into a master coordinate system (subscript m) using measurements to common points with known coordinates in both systems, providing six transformation parameters. During the transformation, the translation vector, defined by three translation parameters (shown in red), moves the origin O_s to O_m. The orientation of the slave frame is then adjusted by the three rotations (shown in green) about its axes until the slave frame aligns with the master frame.

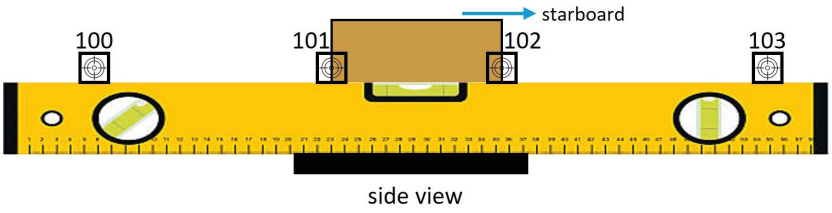


Fig. 5 Target arrangement on the level for measuring roll angle. A single cube target was used at four locations (100, 101, 102, and 103) separated by approximately 20 cm. In this experiment, the level was positioned directly on top of the IMU.

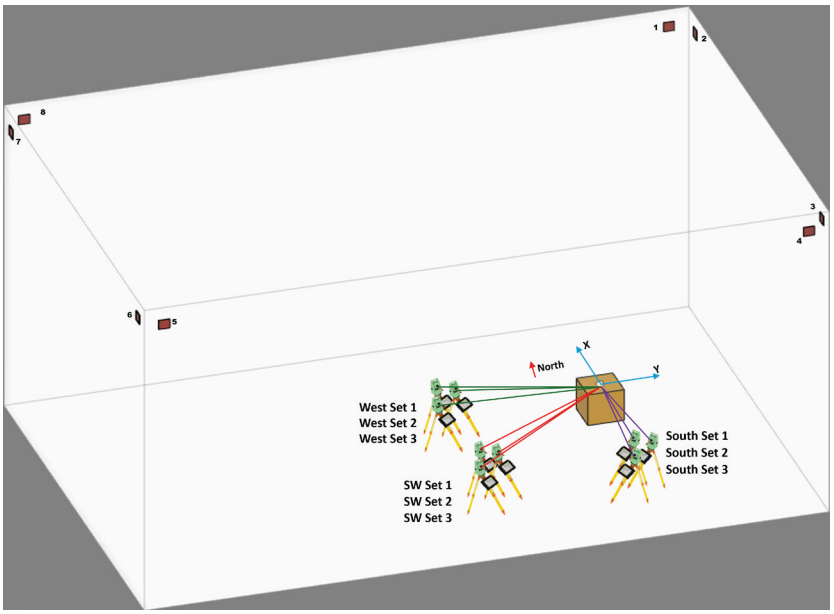


Fig. 6 Conceptual figure showing the 9 different station setups: three from each orientation (South, Southwest, and West). The 8 reference points are also depicted. All local coordinate systems were approximately aligned to the north with the origin (100mN, 100mE, 10mZ).

setups (called slave) in the coordinate system of the first setup (taken as master). As the experiment did not involve any ship, the first setup (master) was treated as the VRF. A schematic of the transformation is provided in Fig. 4.

2.2 Measurements for computing roll, pitch, and yaw angles

During each setup, coordinates of multiple points were measured on a level to calculate the roll, pitch, and yaw angles of the IMU. A single 20 mm cube with one standard Sokkia 20 mm reflective tape with 0.3 mm target lines on one side was used as the target for these measurements. The cube was placed on top of a 1 m long-level to extend the baseline of the smaller IMU, enhancing measurement precision. No observations of any type using the bubble level were taken for this experiment. The level should preferably be placed on manufacturer-recommended reference surfaces or designated reference points. However, because the reference base plate was not available in this experiment, the level was placed directly on top of the IMU, as shown in Fig. 5.

For roll calculations, the level was positioned approximately aligned along the east (Y) axis on top of the IMU, while for pitch, the level was approximately aligned along the north (X) axis. Any deviation from the exact Y or X axis when making the observations will not impact final computed roll and pitch values, as the measured points are projected onto the YZ plane for roll and onto the XZ plane for pitch. To measure yaw, the level was placed flush with the base of the IMU along either the north (X) axis or with the east (Y) axis, depending on the location of the total station, ensuring a clear line of sight. The IMU manufacturer explicitly identifies these edges as the reference edge for heading alignment measurements. For each orientation, the cube was spaced equally along the length of the level, allowing measurements of four points on the level. Regardless of the total station's position, the cube was always oriented perpendicular to the line of sight to maintain measurement consistency.

From each station setup, measurements were taken to points needed to compute roll, pitch, and yaw, along with the eight reference marks on the walls. A total of nine different setups were observed, with three setups taken from the South, Southwest, and West directions, as illustrated in Fig. 6. These varied locations ensured comprehensive spatial coverage and allowed for precise calculation of the IMU's angular offsets.

2.3 Computing roll, pitch, and yaw angles

Once all setups were transformed to the coordinate system of the first setup (master setup), the roll, pitch, and yaw angles between the master coordinate frame and the IMU's coordinate frame were calculated. A dedicated Python script was developed to handle these computations, providing the flexibility to specify the number of points on the level to be used

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for angle calculations. When more than two points were used, a 3D least squares line fitting was applied to the measured points. This fitted line was then used to compute the inclination angles (roll, pitch, or yaw) relative to the coordinate system of the master setup, which is taken as the VRF in this context. The measured inclination angles are then converted to the corresponding mounting rotation angles required for system configuration. In practice, this conversion is typically performed using a built-in utility or wizard provided in the IMU manufacturer's configuration software. The procedure used for this conversion is beyond the scope of the present study.

A set of results obtained from the custom Python script were cross-validated against calculations performed using commercially available software (Coulson, 2024). The differences between the two methods were in the order of 10^{-5}°, making them negligible and confirming the achievable accuracy using the developed script.

The combination of the nine different setups, the four targets on the level, and the eight reference targets provided multiple variables that could be analyzed for their influence on the computed roll, pitch, and yaw values. This setup enabled a comprehensive examination of how different observational configurations and reference points affected the uncertainty of the angular measurements.

2.4 Experimental setup 2: EC150 transducer face

This experimental data collection was part of an actual VOS for the EV Nautilus, which was in a floating dry dock as seen in Fig. 7. The same Sokkia NET05AXII industrial total station used for experimental setup 1 was used for all observations. A new sonar, the Simrad EC150, had been installed at the bottom of the keel (Fig. 8). The primary objective of this VOS was to accurately determine the position and orientation of the EC150 transducer with a diameter of 346 mm (Simrad, 2019) relative to the previously established VRF.

For this purpose, coordinates of nine evenly distributed points on the face of the EC150 transducer (Fig. 9) were collected from three independent total station setups. Three total station setup locations were selected around the EC150: one forward of the EC150 near the vessel centerline, one to starboard of the EC150 across the centerline, and one aft of the EC150 near the vessel centerline. These locations were selected to maximize direct line-of-sight visibility to the EC150 transducer face and a minimum of eight previously established control points. The transducer face was recessed compared to the vessel's keel, which prevented straightforward extension of the plane of the transducer's bottom face using a level similar to one done in experimental setup 1 (IMU). This experimental setup was ideal for evaluating the effectiveness of roll and pitch calculations using a fitted plane to the points on the circular transducer face compared to the shorter baseline available.



Fig. 7 EV Nautilus in floating dry dock Kapolei, Hawaii, December 2022.



Fig. 8 Newly installed EC150 transducer.

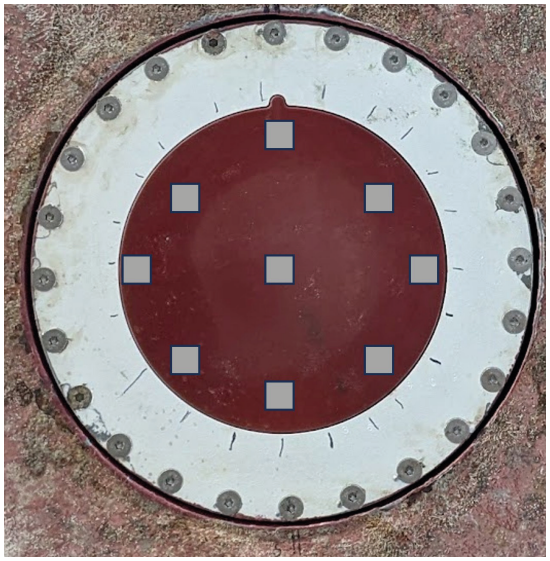


Fig. 9 EC150 transducer face with nine squares representing the approximate locations used for position measurements. A single 20 mm cube with one standard Sokkia 20 mm reflective tape with 0.3 mm target lines on one side was used as the target for these measurements similar to the one used in experimental setup 1.

3 Data analysis, results, and discussion

This section is divided into subsections, and each has a focus on analyzing the impact of different parameters on the uncertainty of the VOS. To maintain clarity and conciseness, only the results for one of the computed angles, either roll or pitch, whichever has the most stringent uncertainty requirements, are discussed below.

3.1 Instrument accuracy

To investigate the effect of instrument accuracy on the VOS results, the ideal approach to obtain real-world values would be to collect parallel datasets using a separate instrument with lower accuracy. However, due to time constraints and the complexity of data collection, a Monte Carlo based simulation approach was adopted instead. Specifically, to simulate results from an instrument with accuracy of ±1" for angular measurement and ±1 mm for linear measurements, the raw measurements from the Sokkia Net05AXII were modified to simulate lower-accuracy results. This was achieved by adding normally distributed random errors of ±0.866" for angular measurements and ±0.866 mm for linear measurements to the raw measurements from the Sokkia Net05AXII with stated manufacturer's accuracy of ±0.5" for angular measurements and ±0.5 mm + 1 PPM for linear measurements. The expected random error after this simulation is ±1 for angular measurements in seconds and linear measurements in mm. A total of 11 simulated datasets were generated each containing 9 observations, resulting in 99 simulated estimates of the IMU mounting angles.

This approach ensured that all random observational errors present in the original data remained consistent, with the only variable being the simulated random instrument errors. The modified measurements were then used to compute the final 3D point coordinates. These modified datasets, incorporating the added random errors, were subsequently processed in the same manner as the original data to compute the roll, pitch, and yaw of the IMU. The results of this analysis are summarized in Tables 3 and 4.

All consecutive results in this section are arranged in a similar manner to Table 3. The table is organized into two primary sections: Computed angle values and Statistics. Each row corresponds to a specific location, denoted as S (South), SW (Southwest), and W (West), while each column represents either a computed value from a setup or a statistical metric.

The computed angle values section displays the computed roll from three distinct experimental setups labeled Setup1, Setup2, and Setup3. For each location, the table lists three corresponding roll values derived from these setups. These values represent the core data from which the subsequent statistical analysis is drawn. The headers from the statistic sections are self-explanatory and offer a summary of computed values for each location (by row). The last row in green-colored values in the statistic section summarizes the statistics for nine roll values from the three locations and three setups per location. This structured organization allows for an intuitive comparison between the different setups and locations, as well as a clear understanding of the statistical characteristics of the computed values. Please note that all values in the presented tables are expressed in degrees unless specified otherwise.

The average roll angle of -0.27°, as seen in the last row in Table 3, and the average roll value of -0.29°, as seen in the last row in Table 4 indicate that, for the simulated observation scheme used in this study, there is no substantial difference in the estimated mean roll angle when using the higher-accuracy instrument data and the simulated lower accuracy observations. However, a substantial difference is observed in the standard deviation of the individual roll estimates between the two cases (0.05° versus 0.15°).

However, the standard error of the mean obtained from 9 original observations in Table 3 is ±0.017° ($0.05 / \sqrt{9}$), while the corresponding value obtained from 99 simulated observations in Table 4 is ±0.015° ($0.15 / \sqrt{99}$) and both values are within the required tolerance of ±0.02°. These standard errors of the mean represent the Type A standard uncertainty of the estimated roll angle referred to hereafter in this paper as the Type A standard uncertainty and were calculated from repeated observations in accordance with the Guide to the Expression of Uncertainty in Measurement (JCGM, 2008). This indicates that a lower-accuracy instrument may still yield a comparable uncertainty in the estimated mean roll angle if a sufficiently large number of observations is acquired. However, in practical field applications, acquiring 99 observations for a single sensor is not realistic, and even the 9 setups used in this experiment may be difficult to achieve under routine survey conditions.

Table 5 presents results obtained by randomly selecting 9 observations from the 99 simulated observations, thereby matching the number of observations acquired with the higher-accuracy total station. Although the estimated mean roll value remains comparable (-0.27°) between the two instrument-accuracy cases, the Type A standard uncertainty increases substantially to 0.053° ($0.16 / \sqrt{9}$) for the simulated lower-accuracy instrument. This indicates that, when the number of observations is held constant, the lower-accuracy instrument does not meet the manufacturer's 0.02° uncertainty expectation.

The standard error of the mean is ±0.017° in the case of Table 3 and ±0.015° in the case of Table 4. Since all other parameters remained constant between the two sets of observations, the simulated reduction in instrument accuracy did not materially affect the uncertainty of the estimated mean roll value when a sufficiently large number of observations was used. This suggests that, in this case, the

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Table 3 Roll values and associated statistics for the Sokkia Net05AXII (0.5 mm and 0.5" accuracy). The values are shown in degree and computed using two innermost targets, 101 and 102 (Fig. 5).

Location	Computed roll values			Statistics				
	Setup1	Setup2	Setup3	Min	Max	Diff (Max-Min)	Mean	Stdv
S	-0.27	-0.25	-0.30	-0.30	-0.25	0.05	-0.27	0.03
SW	-0.38	-0.25	-0.24	-0.38	-0.24	0.14	-0.29	0.08
W	-0.27	-0.24	-0.19	-0.27	-0.19	0.08	-0.23	0.04
				-0.38	-0.19	0.19	-0.27	0.05

Table 4 Roll angle associated statistics derived from modified observations recomputed with added theoretical normally distributed random errors corresponding to instrument accuracies of 1 mm and 1". The statistics were computed from 99 roll angle values, obtained from 11 modified datasets, and are not listed individually due to space limitations. The roll angles were computed using the two innermost targets (101 and 102; Fig. 5) and are reported in degrees.

Location	Statistics				
	Min	Max	Diff (Max-Min)	Mean	Stdv
S	-0.63	0.27	0.90	-0.26	0.19
SW	-0.55	-0.11	0.44	-0.30	0.11
W	-0.58	0.00	0.58	-0.31	0.16
	-0.63	0.27	0.90	-0.29	0.15

Table 5 Roll values and associated statistics for the modified observations obtained by recomputing the measurements with added theoretical, normally distributed random errors corresponding to equipment accuracies of 1mm and 1" and selecting random 9 values from the 99 simulated observations. The values are shown in degree and computed using two innermost targets, 101 and 102 (Fig. 5).

Location	Computed roll values			Statistics				
	Setup1	Setup2	Setup3	Min	Max	Diff (Max-Min)	Mean	Stdv
S	-0.41	-0.24	-0.58	-0.58	-0.24	0.34	-0.41	0.17
SW	-0.05	-0.35	-0.13	-0.35	-0.05	0.30	-0.18	0.15
W	-0.25	-0.19	-0.19	-0.25	-0.19	0.06	-0.21	0.03
				-0.58	-0.05	0.52	-0.27	0.16

effect of increased observational redundancy compensated for the lower nominal instrument accuracy. Consequently, the simulated lower-accuracy instrument, with approximately 1" angular and 1 mm linear accuracy, produced a comparable Type A standard uncertainty in the estimated mean roll angle to that obtained from the higher-accuracy Sokkia NET05AXII. However, this comparison is based on 9 observations obtained with the higher-accuracy instrument and 99 simulated observations representing the lower-accuracy instrument. In practical field applications, acquiring such a large number of observations for a single sensor installation is generally not feasible. Therefore, instrument selection should be based not only on the required uncertainty of the final result but also on the practical number of observations that can realistically be acquired in the field.

3.2 Direct and indirect observations

The next parameter examined during the experiment was the effect of using direct-only observations versus both direct and indirect observations. As previously discussed, combining adjusted direct and indirect observations helps to eliminate any residual internal instrument systematic errors (Schofield, 2001) after calibration, while also minimizing the impact of random errors, such as pointing errors. In the field, both direct and indirect observations were performed for each angle and distance measurement targeting a single cube on a level. The resulting computed roll values are presented in Table 3. To assess the 3D position values based solely on direct observations, the indirect observations were manually removed from the raw data prior to calculating the 3D positions of the points. These points were then used to compute the roll values based on direct observations alone, as shown in Table 6.

As shown in the last row of Tables 3 and 6 (green-colored), the mean roll angle differs by only 0.01° between the two results (-0.27° and -0.28°). The standard deviation computed from the nine observations remains consistent at 0.05° in both cases. This suggests that, at relatively short distances (approximately 3 meters in this case), the residual systematic errors in horizontal and vertical angles, stemming from instrument inaccuracies such as collimation error, misalignment in the horizontal plane of rotation, or the vertical plane not being exactly perpendicular, with the used total station (with its magnitude of calibration parameters) and in this particular scenario,

Table 6 Roll values and associated statistics using direct observations only. The values are shown in degree and computed using two innermost targets, 101 and 102 (Fig. 5).

Location	Computed roll values			Statistics				
	Setup1	Setup2	Setup3	Min	Max	Diff (Max-Min)	Mean	Stdv
S	-0.22	-0.22	-0.30	-0.30	-0.22	0.08	-0.25	0.05
SW	-0.38	-0.25	-0.27	-0.38	-0.25	0.13	-0.30	0.07
W	-0.33	-0.27	-0.24	-0.33	-0.24	0.08	-0.28	0.04
				-0.38	-0.22	0.16	-0.28	0.05

do not significantly impact the results. However, this finding may change in the presence of larger systematic errors or when observations are made over longer distances. Additionally, this implies that when instruments are calibrated by a certified servicing center and subsequently verified on-site by the surveyor prior to data acquisition, surveyors can rely on direct observations alone for shorter distances. Nevertheless, prior to data acquisition, the calibration parameters should be verified by the surveyor to ensure the integrity and reliability of the measurements, particularly in applications demanding high accuracy. When operational time permits, performing direct and indirect observations is advisable, as this practice further enhances measurement precision and robustness.

3.3 Baseline length

The accuracy of 3D point coordinates on the level is largely independent of the distance between the points. However, the angular offset is computed from the relative positions of the points. Therefore, for the same angular offset, a longer distance between the points (i.e., a longer baseline) should, in theory, reduce the influence of coordinate uncertainty and improve the accuracy of the estimated offset. The authors have observed that, while it is possible to extend baseline lengths using a precise level or any other machined flat surface, surveyors do not always take advantage of this option. In most cases, the shortest baselines are observed with IMUs, where the reference base plate is relatively short (10–30 cm). However, using a precise flat surface, the baseline can be extended to 1 meter or more, provided there are no obstructions such as bulkhead walls or mounting screws.

To quantify any improvement in precision with a larger baseline, selective points were used to compute the angular offsets. As previously described, four equally spaced points were measured on the level from each setup (see Fig. 5). This allowed the innermost two points (101 and 102) to be used for the computation of roll offsets (see Table 3) with a shorter baseline, while the outermost two points (100 and 103) were used to compute a second set of roll offsets (Table 7) with a longer baseline. The difference between these two sets of angular offsets was used to assess the improvement in standard deviation.

Upon reviewing Tables 3 (short baseline) and 7 (long baseline), it is evident that the final mean roll value (shown green-colored in the last row of the tables) for the short baseline is -0.27° with a standard deviation of 0.05°, while for the longer baseline it is -0.23° with a standard deviation of 0.04°. Although the improvement in standard deviation is small, the mean value changes by 0.04°, which is notable relative to the required roll uncertainty of ±0.02°. The difference between the minimum and maximum values for the short baseline is 0.19°, compared to 0.11° for the long baseline. If only one observation were performed, the min-max difference obtained from the set of nine observations represents the possible range of the resulting roll value. This range is smaller for the longer baseline, indicating lower variability in the estimated roll values compared with the shorter baseline for the observations considered in this study.

Although the standard deviation of the individual observations (0.04° for the long baseline and 0.05° for the short baseline) exceeds the required roll tolerance of ±0.02° for both configurations, the Type A standard uncertainty obtained from nine observations is ±0.013° for the longer baseline and ±0.017° for the shorter baseline. These values are within the required tolerance. The longer baseline, therefore, provides a smaller uncertainty. Furthermore, the standard deviation of the mean can be reduced either by increasing the number of observations or by eliminating outlier roll values, as discussed in Section 3.7.

3.4 Number of points on the baseline

This section analyzes any improvements in the final mean roll value resulting from measuring multiple points along a baseline. As previously described, a total of four points were measured on the level during data collection. One set of roll values was computed using the two outermost points (Table 7), while another set of roll values

Table 8 was calculated using a best-fitting 3D line through all four points. The mean roll values from Table 7 (-0.23°) and Table 8 (-0.24°) are nearly identical, both with a standard deviation of 0.04°. Using only two points, particularly the outermost points, introduces higher sensitivity to outliers, as these points act as leverage points and strongly influence the fitted line. Therefore, including additional points provides redundancy and allows potential outliers to be detected during post-processing. However, in this case, the nearly identical mean roll values suggest

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Table 7 Roll angle values and associated statistics for long baseline using outer targets (100 and 103). Values are reported in degrees and were computed from adjusted direct and indirect observations.

Location	Computed roll values			Statistics				
	Setup1	Setup2	Setup3	Min	Max	Diff (Max-Min)	Mean	Stdv
S	-0.27	-0.22	-0.22	-0.27	-0.22	0.05	-0.24	0.03
SW	-0.32	-0.21	-0.22	-0.32	-0.21	0.11	-0.25	0.06
W	-0.22	-0.21	-0.23	-0.23	-0.21	0.02	-0.22	0.001
				-0.32	-0.21	0.11	-0.23	0.04

Table 8 Roll values and associated statistics computed using all four points on the baseline. All values are shown in degrees.

Location	Computed roll values			Statistics				
	Setup1	Setup2	Setup3	Min	Max	Diff (Max-Min)	Mean	Stdv
S	-0.27	-0.23	-0.23	-0.27	-0.23	0.048	-0.24	0.02
SW	-0.33	-0.22	-0.22	-0.33	-0.22	0.11	-0.25	0.06
W	-0.23	-0.21	-0.23	-0.23	-0.21	0.02	-0.22	0.01
				-0.33	-0.21	0.12	-0.24	0.04

that no outliers are present. Under this assumption, the results indicate that the number of points used in the roll computation has an insignificant effect on the uncertainty of the computed roll. Instead, the baseline length plays a more significant role in determining the uncertainty than the number of points measured on the baseline, as discussed in Section 3.3.

3.5 Number of reference points

In geodetic network adjustment, the precision of estimated parameters, in this case the roll value, is influenced by both the number of observations and the spatial distribution (geometry) of the reference points. A limited point distribution can weaken the network geometry and increase the uncertainty of the transformation parameters and ultimately that of the roll value. As previously described, nine independent local setups were established in their respective coordinate systems. One setup was selected as the master coordinate system, and the remaining eight setups were transformed into this system using observations to eight common reference points. This section investigates the impact of the number of reference points used during the transformation on the computed mean roll values. For the roll values presented in Table 9, only three reference points (6, 7, and 8) were used during the transformation. Although this configuration results in a limited spatial distribution of reference points, it was intentionally selected to represent constrained measurement geometries that may occur in practical environments, such as narrow corridors or hallways, where observations are often performed. This configuration, therefore, represents a near worst-case scenario. The positions of the two outermost targets on the level were then used to compute the associated roll value. A similar process was applied using all eight reference points, resulting in the roll values shown in Table 7.

As shown in Table 9, using three reference points yielded a mean roll value of -0.25°, with a standard deviation of the observations of 0.05° (last row of the table in green color). According to Table 7, when all eight reference points were used, the mean roll value is -0.23°, while the standard deviation of the observations decreased slightly to 0.04°. The corresponding standard deviation of the mean is approximately 0.017° for the three-reference point configuration and 0.013° when eight reference points are used. These results indicate that, in this case, using eight reference points yields only a small reduction in uncertainty compared with using the three reference points in Table 9. This suggests that the positional errors of the three reference points are small and that the number of reference points has a limited influence on the computed roll values. Similar behavior was observed for the pitch and yaw values.

However, this may not always be the case in field conditions. If one of the three reference points had a relatively large positional error, it would likely impact the accuracy of the computed roll values. Using multiple reference points minimizes the influence of error from any single reference point through least squares estimation, and any erroneous reference point can be identified by higher residual values following the least squares adjustment. Another important consideration when using three reference points is their orientation. The orientation of the reference points relative to the total station can affect how positional errors associated with the reference points affect the positional error of the total station computed using the resection process. Furthermore, the orientation of the IMU with respect to the total station will influence how positional errors in the total station translate to the position of the targets on the level.

In practical field conditions, surveyors are often constrained by restricted geometry, leading to orientations similar to those used in this case. Therefore, it is essential to use multiple reference points to account for both the orientation of the total station with

Table 9 Roll values and associated statistics computed after transforming the 8 setups to the first (Master) setup using only three common points (6, 7, and 8). The two outermost targets on the level were then used for the roll computation. All values are reported in degrees.

Location	Computed roll values			Statistics				
	Setup1	Setup2	Setup3	Min	Max	Diff (Max-Min)	Mean	Stdv
S	-0.27	-0.25	-0.30	-0.30	-0.25	0.05	-0.27	0.03
SW	-0.33	-0.17	-0.22	-0.33	-0.17	0.16	-0.24	0.08
W	-0.27	-0.27	-0.22	-0.27	-0.22	0.06	-0.25	0.03
				-0.33	-0.17	0.16	-0.25	0.05

Table 10 Pitch values and associated statistics for the three measurement locations (S, SW, and W).

Location	Computed roll values			Statistics				
	Setup1	Setup2	Setup3	Min	Max	Diff (Max-Min)	Mean	Stdv
S	-0.04	-0.08	-0.03	-0.08	-0.03	0.05	-0.05	0.03
SW	-0.09	-0.04	-0.04	-0.09	-0.04	0.05	-0.06	0.03
W	-0.07	-0.07	-0.04	-0.07	-0.04	0.03	-0.06	0.01
				-0.09	-0.09	0.06	-0.06	0.02

Table 11 Yaw values and associated statistics for the three measurement locations (S, SW, and W).

Location	Computed roll values			Statistics				
	Setup1	Setup2	Setup3	Min	Max	Diff (Max-Min)	Mean	Stdv
S	-0.35	-0.44	-0.45	-0.45	-0.35	0.10	-0.41	0.06
SW	-0.43	-0.38	-0.39	-0.43	-0.38	0.05	-0.40	0.03
W	-0.41	-0.40	-0.38	-0.41	-0.38	0.03	-0.40	0.02
				-0.45	-0.35	0.10	-0.40	0.03

respect to the reference points and to identify and eliminate any high-error reference points during the computation process.

3.6 Effect of the location of the total station

This section examines the influence of the observation location on the computed orientation parameters. Roll, pitch, and yaw values were computed for three different measurement locations (S, SW, and W), each based on three independent setups. The resulting values and their associated statistics are presented to evaluate the variability of the estimated parameters for the different observation configurations.

Upon reviewing the tables presented in the analysis (from Tables 3 to 9), it is evident that the S and W orientations consistently exhibit lower standard deviations (shown in the last column, not green-colored) compared to the SW orientation, indicating that, for roll-angle estimation, the S and W station locations yielded lower variability than the SW location. However, no such pattern was observed in the case of pitch (Table 10) and yaw (Table 11) computations.

Table 10 presents the computed pitch values and associated statistics for the three measurement locations (S, SW, and W). The S and SW locations exhibit comparable variability, each yielding a standard deviation of 0.03° across the three setups, whereas the W location shows a smaller standard deviation of 0.01°. This behavior differs from that observed for the roll values, where the S and W locations generally exhibited lower variability than the SW orientation.

Table 11 presents the computed yaw values and associated statistics for the three measurement locations (S, SW, and W). The S location exhibits the largest variability, with a standard deviation of 0.06°, while the SW and W locations show smaller standard deviations of 0.03° and 0.02°, respectively. This behavior also differs from that observed for the roll values, where the S and W locations generally exhibited lower variability than the SW orientation.

Given the limited number of observations per location, these results should be interpreted cautiously. With the available data, it is not possible to conclusively determine whether the station location relative to the sensor has a measurable influence on the computed orientation angles. Further field testing, involving a greater number of setups and longer distances, is necessary to draw definitive conclusions.

3.7 Number of station setups: variability and outlier assessment

For this analysis, the means and standard deviations from Table 7 are used. When analyzing the Setup1 values for the three orientations (S, SW, and W), the obtained roll values are -0.27°, -0.32°, and -0.22°. These observations yield a mean roll value of -0.27° with a standard deviation of the observations of approximately 0.05°. The corresponding

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Table 12 Summary of computed pitch and associated statistics for EC150 transducer using three methods. All values are in degrees.

Approach	Computed pitch values			Statistics				
	Setup1	Setup2	Setup3	Min	Max	Diff (Max-Min)	Mean	Stdv
Method 1: 3-Point Line Fit	-0.02	-0.011	-0.07	-0.11	-0.00	0.09	-0.07	0.05
Method 2: 4-Point Plane Fit	-0.04	-0.01	-0.03	-0.06	-0.01	0.05	-0.04	0.03
Method 3: 9-Point Plane Fit	-0.04	-0.04	-0.03	-0.06	-0.04	0.02	-0.05	0.01

standard deviation of the mean, representing the Type A standard uncertainty, is approximately 0.03°. This value exceeds the required uncertainty threshold of 0.02°, indicating that additional independent observations from further station setups would be required to achieve the desired uncertainty level. Additionally, no potential outliers can be identified among the three roll values (-0.27°, -0.32°, and -0.22°), as all observations lie within one standard deviation of the mean value (-0.27°); therefore, none of the observations can be reasonably excluded from the analysis.

When analyzing the Setup2 values for the three orientations (S, SW, and W), the roll observations (-0.22°, -0.21°, and -0.21°) yield a standard deviation of approximately 0.01°. The corresponding standard deviation of the mean is approximately 0.003°, which is below the required uncertainty threshold of 0.02°. A similar result is obtained for Setup3, where the observations (-0.22°, -0.22°, and -0.23°) yield a standard deviation of approximately 0.01° and a standard deviation of the mean of approximately 0.003°.

When three independent angle values, either from different orientations or from different setups, do not meet the required minimum uncertainty threshold, the observations can be examined for potential outliers by evaluating their deviation from the mean relative to the standard deviation of the observations. A new mean and standard deviation can then be calculated using the remaining two values and compared against the required minimum standard deviation. This situation occurs when considering the three setups for the SW orientation, where the value of -0.32° shows the largest deviation from the mean and can be treated as a potential outlier. After excluding this value, the recalculated mean becomes -0.21° with a standard deviation of approximately 0.01°.

Similarly, for the three setups from the S orientation, the value of -0.27° can be considered an outlier, resulting in a standard deviation of 0.00° when excluded.

3.8 Using a fitted plane to compute roll and pitch

To quantify precision and Type A uncertainty in the obtained angles using plane fitting compared to line fitting, data collected for the VOS of EV Nautilus was analyzed. Table 12 presents the pitch values derived using three different methods. Please note that for the EC150 transducer, the required accuracy for roll and pitch mounting angle estimation is 0.02°. For all three methods, the coordinates of the points are initially measured in local coordinate frames and subsequently transformed into the vessel's coordinate frame before computing the pitch and roll angle values.

The first method utilizes a 3D line best fitted to the along-track points on the face of the EC150 transducer (as shown in Fig. 10a). The fitted line represents the longitudinal orientation of the transducer. To compute the pitch angle, the fitted line is projected onto the vessel's *XZ* plane (forward–down), eliminating the *Y* (across-track) component. The pitch angle is then derived from the slope of this projected line relative to the vessel's longitudinal (*X*) axis. The second method

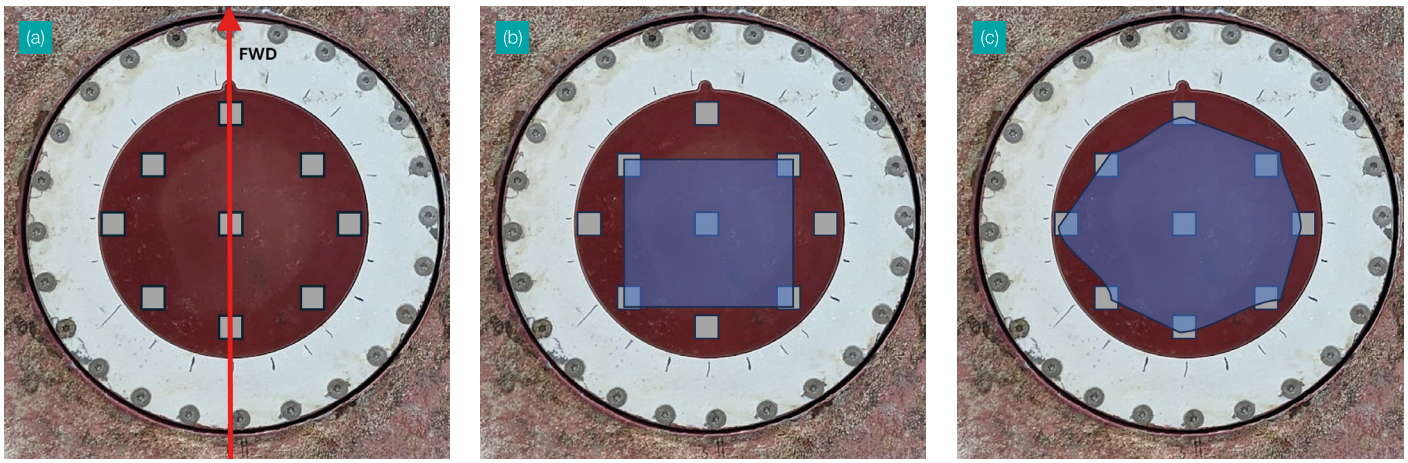


Fig. 10 (a) EC150 transducer face with 9 squares used for measurements. (b) EC150 transducer face with four points used for plane fitting. (c) EC150 transducer face with all 9 points used for fitting.

involves a normal vector to a 3D best-fit plane, fitted using four out of nine points measured on the face of the transducer (Fig. 10b). The third method uses a normal vector to a 3D best-fit plane fitted to all nine points on the transducer's surface (Fig. 10c). In the second and third methods, the normal vector is projected onto the vessel's *XZ* plane (forward–down), and the pitch angle is computed as the angle between the projected normal vector and the *Z* axis of the vessel reference frame. The orientation angles are derived from geometric relationships between the measured point coordinates and the vessel reference frame. The direction vector of the fitted line or the normal vector of the fitted plane defines the orientation of the transducer surface, from which the pitch and roll angles are computed.

From Table 12, it can be observed that the standard deviation is highest for the first method, which uses only three points in the along-track direction. The standard deviation decreases to 0.03° for the second method, which fits a plane using four points, and further decreases to 0.01° for the third method, which fits a plane using all nine points to compute the pitch angle. The corresponding standard deviation of the mean (Type A standard uncertainty for three samples) is approximately 0.029°, 0.017°, and 0.006° for the three methods, respectively. Similar improvements were observed for the roll angle.

It should be noted that the face of the EC150 transducer is designed to be planar; therefore, fitting a plane to multiple points on the transducer surface provides a stable estimate of its orientation. These results indicate that for circular transducers, such as the EC150, using the normal vector of a fitted plane to multiple points on the transducer surface provides improved roll and pitch estimations. This approach is particularly advantageous when physical constraints restrict the use of a level to extend the baseline length of the transducer for improving the accuracy of angle measurements.

4 Conclusions

Although a priori and a posteriori uncertainty analysis can be derived from the mathematical relationships between measured quantities and estimated parameters, this study focused on quantifying the variation of the final estimated installation parameters through simulated and real-world observations. Two complementary case studies were used. A simulated IMU configuration was employed to evaluate the influence of survey design and measurement factors on the precision of the estimated parameters, while field measurements from EV Nautilus were used to assess the influence of the computation method on the precision of roll and pitch estimates. Collectively, these analyses provide insight into how observation strategy, measurement geometry, redundancy, and processing methodology influence the precision and Type A standard uncertainty of the estimated orientation parameters obtained during VOS.

4.1 Observation method and instrument factors (instrument accuracy and direct–indirect observations)

Within the short-distance experimental configuration tested in this study, instrument accuracy had a measurable influence on the precision of the estimated parameters, whereas the use of direct versus combined direct–indirect observations did not produce a measurable change in the estimated angles or in their associated precision metrics, including the standard deviation of the observations and the Type A standard uncertainty. Under the tested conditions, observations obtained with the higher-accuracy instrument (0.5"/0.5 mm) using 9 observations and simulated lower-accuracy observations (1"/1 mm) using 99 observations produced comparable mean angular estimates and comparable Type A standard uncertainties. However, when the number of observations was held constant, the higher-accuracy instrument provided lower Type A uncertainty and therefore greater confidence in the estimated parameters than a randomly selected subset of 9 observations from the simulated lower-accuracy datasets. This indicates that lower nominal instrument accuracy may be compensated for by substantially increasing the number of observations, although such observation counts are often impractical in field applications.

By contrast, the use of only direct observations did not produce a significant increase in the uncertainty of the estimated parameters under the conditions of this experiment setup, suggesting that random observational variability had a greater influence on the final estimates than the residual systematic errors remaining after instrument calibration. This observation is limited to the tested configuration and does not reduce the importance of identifying and minimizing systematic errors in general survey practice. Systematic effects, typically mitigated through direct–indirect observations, were likely small in this case because of the short observation distances and the limited range of zenith angles. In practical vessel installations, however, different sensors may be observed under different geometric configurations and zenith-angle ranges, which may increase sensitivity to systematic deviations. Accordingly, standard survey practice should still include the use of instruments with appropriate nominal accuracy, proper factory and field calibration, and direct–indirect observations.

4.2 Baseline geometry (baseline length and number of points on baseline)

Baseline length had an influence on the precision of the estimated roll offsets. As expected, longer baselines reduced the standard deviation of the estimated parameters because the same linear measurement uncertainty translated into a smaller angular uncertainty. In contrast, increasing the number of points used to define the baseline from two to four did not produce a noticeable reduction in the dispersion of the estimated roll values under the tested conditions. These results are specific to the baseline lengths and

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geometry evaluated in this study. In practical survey applications, extending the baseline length is beneficial when feasible, whereas the number of points used to define the baseline should be selected based on redundancy needs, site constraints, and the expected gain in precision.

4.3 Reference geometry and instrument location (number of reference points and location of the total station)

Within the tested short-range configuration, increasing the number of reference points from three to eight did not significantly improve the precision of the estimated parameters, and the location of the total station relative to the measured object did not produce a measurable change in the estimated angles. These outcomes are specific to the experimental measurement configuration evaluated in this study. In theory, a larger number of reference points strengthens the observation network and reduces sensitivity to individual point-coordinate errors; however, in this case, the positional errors of the three reference points were small, which likely limited any observable improvement in the computed roll values. The available data also does not permit a conclusive assessment of the influence of station location, as the number of observations per station location was limited. Nevertheless, using only the minimum of three reference points is not recommended in practice because it provides no redundancy for identifying point-coordinate errors during post-processing. Additional, well-distributed reference points enable least-squares adjustment and improved detection of positional inconsistencies when transforming local coordinates into the master coordinate system. This analysis was performed for a single sensor and therefore does not evaluate the full internal vessel sensor network.

4.4 Observation redundancy and quality control

Observation redundancy (number of station setups) had a direct influence on the precision of the estimated roll value and on the ability to identify potential outliers. Nine independent station setups were analyzed to examine how the standard deviation of the derived roll values changed with the number of setups. In the tested configuration, two independent setups with different orientations were sufficient to produce roll estimates with a standard deviation below 0.02°. However, this standard deviation reflects only the precision of the estimated roll values and not their absolute accuracy. Although two setups were sufficient in this experimental case, reliance on only two observations is not recommended in practical survey work. If one observation is later identified as an outlier during processing, it may not be possible to return to the field and acquire an additional setup. For this reason, at least three independent station setups are recommended in practice to provide redundancy for outlier detection and to improve confidence in the estimated orientation parameters.

4.5. Computation method (fitted plane vs. line fitting)

The computation method had a substantial effect on the precision of the estimated roll and pitch parameters. For sensors or surfaces that can reasonably be treated as planar, fitting a plane to the maximum possible number of observed points produced lower standard deviations and lower Type A standard uncertainties than line fitting or plane fitting with fewer points. This is expected because the fitted-plane approach uses more observations and better represents the full sensor surface geometry, thereby reducing sensitivity to individual point-measurement noise. In contrast, line fitting relies on fewer points and is therefore more sensitive to local observation errors. This effect was especially important for short baselines and for sensors with narrow dimensions in the direction relevant to the angle being estimated.

For non-circular or linear-array sensors, such as multibeam transducers and some IMUs, plane fitting should be used to compute roll and pitch whenever sufficient points are available. When plane fitting is not feasible, such as in constrained spaces around an IMU, a line fit should be used with the longest possible baseline, since increasing baseline length improves the precision of the estimated angles. This is particularly important for roll estimation in narrow multibeam transmitters and pitch estimation in narrow multibeam receiver arrays. For circular sensors such as the EC150, the fitted-plane method based on nine points substantially reduced the Type A standard uncertainty relative to short-baseline line fitting.

For azimuth or heading offset estimation, plane fitting is generally not applicable, and the surveyor must instead use manufacturer-identified edges, marks, or machined reference surfaces, as is often the case for IMU base plates. In such cases, a line fit using the longest feasible baseline should be applied. For circular arrays, including IMUs with circular base plates and circular transducers, baseline extension is often not possible for heading estimation. In these situations, multiple two-point line-based heading measurements should be acquired, and the mean value together with the standard deviation of the observations should be used to estimate the most reliable heading offset and to identify potential outliers. For larger linear transducers, such as lower-frequency sonar arrays, the full length of the transmitter or receiver edge should be used wherever possible to compute along-axis or across-axis heading angular offsets. In practical applications, the choice between plane fitting and line fitting should therefore be guided by actual sensor geometry, available access, and the number and distribution of observable points.

4.6 Overall implications

Taken together, the results indicate that for short-range VOS configurations, the precision and Type A standard uncertainty of the estimated installation parameters are governed primarily by instrument accuracy, observation geometry, redundancy, and

computation method. Within the tested range, lower nominal instrument accuracy can be partially compensated for by increasing the number of observations, but this is often impractical in field conditions. By contrast, the tested direct-only observation strategy did not significantly degrade the estimated uncertainties in this short-range, well-calibrated configuration. Accordingly, instrument selection should be based not only on nominal specifications but also on the number of repeat observations that can realistically be collected, the target uncertainty of the estimated installation parameters, and the expected sensitivity of the observation geometry to residual systematic effects.

These findings do not establish a universal accuracy standard for all hydrographic survey categories under IHO S-44. Rather, they represent a step toward a more standardized and technically defensible methodology for dimensional control vessel offset surveys that can meet or exceed manufacturer requirements and support uncertainty estimates that are traceable and practically achievable. More realistic uncertainty estimates for installation parameters are expected to improve subsequent uncertainty propagation into final bathymetric products, although that propagation was not explicitly evaluated in this study.

4.7 Future work

Future work should examine longer observation distances, broader station geometries, additional sensor configurations, and the propagation of installation-parameter uncertainty into final bathymetric uncertainty in both the vertical and horizontal components. A more rigorous least-squares analysis, including cofactor propagation, redundancy measures, and controllability of observations, would also provide additional insight into the strength of the measurement configuration and the sensitivity of the estimated parameters to observation geometry.

References

Applanix (2015). *POS MV WaveMaster II Specifications*. Applanix Corporation, Richmond Hill, ON, Canada. https://www.uniquegroup.com/wp-content/uploads/2022/10/POSMV-Spec-Sheet-2015.pdf (last accessed 26 April 2026).

Applanix (2017). *POS MV V5 Installation and Operation Guide*. Applanix Corporation, Richmond Hill, ON, Canada. https://www.applanix.com (accessed on 1 May 2021).

Applanix (2025). *Trimble Applanix POS MV*. Applanix Corporation, Richmond Hill, ON, Canada. https://www.applanix.com/products/posmv.htm (last accessed 26 April 2026).

Class of 2023 (2023). *Field report for Lemoyne VOS*. Hydrographic Science Program, University of Southern Mississippi.

Coulson, A. (2024). *SC4W (Survey Calculations 4 Windows)*. Smith & Coulson Ltd., United Kingdom. https://www.sc4w.com/ (last accessed 26 April 2026).

ELAC Sonar (2021). *SB 3050 2G Medium-Depth Multibeam System – For Mapping the Continental Slope*. ELAC SONAR GmbH, Kiel, Germany. https://www.elac-sonar.de/fileadmin/content/downloads/sb-3050-2g-product-brochure.pdf (last accessed 26 April 2026).

Ghilani, C. D. and Wolf, P. R. (2012). *Elementary surveying: An introduction to geomatics* (13th ed.). Prentice Hall.

Hiroji, A. and Oderinde, O. (2022, December). *EV Nautilus vessel offset measurement survey report*. School of Ocean Science and Engineering, University of Southern Mississippi, USA.

Hughes Clarke, J. E. (2003). A reassessment of vessel coordinate systems: What is it that we are really aligning? *Proceedings of the US Hydrographic Conference*, 1–12.

Hughes Clarke, J. E. (2018). Multibeam echosounders. In A. Micallef, S. Krastel and A. Savini (Eds.), *Submarine geomorphology* (pp. 25–41). Springer International Publishing. https://doi.org/10.1007/978-3-319-57852-1_3

IMTEC Group. (2021, June). *RV Sally Ride AGOR-28 EM124 TX/RX, EM712 TX/RX, SBP, ADCP orthogonal coordinate survey*.

IHO (2022). *Standards for Hydrographic Surveys* (Ed. 6.1.0). IHO Special Publication S-44, International Hydrographic Organization, Monaco. https://iho.int/uploads/user/pubs/standards/s-44/S-44_Edition_6.1.0.pdf (last accessed 26 April 2026).

JCGM (2008). *Evaluation of measurement data—Guide to the expression of uncertainty in measurement* (JCGM 100:2008). Joint Committee for Guides in Metrology. www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf (last accessed 26 April 2026).

Kongsberg (2021, May). *Kongsberg EM 304 Installation Manual*. Kongsberg Maritime AS, Kongsberg, Norway.

Kongsberg (2024). *Kongsberg Seapath 380*. Kongsberg Maritime AS, Kongsberg, Norway. https://www.kongsberg.com/discovery/discontinued/seapath-380---utilising-gps-glonass-galileo-beidou-and-qzss/ (last accessed 26 April 2026).

LEICA (2014). *Leica FlexLine TS07 Manual Total Station*. Leica Geosystems AG, Heerbrugg, Switzerland. https://leica-geosystems.com/-/media/files/leicageosystems/products/datasheets/leica%20flexline%20ts07%200221%20en-in%20lr.pdf (last accessed 26 April 2026).

LEICA (2020). *Leica Nova MS60 Data Sheet*. Leica Geosystems AG, Heerbrugg, Switzerland. https://leica-geosystems.com/-/media/files/leicageosystems/products/datasheets/leica_nova_ms60_ds.ashx%3Fsc_lang%3Den%26hash%3D74DB2830F-27BF20A75AC01710764345D (last accessed 26 April 2026).

MAC (2024). *Tech Reports*. Multibeam Advisory Committee. https://mac.unols.org/reports/ (last accessed 26 April 2026).

SBG (2025). *Discover Apogee Series*. SBG Systems, Carrières-sur-Seine, France. https://www.sbg-systems.com/products/apogee-series-high-accuracy-ins-gnss/ (last accessed 26 April 2026).

Schofield, W. (2001). *Engineering surveying: Theory and examination problems for students* (5th ed.) Elsevier.

Simrad (2019). *Simrad EC150-3C Installation Manual*. Kongsberg Maritime AS, Kongsberg, Norway. https://www.simrad.online/td_150/ec150_3c/ec150_3c_ins_en_a4.pdf_ (last accessed 26 April 2026).

SOKKIA (2022). *NET05 AXII Industrial Monitoring and Measurement*. Sokkia Corporation, Olathe, USA. https://us.sokkia.com/products/optical-instruments/monitoring-specialty-systems/net-ax-industrial-monitoring-and (last accessed

https://doi.org/10.58440/ihr-32-1-a01

26 April 2026).

Teledyne Marine (2022). *HydroSweep Deep-Sea Multibeam Echosounder*. Teledyne RESON A/S, Slangerup, Denmark. https://www.teledynemarine.com/en-us/products/SiteAssets/RESON/Hydrosweep%20DS%20product%20leaflet.pdf (last accessed 26 April 2026).

TOPCON (2016). *MS AXII Series High Accuracy Measuring Station*. Topcon Corporation, Tokyo, Japan. https://www.topconpositioning.com/content/dam/topcon_digital_asset_hub/collateral/brochures/MSSeries_MSAXII_Broch_T547EN_TEAM_EN_EU_HiRes.pdf (last accessed 26 April 2026).

TOPCON (2018, March). T*opcon GM-50 Total Station*. Topcon Corporation, Tokyo, Japan. https://mytopcon.topconpositioning.com/na/total-stations/manual-total-stations/gm-50 (last accessed 26 April 2026).

TOPCON (2019). *NET05AXII, NET1AXII 3D Station*. Topcon Corporation, Tokyo, Japan. https://geo-tronics.com/wp-content/uploads/2021/04/Datasheet-NETAXII-1.pdf (last accessed 26 April 2026).

TOPCON (2025). *Topcon GT 1201 | Robotic Total Station*. Topcon Corporation, Tokyo, Japan. https://www.skippertech.com/product/gt-1201/ (last accessed 26 April 2026).

Trimble (2015). *Trimble S9*. Trimble Inc., Westminster, USA. https://geospatial.trimble.com/products/hardware/trimble-s9 (last accessed 26 April 2026).

Trimble. (2023). *Trimble SX12*. Trimble Inc., Westminster, USA. https://geospatial.trimble.com/en/products/hardware/trimble-sx12 (last accessed 26 April 2026).

Vaníček, P. and Krakiwsky, E. J. (2015). *Geodesy: The Concepts* (2nd ed.). Elsevier.

Westlake Consultant (2021). *RV Okeanos Explorer R337 Survey of Ships Mission and Scientific Equipment*.

Authors' biographies

Anand Hiroji is an Associate Professor of Hydrography in the Division of Marine Science, School of Ocean Science and Engineering, at The University of Southern Mississippi, USA. His research interests include multibeam sonar backscatter optimization and calibration, bathymetric positioning accuracy, uncrewed surface vessels, and hydrographic vessel configuration surveys. He earned a B.E. in Civil Engineering from Shivaji University, India, in 2005, and an M.E. in Geomatics Engineering in 2011 and a Ph.D. in Ocean Mapping in 2016 from the University of New Brunswick, Canada.



Anand Hiroji

Olaoluwa Oderinde is a Category-A Hydrographer with over nine years of experience in offshore hydrographic and marine geophysical surveys. He holds a B.Sc. in Surveying and Geoinformatics from the University of Lagos, Nigeria, and an M.Sc. in Hydrographic Science from the University of Southern Mississippi, USA. His work focuses on high-resolution seabed mapping, geophysical data processing, geohazard identification, and the application of uncrewed survey systems, supporting offshore energy, maritime safety, and coastal resilience initiatives.



Olaoluwa Oderinde

PEER-REVIEWED ARTICLE

Satellite-derived bathymetry and the CHS iterative process: operational challenges with accuracy assessment

Authors

René Chénier[1], Genevieve George[1], Loretta Abado[1] and Khalid Omari[1]

Abstract

The Canadian Hydrographic Service (CHS) uses several satellite derived products to enhance navigational safety, with Satellite-Derived Bathymetry (SDB) representing a key remote-sensing product. At the CHS, SDB supports mission planning through an iterative process in which preliminary models are developed to guide data acquisition and ensure crew safety, then refined with the collected survey data. Through successive iterations, refined SDB models demonstrate improvements in global performance metrics while extending model confidence across previously unsurveyed regions. Understanding the precision of SDB techniques, along with the accuracy and uncertainty of the resulting products, is essential for defining appropriate and responsible use of SDB in nautical products.

Keywords

satellite-derived bathymetry · hydrography · navigation safety · remote sensing · Canadian Hydrographic Service · accuracy · product uncertainty

Resumé

Le Service hydrographique du Canada (SHC) utilise plusieurs produits dérivés de satellites afin d'améliorer la sécurité de la navigation, parmi lesquels la bathymétrie dérivée de satellites (SDB) constitue un produit clé dérivé de la télédétection. Au SHC, la SDB appuie la planification des missions au moyen d'un processus itératif dans lequel des modèles préliminaires sont élaborés afin de guider l'acquisition des données et d'assurer la sécurité des équipages, puis sont affinés à l'aide des données de levés recueillies. Au fil des itérations successives, les modèles de SDB affinés montrent une amélioration des indicateurs globaux de performance tout en élargissant le niveau de confiance accordé au modèle dans des régions auparavant non levées. La compréhension de la précision des techniques de SDB, ainsi que de l'exactitude et de l'incertitude des produits qui en résultent, est essentielle pour définir une utilisation appropriée et responsable de la SDB dans les produits nautiques.

✉ René Chénier · rene.chenier@dfo-mpo.gc.ca

[1] Department of Fisheries and Oceans Canada (DFO), Canadian Hydrographic Service (CHS), Ottawa, Ontario, Canada

Resumen

El Servicio Hidrográfico de Canadá (CHS) usa varios productos derivados de satélites para mejorar la seguridad de la navegación, y la Batimetría Derivada de Satélites (SDB) es uno de los productos clave de detección remota. En el CHS, la SDB apoya la planificación de misiones mediante un proceso iterativo en el que se desarrollan modelos preliminares para dirigir la adquisición de datos y garantizar la seguridad de la tripulación, y después se refinan con los datos topográficos recogidos. Mediante iteraciones sucesivas, los modelos SDB refinados muestran mejoras en los indicadores de rendimiento globales, mientras amplían la confianza del modelo en regiones que levantadas previamente. Comprender la precisión de las técnicas de SDB, junto con la exactitud e incertidumbre de los productos resultantes, es esencial para definir un uso apropiado y responsable de la SDB en los productos náuticos.

1 Introduction

Hydrographic Offices (HOs) play a vital role in ensuring maritime safety by collecting hydrographic data and producing authoritative nautical information. In Canada, this responsibility is carried out by the Canadian Hydrographic Service (CHS). Like many HOs, the CHS faces ongoing challenges in maintaining up-to-date hydrographic data across all navigable waters. The vast scale of Canada's waters, combined with dynamic environments and adverse weather conditions such as seasonal ice, limits the timely collection of traditional survey data. These challenges are most pronounced in the Arctic, where remoteness, harsh conditions, and a short survey season further restrict survey operations.

To help address these gaps, the CHS received targeted funding through the Oceans Protection Plan (TC, 2023) to enhance hydrographic data collection in the Arctic. Despite recent advances in modern surveying technologies, only 18 % of the Northern Canada Vessel Traffic Services Zone (NORDREG) is currently covered by surveys meeting modern adequacy standards (i.e., CATZOC A and B), as shown in Figure 1. Areas classified as CATZOC C, while still represented on charts, do not meet current definitions of modern or adequate survey coverage and therefore contribute to the overall gap. This limited coverage highlights the ongoing need for improved data acquisition and the importance of investing in innovative techniques to fill data gaps.

In recent years, the CHS has increased its efforts to integrate remote sensing technologies to supplement traditional survey methods and improve navigational safety. The need to accelerate the integration of remote sensing in the Canadian Arctic has been widely documented (Chénier et al., 2018; Ahola et al., 2020; Chénier et al., 2020a; Chénier et al., 2020b; Chénier et al., 2025; Knudby, 2025). Over the past eight years, the CHS, through the Oceans Protection Plan (OPP), has significantly expanded Arctic data-collection efforts while investing in remote sensing innovation. Although remote sensing is highly effective for detecting hazards to navigation, the scale of the region - approximately 3.7 million km^2 – means that considerable work remains to fully identify hazards and update all associated nautical products. To date, regions of high maritime traffic have been screened for hazards using remote sensing and artificial intelligence (Chénier et al., 2018), establishing hazard detection and charting as an ongoing operational activity. The CHS Remote Sensing Centre of Expertise (RSCoE) has made considerable progress in developing methodologies tailored specifically to hydrographic applications (Chénier et al., 2020a), positioning remote sensing as a valuable tool for expanding data coverage. The RSCoE produces a range of satellite-derived products, including bathymetry, shoreline mapping, intertidal zone delineation, identification of navigational hazards, and change-detection analyses for monitoring dynamic coastal environments. Among these, Satellite-Derived Bathymetry (SDB) is particularly significant, as it supports both survey operations and emergency response by highlighting hazardous areas and filling data gaps where traditional survey data are limited or unavailable. Although SDB has been in use for over 50 years (Polcyn et al., 1970), recent advances in multispectral sensors and machine-learning-based depth-estimation techniques have improved its accuracy and reliability.

SDB encompasses several methodological approaches, including photogrammetric methods based

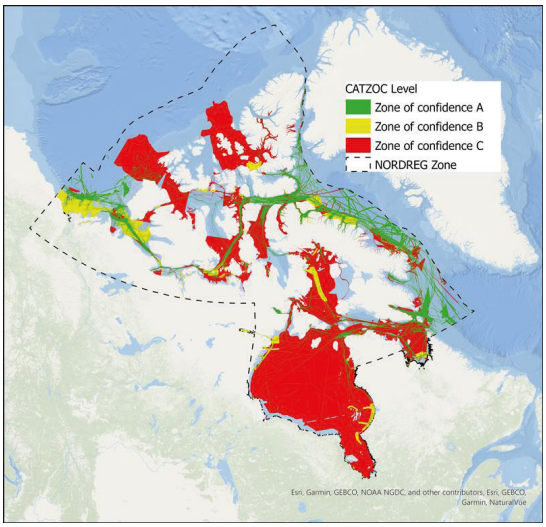


Fig. 1 CHS Category Zone of Confidence (CATZOC) coverage in the Northern Canada Vessel Traffic Services Zone (NORDREG). CATZOC A and B are considered adequately surveyed.

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on image matching and stereoscopy (Chénier et al., 2016, 2018; Hodúl et al., 2018), and spectral-based techniques derived from multispectral imagery. These spectral-based techniques include both physics-based approaches that model light propagation within the water column (Lee et al., 1999; Mobley, 2022; Lyzenga et al., 2006; Dekker et al., 2011), and empirical methods that estimate water depth from spectral reflectance relationships between bands (Lyzenga, 1978, 1985; Lyzenga & Vid Lyzenga, 1981; Stumpf et al., 2003; Knudby et al., 2016; Kerr & Purkis, 2018). The RSCoE primarily relies on spectral-based empirical approaches due to their simplicity, lower cost, and demonstrated effectiveness in shallow coastal environments.

In this study, SDB refers primarily to the spectral-based empirical approach used operationally within the RSCoE. SDB can be an effective method for HOs to estimate water depths in shallow coastal regions. The CHS began incorporating SDB into its nautical charting workflow in 2018. In June 2018, CHS released its first nautical chart updated using SDB data, Chart 4955 (Havre-aux-Maisons) (Chénier et al., 2018; Chénier et al., 2020a). Since then, CHS has continued to leverage SDB to enhance nautical charting and support mission planning. Empirical methods remain the most frequently used SDB approaches within the CHS RSCoE.

Although SDB offers clear advantages for CHS operations-particularly its ability to address survey gaps with cost- and time-efficient coverage (Chénier et al., 2018; Chénier et al., 2020a; Chénier et al., 2025)—its operational deployment remains constrained by environmental, methodological, and data-related limitations that must be rigorously evaluated to ensure safe and appropriate application in hydrographic contexts.

Within this operational context, SDB is also used to support survey mission planning under strict time constraints. The purpose of SDB mission support is not to create a product suitable for nautical use, but to rapidly generate a preliminary SDB surface that meets the timelines imposed by scheduled field surveys. This preliminary SDB is intended to provide timely depth information to support survey mission planning, guide data acquisition in priority areas, and enhance navigational safety, thereby helping to ensure the safety of survey crews during field operations. To meet these strict timelines, the RSCoE compiles and integrates all available sources of water depth information. Highest priority is assigned to in situ CHS data that have already been calibrated to chart datum, typically Lower Low Water Large Tide (LLWLT). When these data are unavailable or insufficient to fill critical gaps, the RSCoE supplements them with additional sources, including laser altimetry from the Ice, Cloud, and Land Elevation Satellite 2 (ICESat-2) and Crowdsourced Bathymetry (CSB).

Building on this operational context, this paper examines the applications of SDB within a hydrographic framework that prioritizes navigational safety and nautical chart reliability. It presents the iterative approach developed by the CHS RSCoE, emphasizing the practical treatment of accuracy, precision, and uncertainty, and positioning SDB as a complementary input to chart modernization.

2 Methodology

2.1 The iterative process

A major limitation in the operational use of empirical SDB is the scarcity of in situ data required both to train the models and to validate the resulting depth estimates. This challenge is particularly relevant for the CHS, as SDB is typically employed to address critical data gaps, precisely in regions where the CHS has little or no existing survey data. For empirical SDB approaches, reference data are essential for model training and accuracy assessment and for ensuring proper calibration to the chart vertical datum. The RSCoE employs an iterative workflow to develop SDB models, with methodological approaches adapted to the availability of bathymetric data. Initial models are used to support survey mission planning, and data collected during surveys are subsequently used to refine model performance and improve the reliability of the resulting bathymetric products (Fig. 2).

2.1.2 Model refinement

Once the field survey is complete, the newly collected data are used to recalibrate and validate the SDB model, thereby improving its accuracy, reliability, and suitability for hydrographic applications. Following the accuracy assessment of the refined SDB, the RSCoE identifies and extracts the portions of the dataset that would improve the safety of nautical products.

The benefit achieved by this two-step iterative approach varies by site and is strongly influenced by both the quality of the original mission planning SDB and the quality of the survey data collected to generate the refined SDB model. In cases where the first iteration mission planning SDB incorporated high quality data and achieved high accuracy, the added value of further model refinement in Step 2 may be reduced. In contrast, where the initial mission-planning SDB relied on limited or poor-quality input data, the collection of depth information in shallow areas within the AOI can lead to significant model improvement. Irrespective of model accuracy improvement, additional survey data still provide valuable information for SDB validation across a larger spatial extent and thus increases confidence in the final SDB product.

2.2 SDB approaches for sites with and without bathymetric data

The RSCoE must create operational remote sensing derived depth products to support mission planning across both charted and uncharted areas of Canadian waters. In most cases where in situ data is available from surveys or LiDAR, satellite derived bathymetry is produced using the empirical approach. In the cases where no in situ data is available, the RSCoE employs an alternative approach by linearly scaling between the 0 m shore and the extinction depth of light in the image, which is estimated on a site-by-site basis

based on comparison of charted depths with satellite imagery.

Empirical modeling is the standard SDB approach employed by the RSCoE. This method combines existing depth data with one or more satellite images to model the relationship between depth and pixel colour and apply the model to areas where there is no in situ data. Depth data collected from CHS surveys, ICESat-2 and CSB are identified around the area of interest and assessed for their suitability. The training/validation split typically allocates about 67 % of the data for training and 33 % for validation. However, this ratio can vary because the data are based on data quality, depth range, depth distribution, and geographic coverage. These filters ensure that the final depth dataset is representative of the area of interest and aligns with the spatial extent of the available imagery. Satellite imagery for each area is selected based on the requirements of the project and the location of the AOI, including image resolution, cloud and ice cover, tidal range and heights, and water clarity. Imagery is clipped to ensure that both the AOI for SDB and the area with survey data are included in the image. All SDB analyses with available in situ survey data used an XGBoost machine learning regression model (Chen & Guestrin, 2016), with spectral bands (red, green, blue, and near-infrared) and band-ratio features derived from the logarithmic ratios of visible bands as predictor variables. Model hyperparameters were optimized through randomized cross-validation.

In the absence of in situ depth values, SDB can still be produced; however, its accuracy cannot be measured and must be assumed to be reduced. As its primary purpose is to provide approximate depth values for survey mission planning rather than precise measurements, it can nevertheless offer valuable guidance. In these situations, an adaptation of the linear band ratio method (Stumpf et al., 2003) is employed. This adaptation uses anchor depth points at 0 m and the approximate extinction depth of light in the water, to linearly scale the log ratio of the blue and green bands. The 0 m points are created by extracting the shoreline from lowest available tide imagery and then adjusting for tide height corresponding to the zero of chart datum (water level at 0 m at the LLWLT). Acquiring imagery exactly at the chart datum is often difficult and obtaining a perfect zero-line snapshot is not always feasible. However, with the wide range of available satellite sources, it is usually possible to obtain images taken within a few centimeters of the lowest water line. For example, Planet's PlanetScope constellation, comprising of 180 satellites, increases the likelihood of capturing imagery remarkably close to the zero line. Maximum observable depth, defined as the depth at which the seabed remains visible in satellite imagery, is estimated by referencing nearby locations with known depths acquired under comparable conditions (e.g., charted depths from same-date imagery). This estimate is based on visual seabed detectability and may vary spatially with turbidity and bottom reflectance.

The performance of the empirical SDB techniques is calculated by comparing the predicted depth value from the model with coincident in situ depth from survey points in the test dataset and calculating the mean error/bias, the root mean squared error (RMSE), and the 95th percentile of the absolute error. These metrics were selected to provide a well-rounded assessment of the model performance, including at sites with non- normal error distributions. It is important to note that because the empirical approach for SDB uses in situ data to both train and test for accuracy assessment, the confidence in the results is impacted by the quality of the input data. The use of high-quality survey data collected from official sources can mitigate

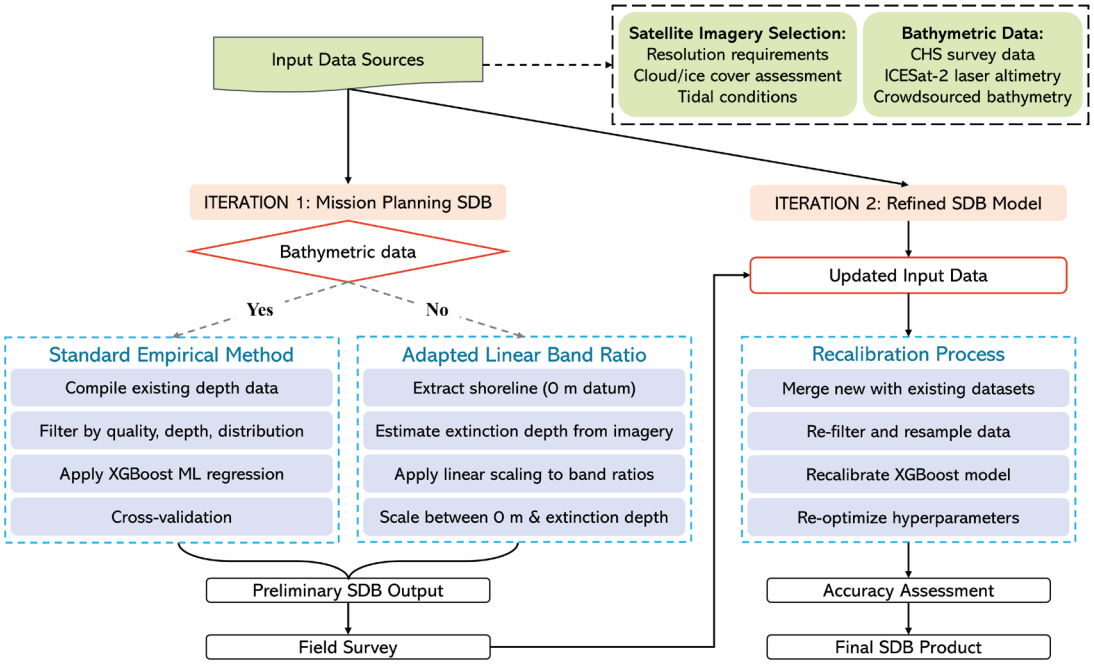


Fig. 2 Overview of the RSCoE iterative process for SDB.

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this concern, but in areas where there are limited data options (e.g. CSB, satellite altimeters) a high accuracy score only indicates high accordance with the in-situ data. Depending on the data quality, this may or may not translate to trustworthy output SDB. In the case of the iterative approach in areas with no bathymetric data for the original SDB, accuracy is expected to be low when compared with newly collected data as the error distribution can be non-normal and incorrect model assumptions can bias the error.

2.3 Case studies

The approaches used to create operational SDB always need to be tailored to a range of factors, such as in situ data availability, imagery quality, and site characteristics. To demonstrate the iterative SDB process employed by the CHS RSCoE, two study sites were selected: (1) the Koksoak Approach, a northern region of Quebec near Kuujjuaq in Ungava Bay, where in situ data were lacking; and (2) Rankin Inlet, Nunavut, where in situ data were available close to the area of interest, which comprises three distinct sub-areas (Fig. 3).



Fig. 3 Location of study sites at the Koksoak Approach near Kuujjuaq, QC, in Ungava Bay, and at Rankin Inlet, NU, comprising three separate areas of interest.

2.3.1 Koksoak Approach

Site and imagery

Koksoak Approach is located within the extent of CHS Paper Charts 5300, 5467, and 5376 but is directly in chart "whitespace", where there are no soundings or other depth information (Fig. 4). Fig. 4 shows the area of interest for initial mission planning SDB (red) and the extent of in situ collected survey (pink) against the Sentinel-2 image (left) and the CHS charts for the area (right). A Sentinel-2 L2A image from 2023-06-29 (3.6 m tide) was used for both the initial SDB for survey mission planning and the second iteration SDB using the newly collected survey data. The tidal range in this area is extremely high (approximately 10 m), and the 3.6 m tide image represents the lowest tide image suitable for SDB, with clear water and no obstruction from cloud or ice.

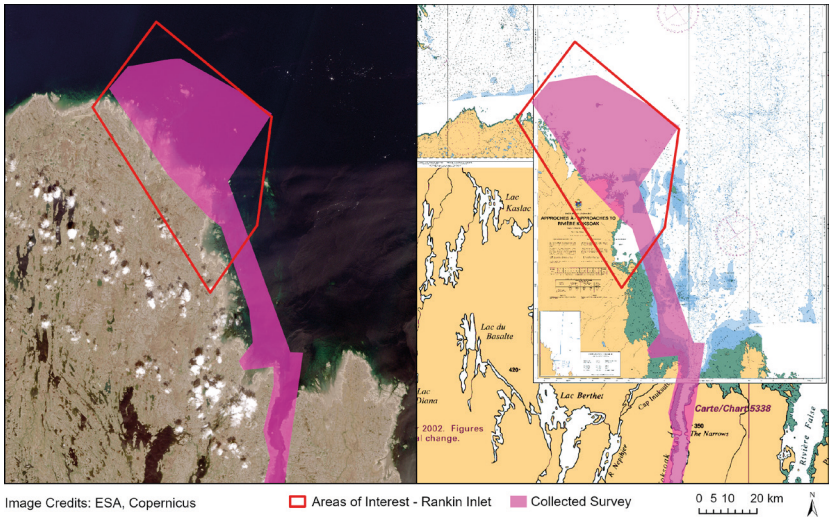


Fig. 4 Area of interest for Koksoak Approach, north of Kuujjuaq in Ungava Bay, QC. Left: Sentinel-2 image from 2023-06-29 covering S2 tiles 19VEF and 19VEE. Right: CHS Charts 5300 (bottom), 5467 (top left), and 5376 (top right).

Bathymetric data and applied methodology

The first iteration of the SDB to support the survey mission was done without in situ data to calibrate a model. The area of interest has no bathymetric information, and the survey data that exist outside of the AOI were unsuitable for model calibration due to insufficient high-quality data at shallow depths within the extent of the Sentinel-2 tile. Instead, the adapted linear band ratio method was used. The 0 m points were created along the land/water boundary of the Sentinel-2 image and then adjusted for tide height. The extinction depth of light in the area was estimated at 13 m based on a comparison of the limited nearby survey data with the satellite image.

The second iteration of the SDB leveraged the CSB survey data collected by the Community Hydrography Program (DFO, 2026) (pink area in Fig. 4) to run an empirical SDB model. The collected CSB data were filtered to depths less than 13 m. Due to the large tidal range in this area, and the path of the survey vessel, the majority of survey data were collected in the intertidal zone (depths above 0 m when adjusted to chart datum LLWLT), leading to a depth range of 5 m above chart datum to 13 m. The dataset was split 67:33 for training and testing, with 63,400 and 27,172 points, respectively. Although spatial autocorrelation may inflate apparent performance metrics, the same data-splitting strategy was applied consistently across all iterations to ensure relative comparability among models.

2.3.2 Rankin Inlet

Site and imagery

The Rankin Inlet site is split into three AOIs that intersect with parts of CHS Charts 5449, 5630, and 5629 (Fig. 5). The three AOIs correspond to different areas of chart whitespace, where there is no

bathymetric information. The original mission planning AOI covered only the central area that corresponds to the unsurveyed region from chart 5630 (shown in turquoise in Fig. 5). The second iteration of the SDB covered a larger area, incorporating all available bathymetric data and extending the coverage to three AOIs (shown in purple in Fig. 5).

Both the first and second iteration SDB derived products used Sentinel-2 L1C imagery from 2018-07-15. For the initial mission planning SDB with a smaller AOI, a single tile 15VWK was used. For the final SDB covering the expanded 3 AOIs, a same-date mosaic covering Sentinel tiles 15VWK and 15VWJ was generated.

In both cases, comparison of the results with the L2A surface reflectance product and the L1C top-of-atmosphere product demonstrated that the L1C imagery yielded slightly higher accuracy, due to reduced performance of the Sen2Cor atmospheric correction over coastal waters in L2A products (Warren et al., 2019).

Bathymetric data and applied methodology

The first SDB iteration supporting mission planning in the Rankin Inlet area used all available CHS multibeam survey data from shallow depths (<15 m). These data were located entirely north of the AOI and did not spatially overlap with it. Of the survey points shallower than 15 m, 87 % were derived from surveys with CATZOC A1 classification and 13 % from surveys classified as CATZOC B. The depth distribution of survey points was strongly right skewed, biasing the dataset toward deeper water. To reduce this bias and improve model performance at shallow depths, the survey points were resampled to approximate a more uniform depth distribution. The filtered dataset was then split into training and testing subsets at a 67:33 ratio, comprising 81,673 and 40,227 points, respectively.

The second iteration of SDB in Rankin Inlet combined the original mission planning dataset with the newly collected CSB data (shown in pink in Fig. 5). Although the CSB data increased the total number of depth points by only 0.06 % (approximately 10,000 points), they improved spatial coverage by providing depth measurements directly within the AOI rather than being confined to areas north of Rankin Inlet. The original CHS training and testing splits were retained, while the CSB data were partitioned using the same 67:33 train test ratio (2,587 training and 5,250 testing points) and subsequently merged with the existing datasets.

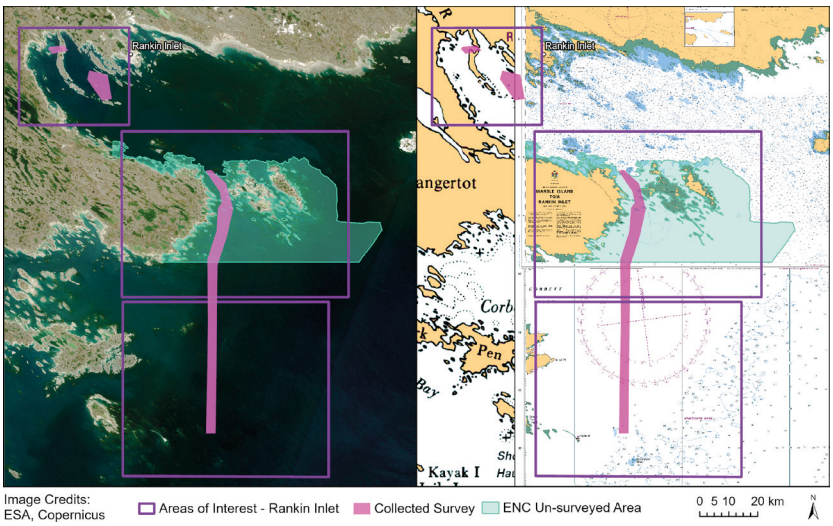


Fig. 5 Areas of interest for Rankin Inlet. Left: Sentinel-2 image from 2020-07-22 covering S2 tile 15VWK. Right: CHS Charts 5449 (left), 5630 (top right), and 5629 (bottom right).

3 Results

3.1 Koksoak Approach

The initial mission planning SDB was produced without an accuracy score because of the absence of in situ data for validation. Its accuracy was evaluated post-mission, once CSB in situ data became available, yielding a mean error of -3.42 m, an RMSE of 4.22 m and 95th percentile of the absolute error of 7.82 m. The resulting surface is shown in Fig. 6a. Table 1 gives an overview of SDB accuracy by depth. The final SDB model was a machine learning model which achieved a mean error of 0, an overall RMSE of 1.8 m, and the 95th percentile of the absolute error of 4.21 m. The resulting surfaces and a direct comparison of the two iterations are shown in Fig. 6. Table 1 provides an overview of SDB accuracy by depth interval for both SDB iterations. Fig. 7 presents the comparison between in situ and predicted depth for each data point and the histogram distribution of error for all the survey points that overlapped the SDB achieved a mean error of 0, an overall RMSE of 1.8 m and the 95th percentile of the absolute error of 4.21 m.

The initial mission planning SDB error showed a strong bias toward overestimation, with predicted SDB depths consistently deeper than observed values. The error distribution was bimodal, with a primary peak around -2 m and a secondary, smaller peak around -6 m (Fig. 7b). Table 1 summarizes error statistics by depth interval, highlighting the same error patterns observed in Fig. 6a. Fig. 7a demonstrates that the original mission planning SDB systematically overestimated depth, particularly in the mid-depth range, but was broadly concordant with the CSB measurements. The bias and high error can be attributed to two things: an incorrect assumption on the extinction depth of light in this area, and complex benthic environment that could not be linearly correlated with pixel brightness. Comparison of the newly collected data within the imagery suggests that the maximum depth in this area varies between 5 m and 10 m below chart datum, for a full range of 9-14 m of water in the selected image (tide of 3.6 m), rather than the 17m initially estimated. The influence of non-uniform benthic environment is shown in Fig. 8, where the first iteration SDB model correlated vegetative substrate with deep water, while the second iteration model better predicted the area as shallow. Although imperfect, the resulting first iteration

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Table 1 Comparison of error between original SDB estimated with no in situ data and the updated SDB modelled with CSB data for Koksoak Approach. SDB surfaces were assessed for accuracy using the test dataset from the second iteration updated SDB model.

Depth interval (m)	Count of test survey points	Iteration 1 – Mission planning SDB			Iteration 2 – Updated SDB		
		Mean error	RMSE	Absolute error P95	Mean error	RMSE	Absolute error P95
[-5,0]	9,823	-2.21	2.45	4.05	-0.04	0.35	0.74
[0,5]	9,354	-5.70	6.06	8.55	-1.00	1.98	4.42
[5,10]	4,954	-3.45	3.94	6.26	0.25	1.89	3.79
[10,13]	3,041	-0.31	1.25	2.33	2.80	3.39	6.34
Overall	27,172	-3.42	4.22	7.82	0.00	1.83	4.21

surface provided valuable supplementary information that enhanced the safety of survey operations by improving situational awareness for mariners collecting new data.

The results were clearly improved for the site when the addition of newly collected data allowed for empirical SDB modeling at the site. The second iteration of SDB modeling at the site demonstrated significant improvement in SDB performance when using CSB data (Fig. 7c and d). However, despite the reduced RMSE, the significant spread of error at depths exceeding 0 m (Fig. 7c) indicates that the second iteration SDB is still of insufficient quality for direct charting applications.

Table 1 shows significantly decreased RMSE outside of the intertidal zone (depths > 0 m), however the RMSE did not decrease monotonically with depth; accuracy improved near 6 m before decreasing again around 10 m. This pattern is also evident in Fig. 7c, where the predicted error starts to be underestimated around 10 m, and in Fig. 6b, where deeper areas were represented by intermediate values (~10 m) rather than the expected maximum depths (~13 m). This behaviour reiterates the limitation in depth retrieval near 10 m, with an effective optical extinction depth of approximately 14 m, given that the survey data depth range began at 4 m above chart datum.

Fig. 6c illustrates the magnitude and spatial distribution of the change between the two SDB surfaces. The updated model produced predominantly shallower depths across most of the AOI (shown in orange), consistent with the reduction in depth overestimation observed when comparing Figs. 7a and 7c. Areas closer to shore exhibited smaller magnitude depth reductions, reflected by darker orange tones in Fig 6c.

For both the mission planning SDB and the updated SDB, complex benthic environments likely contributed to the broad error distributions, as observed in the widely dispersed shapes of the scatter plots and error histograms (Figs. 7a and c). Variability in substrate reflectance, such as dark shallow substrates and bright deeper substrates, can contribute to model uncertainty even where sufficient training data are available, due to limited spectral variance across benthic types.

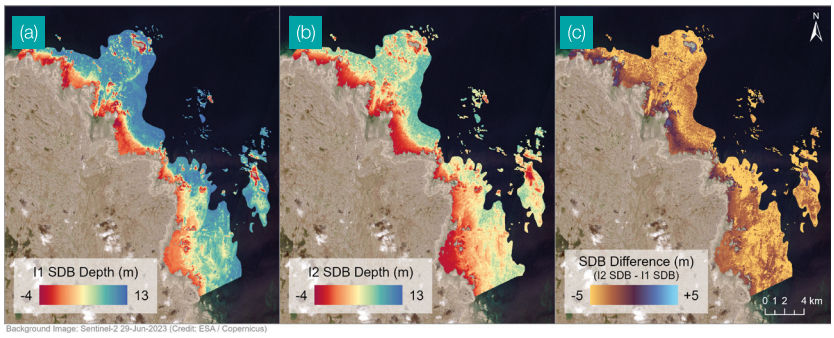


Fig. 6 Comparison of Koksoak Approach SDB results for the two iterations of SDB, mission planning and updated SDB. (a) Iteration 1 (I1) mission planning SDB. (b) Iteration 2 (I2) updated SDB. (c) difference between the two SDB surfaces.

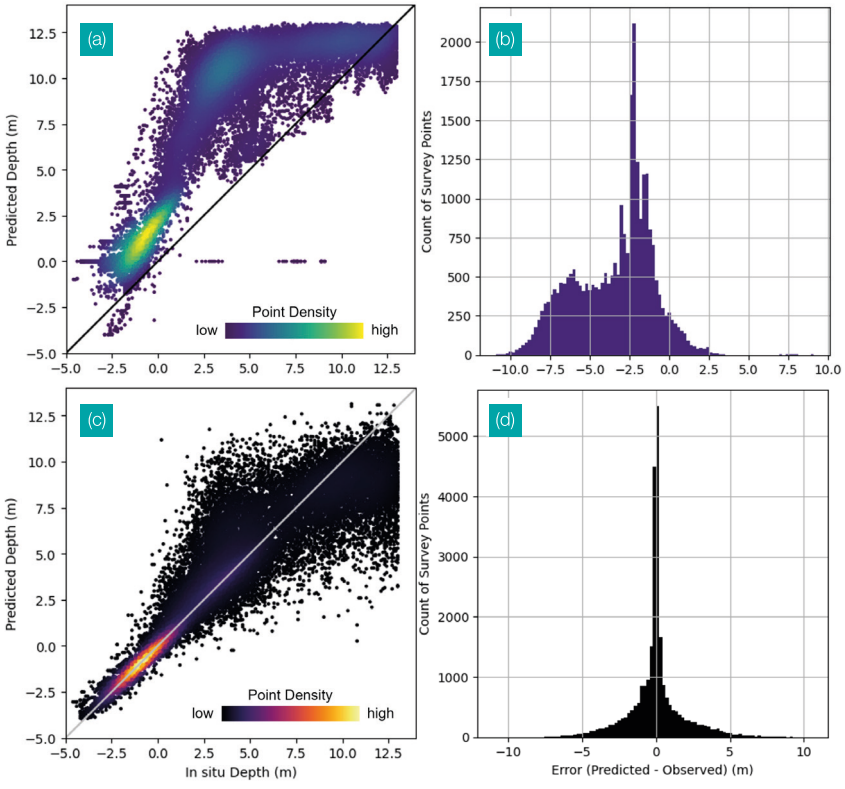


Fig. 7 Comparison of error distribution for mission planning SDB and updated SDB modeled with CSB data for Koksoak Approach. Top row is original SDB and bottom row is updated SDB. (a) Comparison of predicted and in situ depth for mission planning SDB. (b) Error distribution for mission planning SDB. (c) Comparison of predicted and in situ depth for updated SDB. (d) Error distribution for updated SDB.

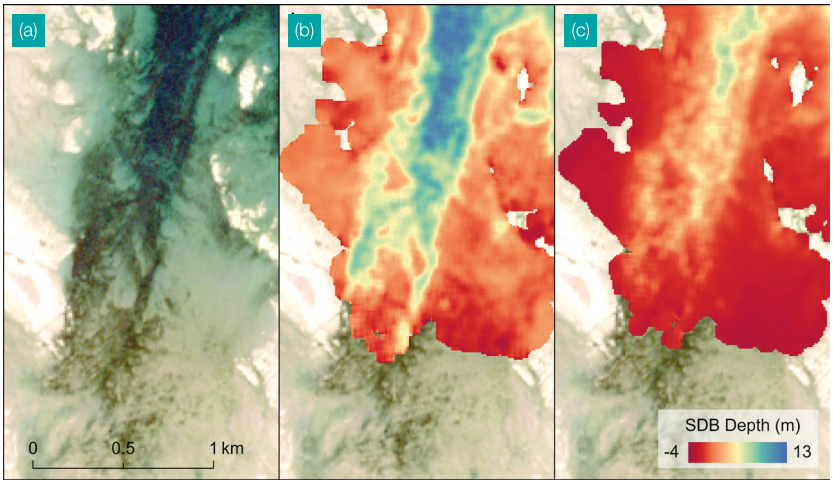


Fig. 8 Iterative improvement of SDB results in a non-uniform benthic setting. (a) Initial output influenced by substrate variability; (b) refined model with improved shallow-water representation; (c) final SDB surface, demonstrating enhanced consistency through iteration.

3.2 Rankin Inlet

The original mission planning SDB for Rankin Inlet exhibited high accuracy, with a mean error of -0.01, an overall RMSE of 0.72 m and the 95th percentile of the absolute error of 1.49 m. The final SDB surface for the three AOIs (Fig. 5) is shown in Fig. 9. RMSE decreased slightly with increasing depth but remained low across the full 0–15 m depth range (Table 2). The error distribution shown in Figs. 10a and b indicates strong model performance, with most survey points aligned with the 1:1 line.

The updated SDB model incorporating the newly collected survey points produced no substantial change in overall accuracy, with an updated mean error of -0.01, overall RMSE of 0.82 m and the 95th percentile of the absolute error of 1.74 m. The resulting surface is shown in Fig. 9b and the difference between the original and updated surfaces is shown in Fig. 9c. Table 2 summarizes model accuracy by depth interval before and after the inclusion of CSB data, demonstrating a consistent and minor increase in RMSE across depth intervals, resulting in an overall increase of approximately 0.1 m. The error distribution (Figs. 10c and 10d) demonstrates minimal difference between the two models, with only a slight increase in the spread of points in Fig. 10c. This limited change is consistent with Fig. 9 which indicates only minor differences between the two surfaces with no distinct pattern, mostly attributable to noise. The exception to this is in the southernmost AOI where the updated SDB appears more sensitive to the image seamline, likely because the additional survey data in this area was collected solely on the eastern side of the image divide (Figs. 5 and 9i).

The minor increase in error likely resulted from the expanded spatial extent of the training data, which introduced greater variability in pixel spectral values and depth, thus increasing the potential for error. Despite this increase, the broader spatial representation improves the applicability of the model across the AOI and increases confidence in the SDB surface over the expanded area.

4 Discussion

4.1 Iterative approach

Analysis of the two study sites showed that the iterative approach was particularly effective in areas where in situ data were sparse, while providing limited additional benefit in areas with extensive existing survey coverage. In both cases, the first SDB iteration provided valuable safety to navigation information that supported crew safety during data collection and helped identify areas where additional surveys would most improve SDB modelling. Results from Rankin Inlet demonstrated that acceptable SDB results can be achieved in the initial iteration, provided that the available in situ data were sufficient in both quantity and quality. Although the addition of CSB data in the second iteration slightly increased global error metrics, the inclusion of in situ data from previously unsurveyed areas increased overall confidence in the application of SDB across the larger AOI.

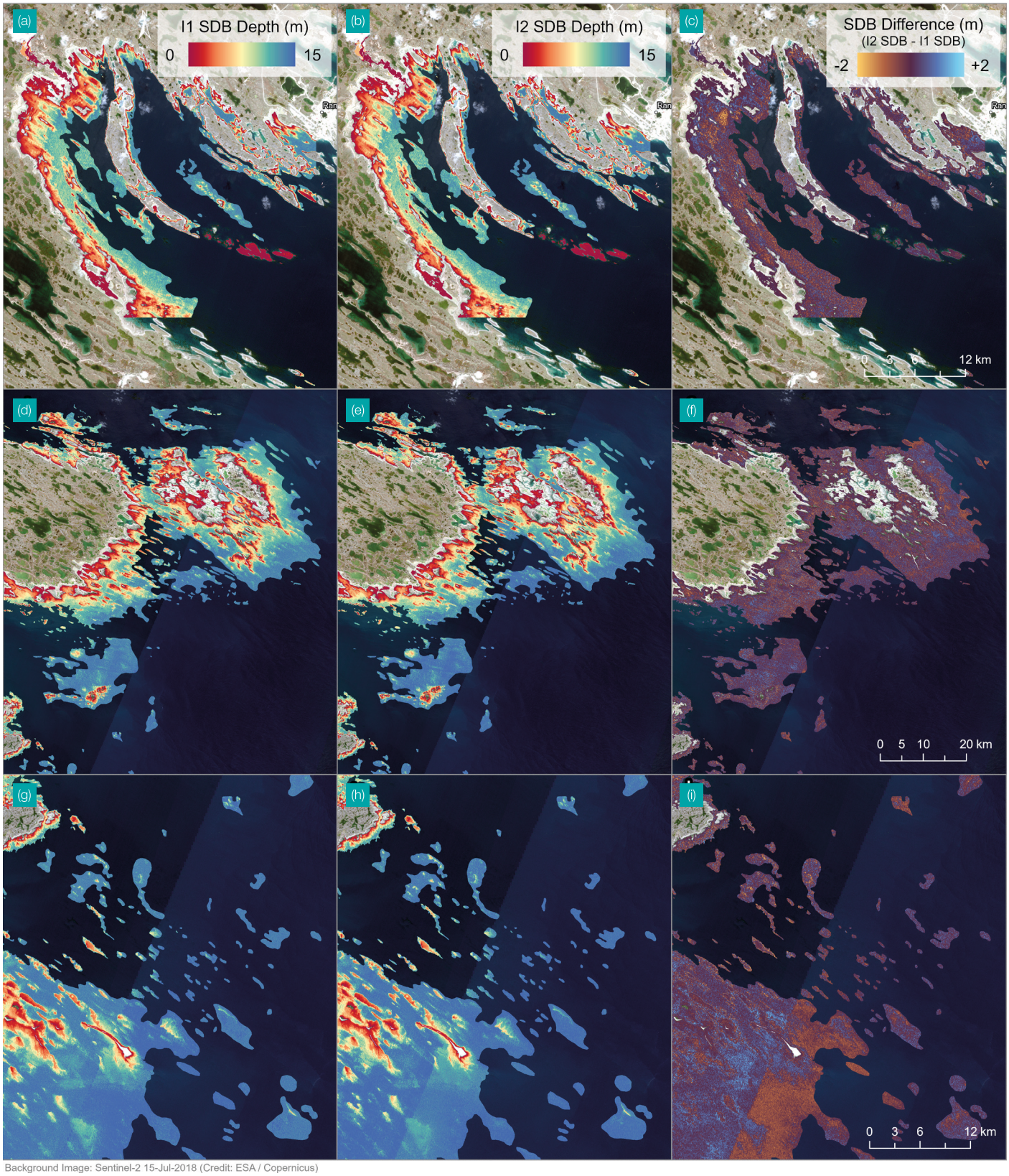
In contrast, the iterative approach produced substantial improvements in the Koksoak Approach region, which initially lacked adequate in situ data, including shallow water surveys across diverse substrates. At this site, the iterative process enabled the development of a markedly improved SDB model that could be used to derive enhanced hydrographic data for updating nautical products.

While SDB offers significant advantages in data-sparse regions, it also presents unique challenges related to its accuracy and uncertainty assessment. Integrating SDB into hydrographic products requires a clear understanding of its quality characteristics, which can be influenced by factors not typically faced by traditional survey methods, including the methodological approaches, the quality of the input data (both survey measurements and imagery), and site-specific environmental conditions (e.g., sediment type, complex benthic environments). Because SDB represents a modeled depth surface, its accuracy cannot be characterized in the same manner as true in situ survey data. To support the responsible use of SDB in nautical products, it is therefore necessary to clearly define, assess, and communicate SDB quality. The following section distinguishes between system precision, reported accuracy, and product uncertainty, and discusses their implications for nautical charting and related hydrographic applications. Establishing this framework provides a consistent basis for evaluating SDB outputs and supports their appropriate use in updating nautical products.

4.2 Accuracy assessment: precision, accuracy, product uncertainty

In this study, precision refers to system repeatability; accuracy denotes statistical agreement with reference

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Background Image: Sentinel-2 15-Jul-2018 (Credit: ESA / Copernicus)

Fig. 9 Comparison of Rankin Inlet SDB results for the two iterations of SDB, mission planning and updated SDB. Top row is for the northern AOI, middle row is for the original central AOI, bottom row is for southern AOI. (a) Iteration 1 (I1) mission planning SDB for north AOI. (b) Iteration 2 (I2) updated SDB for north AOI. (c) difference between the two SDB surfaces for north AOI. (d) Iteration 1 (I1) mission planning SDB for central AOI. (e) Iteration 2 (I2) updated SDB for central AOI. (f) difference between the two SDB surfaces for central AOI. (g) Iteration 1 (I1) mission planning SDB for south AOI. (h) Iteration 2 (I2) updated SDB for south AOI. (i) difference between the two SDB surfaces for south AOI.

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Table 2 Comparison of SDB model error and count of survey test points by depth interval before (CHS only) and after (CHS and CSB) the addition of CSB data for Rankin Inlet.

Depth interval (m)	CHS only				CHS and CSB			
	Mean error	RMSE	Absolute error P95	Count of test survey points	Mean error	RMSE	Absolute error P95	Count of test survey points
[0,5]	-0.13	0.62	1.23	12,190	-0.13	0.64	1.30	13,080
[5,10]	-0.05	0.72	1.53	14,888	-0.09	0.84	1.85	15,699
[10,15]	0.15	0.80	1.62	13,077	0.21	0.95	1.98	13,963
Overall	-0.01	0.72	1.49	40,155	-0.01	0.82	1.74	42,742

in situ depth measurements, and uncertainty as the spatially varying confidence across the SDB surface (ISO, 2008). A key challenge in SDB and its evaluation is that, unlike traditional survey techniques, such as multibeam echosounders (MBES), single beam echosounders (SBES), or LiDAR, SDB lacks a predefined precision or quantified system of confidence. In contrast to SDB, engineered surveying systems are defined by established performance specifications that characterize system precision and expected accuracy prior to deployment, typically in the decimeter range for MBES (Ernstsen et al., 2006) and LiDAR (Pan et al., 2015) systems in shallow water. This distinction is critical when assessing SDB uncertainty. Although accuracy can be evaluated through validation against in situ measurements, the absence of a defined precision prevents reliable quantification of measurement repeatability under identical conditions (Taylor, 1997). Nevertheless, the application of a consistent and systematic processing workflow can enhance output stability and support a limited degree of repeatability in derived products.

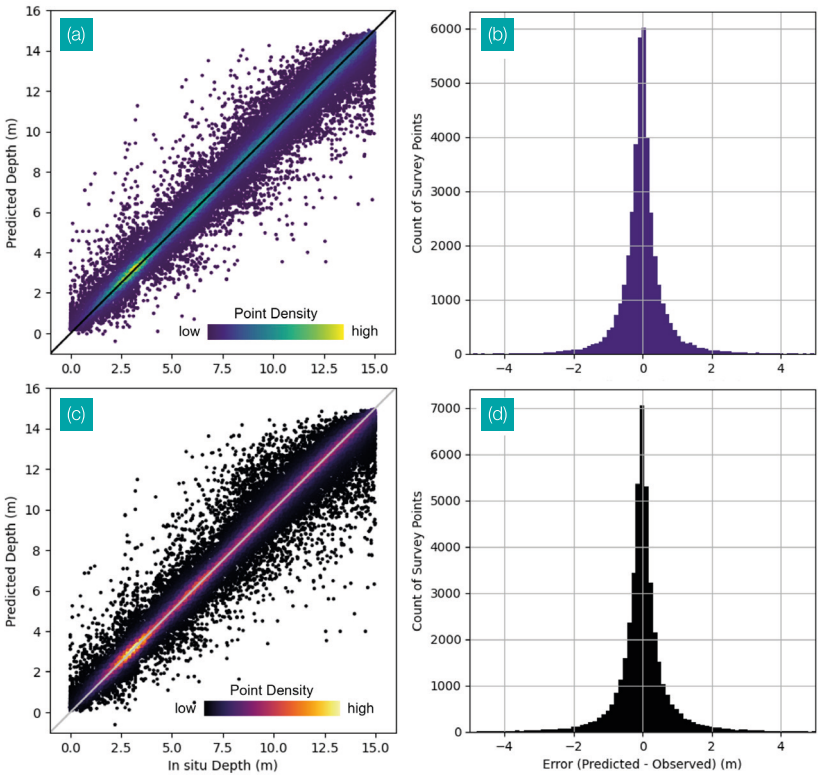


Fig. 10 Comparison of error distribution for mission planning SDB and updated SDB modeled with CSB data for Rankin Inlet. Top row is original SDB and bottom row is updated SDB. (a) Comparison of predicted and in situ depth for mission planning SDB. (b) Error distribution for mission planning SDB. (c) Comparison of predicted and in situ depth for updated SDB. (d) Error distribution for updated SDB.

The accuracy assessment is based on a statistical analysis of the differences between a source of water depth - preferably in situ depth measurements and corresponding SDB estimates. Empirical SDB methods rely on the Beer–Lambert Law, which describes the exponential attenuation of light within an absorbing medium, resulting in decreasing water-leaving radiance with increasing depth (Mobley, 1994). Although additional factors influence performance and accuracy, this physical relationship establishes an inherent depth-dependent limitation, with accuracy generally decreasing as water depth increases (Chénier et al., 2018; Duan et al., 2022; Knudby & Richardson, 2023). Consequently, depth-stratified accuracy evaluation is essential to identify the depth ranges over which SDB provides reliable estimates and to delineate outputs suitable for retention or exclusion. In Canadian waters, SDB typically does not exceed depths of about 15 m, and in some regions the effective range is limited to only a few meters. In certain environments, SDB may be impractical altogether due to insufficient light penetration or site complexity that precludes a stable relationship between depth and spectral response.

The principal limitation in characterizing uncertainty in SDB is the lack of sufficient information to assess product quality across the full range of values. This limitation, combined with the lack of well-defined system precision, limits the ability to robustly quantify SDB uncertainty and reduces confidence in the resulting datasets. Because accuracy cannot be assessed for every image pixel, some level of uncertainty is inherent in most SDB products. This is especially true in areas where neighboring pixels show steep spectral transitions and high variability, such as the contrast between high albedo white sand and adjacent dark benthic substrates. Although statistical accuracy metrics derived from validation points provide a useful global indicator of SDB performance, they do not describe spatially explicit uncertainty and therefore cannot represent the spatially varying uncertainty required to evaluate compliance

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with the International Hydrographic Organization (IHO) S-44 total vertical uncertainty (TVU) requirements. As noted by Taylor (1997), measurement uncertainty arises when observations are incomplete or subject to variable influences, underscoring the importance of error analysis for estimating confidence in measurement results. In the context of SDB, this uncertainty is compounded by environmental and scene-dependent factors, including surface waves, sun glint, suspended sediments, and variability in seabed albedo which introduce spectral variation that complicates depth estimation. The accumulation of systemic and random errors from multiple sources further limits the ability to isolate or eliminate individual error contributions (Taylor, 1997). Consequently, SDB uncertainty and confidence may, in most cases, be difficult to quantify and might need to be acknowledged as an inherent constraint of SDB.

The influence of image resolution on SDB accuracy was not examined in this study, as imagery selection was driven primarily by site extent, with 10 m resolution providing a practical balance of coverage cost, and processing time. Previous work by the CHS RSCoE (Ahola et al., 2020) shows that while higher spatial and spectral resolution can improve SDB performance, environmental conditions have a stronger influence on accuracy than sensor type. As such, freely available medium-resolution imagery can support reliable SDB in appropriate conditions.

It is also important to distinguish spatial resolution from horizontal accuracy, as finer resolution does not necessarily imply improved positional accuracy. However, in complex environments, such as areas with heterogeneous seabed types or steep slopes, medium-resolution data may be insufficient to resolve small but navigationally crucial features, such as isolated rocks. In these cases, higher-resolution imagery is used to support hazard detection, with CHS RSCoE applying ~2 m multispectral data for harbour-scale SDB.

4.3 Application of SDB on nautical products

The most significant limitation to direct application of SDB in official nautical products is the absence of a predefined or guaranteed level of precision. As a result, even when acceptable accuracy is achieved (e.g., ~1 m), quantifying uncertainty across the full SDB surface in accordance with IHO S-44 standards remain extremely challenging (IHO, 2022). This limitation is compounded by the typically sparse availability of validation data, which makes it difficult to assign a reliable Category Zone of Confidence (CATZOC). At the two sites examined, only 1.7 % and 0.4 % of SDB-derived depths could be validated using in situ data at Koksoak Approach and Rankin Inlet, respectively. Given this limited validation coverage, together with environmental and methodological factors affecting depth retrieval, robust evaluation of uncertainty across the full SDB surface is impractical. Accordingly, SDB is not considered reliable for direct incorporation into official nautical products. Consistent

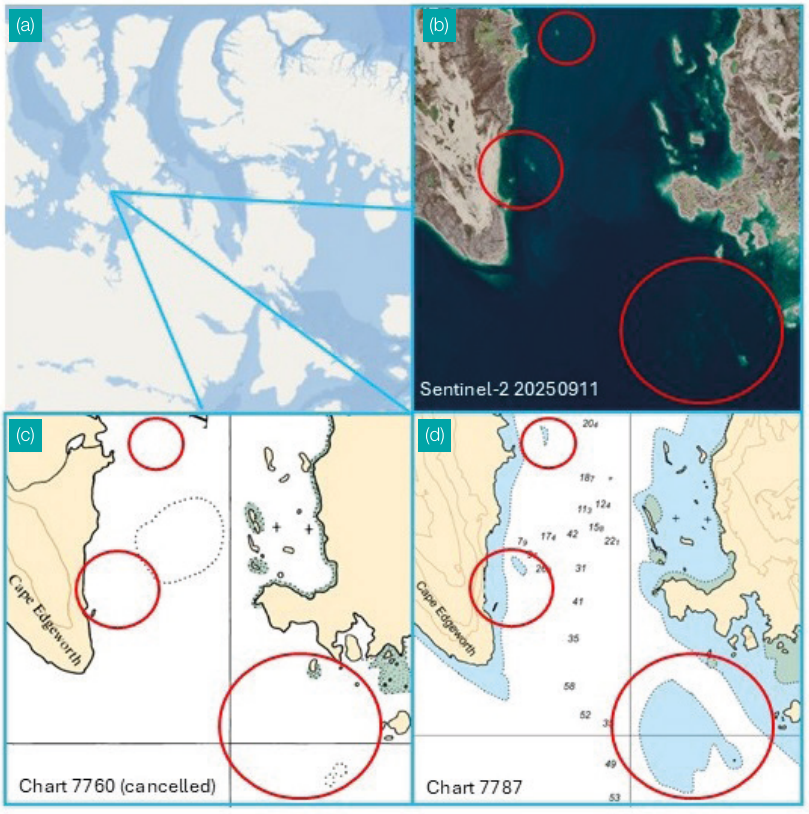


Fig. 11 SDB-derived shoals applied to Chart 7787 without any depth information. Chart 7760 was replaced by Chart 7787, and the shoals were included in an update via NTM.

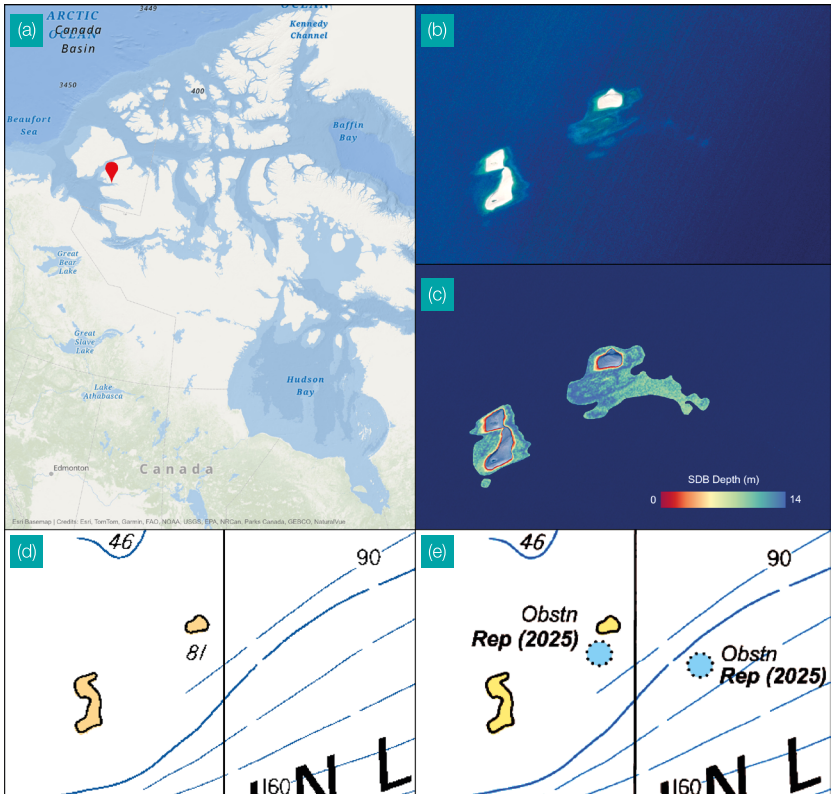


Fig. 12 Chart update with hazard to navigation identified in Minto Inlet, NWT (117.034°W, 71.376°N). (a) Overview image showing location of hazard in Canadian Arctic. (b) Sentinel-2 image acquired 2019-09-06. (c) SDB showing approximate depth of shoal area. (d) Chart 7521 showing an 81 m depth sounding coincident with the shoal shown in (b). (e) Chart 7521 with Oct 2025 update showing newly added obstructions and the removal of the 81 m depth sounding.

with this conclusion, Jai (2025) finds that SDB does not meet S-44 requirements for hydrographic survey data and is better suited for reconnaissance applications. For this reason, the CHS RSCoE does not recommend the direct inclusion of raw SDB in nautical products. When acceptable accuracy is obtained, the RSCoE instead produces derived products, such as isobaths, generated through a combination of SDB and image interpretation to reduce noise and exclude areas that may not represent true water depth.

Despite these limitations, SDB remains a valuable resource for enhancing navigation and mission safety. Even at lower accuracy levels, SDB can support meaningful chart improvements. Fig. 11 illustrates a CHS chart that was updated from SDB that was created without any training or validation data. Due to the resulting low confidence in depth estimates, shoal features were charted using the SDB and imagery analysis. The isobaths extracted were charted as areas of unknown depth rather than assigned discrete depth values. This approach improves navigational safety by identifying potentially hazardous shallow areas while avoiding the dissemination of misleading depth information.

The utility of SDB is particularly evident in highly dynamic environments, where rapid sedimentation and erosion can quickly degrade the relevance of existing hydrographic surveys. In such settings, recently acquired SDB has been shown to outperform echosounder data that are only one year old (Chénier et al., 2018). Beyond its accuracy in change prone areas, SDB offers a major advantage for chart timeliness: the frequent revisit cycles of modern satellite missions enable near continuous monitoring of coastal and shallow water zones. This provides hydrographic offices with a cost-efficient means of updating bathymetric information far more regularly than would be feasible with traditional surveys, which can be financially unsustainable to repeat at the frequency required in rapidly evolving environments.

To ensure the safety to navigation for all its projects, the RSCoE systematically analyzes the imagery and the derived remote sensing products to identify potential hazards and obstructions. When preliminary analysis indicates a possible risk, higher-resolution imagery can be obtained to enable a more detailed assessment and confirmation. Features posing immediate risks to navigation may be issued as Navigational Warnings (NAVWARNs; CCG, 2023), while less urgent updates may be disseminated through Notices to Mariners (NOTMARs; CCG, 2025). Collectively, these mechanisms contribute to timely chart updates and the sustained assurance of navigational safety. Fig. 12 presents an example of a navigational hazard identified using remote sensing techniques and subsequently issued as a NAVWARN.

4.4 Future development

While this paper does not compare different SDB approaches, the uncertainty associated with SDB is not method specific. At CHS, SDB models are generated using a range of approaches (empirical, photogrammetric, and physics-based), each with distinct advantages and limitations. However, all are influenced by fundamental constraints related to light penetration through the water column and reflectance from the seafloor. Where the seafloor is not optically detectable, reliable depth estimation is not possible.

Environmental conditions are a primary source of uncertainty across all SDB approaches. Suspended sediments reduce bottom detectability by scattering or absorbing light, while high sediment albedo can cause the dominant reflectance to originate from the water column or surface rather than the seabed, leading to significant depth errors. Conversely, low-reflectance benthic substrates, such as dark vegetation, produce weak or ambiguous signals that also degrade model performance.

Photogrammetry can offer improved performance in some benthic environments due to enhanced textural contrast, which supports image matching and feature detection (Chénier et al., 2019). However, it is not without limitations: it performs best along sharp edges, and derived depths may correspond to the top of benthic vegetation rather than the true seafloor. Although this effect is reduced in Arctic environments where vegetation is typically low-growing, the limitation remains.

To reduce uncertainty in SDB, the CHS has developed a level-of-confidence approach (Chénier et al., 2019). This method improves confidence in SDB by comparing several independent SDB datasets and retaining only the depth values that agree within 1 m. This filtering step effectively removes large errors from the final product. For example, at a site in Cambridge Bay, approximately 80 % of the SDB values met the 1 m agreement criterion, leaving only 20 % of the SDB surface requiring further evaluation (Chénier et al., 2019). A major limitation of this approach in operational contexts is the substantial time and resources required to generate multiple independent SDB datasets. Producing several SDB layers, regardless of the underlying method, demands additional data acquisition, processing effort, and computational capacity. For instance, photogrammetric SDB requires stereo imagery, which further increases acquisition and processing requirements. As a result, the approach can become costly and difficult to implement routinely in large-scale or time-sensitive environments. It also requires the use of diverse imagery, because not all errors originate from seafloor characteristics. Many issues instead arise from the atmosphere (clouds, haze, shadows), the sea surface (waves, sun glint, suspended sediment, floating aquatic vegetation, and debris), or the water column itself (turbidity, sediment load, light angle, submerged aquatic vegetation). The development of more automated workflows could help reduce the time needed to run the CHS level-of-confidence approach and improve not only the accuracy but, more importantly, the reliability of the results.

Another way to improve understanding of error sources and reduce their influence on SDB is to

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incorporate classification-based approaches. For example, classification methods can be used to identify and map vegetation that interferes with SDB retrieval. Implementing seabed-type classification (Chénier et al., 2019) can help highlight areas that are inherently more challenging for depth estimation. In addition, masking vegetation using a Chlorophyll Index has been shown to effectively remove portions of SDB outputs that do not provide reliable depth information (Caballero et al., 2020).

5 Conclusion

The iterative approach developed by the CHS ensures that SDB products effectively support navigational safety and the ongoing modernization of nautical charts when applied within an operational framework. This approach enables the rapid production of preliminary products that support survey planning and enhance crew safety. In areas with limited in situ data, incorporating recent and higher-quality measurements allows SDB models to be refined, resulting in derived products that are better suited for updating nautical products. A limitation of this study is that validation coverage remains spatially sparse relative to total SDB area, which restricts full characterization of spatial uncertainty patterns.

However, because SDB lacks predefined system precision and robust uncertainty quantification, it cannot achieve the accuracy or confidence levels of MBES data. As a result, raw SDB outputs are unsuitable for direct incorporation into official nautical products. Despite advances in automation and artificial intelligence, expert intervention by remote sensing specialists remains essential to ensure reliable and responsible chart updates (Chénier et al., 2024). When appropriately assessed and integrated, remote sensing products can identify navigational hazards, including previously uncharted shoals, thereby reducing risk to mariners. In highly dynamic environments, where traditional surveys rapidly become outdated, SDB provides a valuable complementary tool for maintaining chart relevance and supporting safe navigation. Improving SDB uncertainty and better quantifying accuracy will remain key priorities for CHS, with ongoing efforts aimed at reducing manual intervention. Future development will be made in better integrating image-classification techniques to identify factors such as benthic environments and sediment that can introduce large errors in SDB. The CHS confidence-level approach should also be better integrated in an operational context by providing a structured way to quantify reliability and build trust in SDB products. Together, these developments move SDB toward more reliable operational use. Continued refinement of confidence metrics, increased automation in feature classification, and improved sensor-driven environmental characterization will be essential to reducing uncertainty and expanding SDB's practical value in hydrographic applications.

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References

Ahola, R., Chénier, R., Sagram, M. and Horner, B. (2020). The impact of sensors for satellite derived bathymetry within the Canadian Arctic. *Geomatica, 74*(2), pp. 46–64. https://doi.org/10.1139/GEOMAT-2019-0022

Caballero, I. and Stumpf, R. P. (2020). Towards Routine Mapping of Shallow Bathymetry in Environments with Variable Turbidity: Contribution of Sentinel-2A/B Satellites Mission. *Remote Sensing, 12*(3). https://doi.org/10.3390/rs12030451

CCG (2023). *Navigational and NAVAREA warnings*. Canadian Coast Guard, Government of Canada, Canada. https://www.ccg-gcc.gc.ca/mcts-sctm/navwarn-avnav-ca-eng.html (last accessed 21 August 2025).

CCG (2025). *Notices to Mariners* (NOTMAR). Canadian Coast Guard, Government of Canada, Canada. https://www.notmar.gc.ca/index-en (last accessed 21 August 2025).

Chen, T. and Guestrin, C. (2016). XGBoost: A Scalable Tree Boosting System. *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, pp. 785–794. https://doi.org/10.1145/2939672.2939785

Chénier, R., Ahola, R., Sagram, M., Faucher, M.-A. and Shelat, Y. (2019). Consideration of Level of Confidence within Multi-Approach Satellite-Derived Bathymetry. *ISPRS International Journal of Geo-Information, 8*(1), 48. https://doi.org/10.3390/ijgi8010048

Chénier, R., Faucher, M. A. and Ahola, R. (2018). Satellite-Derived Bathymetry for Improving Canadian Hydrographic Service Charts. *ISPRS International Journal of Geo-Information 2018, 7*(8), p. 306. https://doi.org/10.3390/IJGI7080306

Chénier, R., Faucher, M.A., Ahola, R., Jiao, X. and Tardif, L. (2016). Remote sensing approach for updating CHS charts. *Proceedings of the Canadian Hydrographic Conference*, Halifax, Canada.

Chénier, R., Faucher, M.-A., Ahola, R., Shelat, Y. and Sagram, M. (2018). Bathymetric Photogrammetry to Update CHS Charts: Comparing Conventional 3D Manual and Automatic Approaches. *ISPRS International Journal of Geo-Information, 7*(10), 395. https://doi.org/10.3390/ijgi7100395

Chénier, R., Omari, K. and Seale, S.-A. (2024). Leveraging Earth Observation Data To Enhance The Safety To Navigation In The Canadian Arctic. *Proceedings of IEEE International Geoscience and Remote Sensing Symposium* (IGARSS), Athens, Greece.

Chénier, R., Omari, K., Blondel, E., Sagram, M. and Jirovec, A. (2020a). Accelerating the Usage of Earth and Oceans Observation Data in Hydrographic Applications. *The International Hydrographic Review, 24*, pp. 103–127. https://ihr.iho.int/articles/accelerating-the-usage-of-earth-and-oceans-observation-data-in-hydrographic-applications/ (last accessed 22 April 2025).

Chénier, R., Omari, K., George, G., Lounissi, L., Seale, S.-A., Abado, L., and Gautam, S. (2025). Remote sensing technology

utilized by CHS to support safety of navigation in the Arctic. *Proceedings of Remote Sensing for Agriculture, Ecosystems, and Hydrology XXVII, 13666*, pp. 26–40. https://doi.org/10.1117/12.3069938

Chénier, R., Sagram, M., Omari, K. and Jirovec, A. (2020b). Earth Observation and Artificial Intelligence for Improving Safety to Navigation in Canada Low-Impact Shipping Corridors. *ISPRS International Journal of Geo-Information, 9*(6), 383. https://doi.org/10.3390/ijgi9060383

Dekker A. G., Phinn S. R., Anstee J., Bissett P., Brando V. E., Casey B., Fearns P., Hedley J., Klonowski W., Lee Z. P., Lynch M., Lyons M., Mobley C. and Roelfsema C. (2011). Intercomparison of shallow water bathymetry, hydro-optics, and benthos mapping techniques in Australian and Caribbean coastal environments. *Limnol. Oceanogr. Methods, 9*. https://doi.org/10.4319/lom.2011.9.396

DFO (2026). *Community Hydrography*. Department of Fisheries and Oceans, Government of Canada, Canada. https://www.dfo-mpo.gc.ca/science/hydrography-hydrographie/opp-ppo/index-eng.html (last accessed January 21, 2026).

Duan, Z., Chu, S., Cheng, L., Ji, C., Li, M. and Shen, W. (2022). Satellite-derived bathymetry using Landsat-8 and Sentinel-2A images: assessment of atmospheric correction algorithms and depth derivation models in shallow waters. *Opt. Express, 30*, 3238–3261. https://doi.org/10.1364/OE.444557

Ernstsen, V. B., Noormets, R., Hebbeln, D., Bartholomä, A., and Flemming, B. W. (2006). Precision of high-resolution multibeam echo sounding coupled with high-accuracy positioning in a shallow water coastal environment. *Geo-Marine Letters, 26*(3), pp. 141–149. https://doi.org/10.1007/s00367-006-0025-3

Hodúl, M., Bird, S., Knudby, A. and Chénier, R. (2018). Satellite derived photogrammetric bathymetry. I*SPRS Journal of Photogrammetry and Remote Sensing, 142*, pp. 268–277. https://doi.org/10.1016/J.ISPRSJPRS.2018.06.015

IHO (2022). *Standards for Hydrographic Surveys* (6th ed.). IHO Special Publication S-44, International Hydrographic Organization, Monaco. https://iho.int/uploads/user/pubs/standards/s-44/S-44_Edition_6.1.0.pdf (last accessed 21 January 2026).

ISO (2008) *ISO/IEC Guide 98-3:2008 - Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*. International Organization for Standardization. https://www.iso.org/standard/50461.html (last accessed 21 January 2026).

Jai, V. (2025). Evaluation of SDB data for near shore mapping around Agatti Island, India: a comparative study with echo sounder survey. *The International Hydrographic Review, 31*(2). https://doi.org/10.58440/ihr-31-2-n07

Kerr, J. M. and Purkis, S. (2018). An algorithm for optically-deriving water depth from multispectral imagery in coral reef landscapes in the absence of ground-truth data. *Remote Sensing of Environment, 210*, pp. 307–324. https://doi.org/10.1016/J.RSE.2018.03.024

Knudby, A. (2025). Satellite imagery for hazard detection: better use of satellite imagery could help prevent groundings in the Canadian Arctic. *The International Hydrographic Review, 31*(2). https://doi.org/10.58440/ihr-31-2-a13

Knudby, A. and Richardson, G. (2023). Incorporation of neighborhood information improves performance of SDB models. *Remote Sensing Applications: Society and Environment, 32*, p. 101033. https://doi.org/10.1016/J.RSASE.2023.101033

Knudby, A., Ahmad, S. K. and Ilori, C. (2016). The Potential for Landsat-Based Bathymetry in Canada. *Canadian Journal of Remote Sensing, 42*(4), pp. 367–378. https://doi.org/10.1080/07038992.2016.1177452;CTYPE:STRING:-JOURNAL

Lee, Z., Carder, K. L., Mobley, C. D., Steward, R. G.and Patch, J. S. (1999). Hyperspectral remote sensing for shallow waters: 2. Deriving bottom depths and water properties by optimization. *Applied Optics, 38*(18), pp. 3831–3843, pp. 3831–3843. https://doi.org/10.1364/AO.38.003831

Lyzenga, D. R. (1978). Passive remote sensing techniques for mapping water depth and bottom features. *Applied Optics, 17*(3), pp. 379–383. https://doi.org/10.1364/AO.17.000379

Lyzenga, D. R. (1981). Remote sensing of bottom reflectance and water attenuation parameters in shallow water using aircraft and Landsat data. *International Journal of Remote Sensing, 2*(1), 71–82. https://doi.org/10.1080/01431168108948342

Lyzenga, D. R. (1985). Shallow-water bathymetry using combined lidar and passive multispectral scanner data. *International Journal of Remote Sensing, 6*(1), pp. 115–125. https://doi.org/10.1080/01431168508948428;ISSUE:ISSUE:DOI

Lyzenga, D. R., Malinas, N. P. and Tanis, F. J. (2006). Multispectral bathymetry using a simple physically based algorithm. *IEEE Transactions on Geoscience and Remote Sensing, 44*(8), 2251–2258. https://doi.org/10.1109/TGRS.2006.872909

Mobley, C. D. (1994). *Light and Water: Radiative Transfer in Natural Waters*. Academic Press.

Mobley, C. D. (ed.) (2022). *The Oceanic Optics Book*. International Ocean Colour Coordinating Group (IOCCG), Dartmouth, NS, Canada, 924pp. https://doi.org/10.25607/OBP-1710

Pan, Z., Glennie, C., Hartzell, P., Fernandez-Diaz, J. C., Legleiter, C. and Overstreet, B. (2015). Performance Assessment of High Resolution Airborne Full Waveform LiDAR for Shallow River Bathymetry. *Remote Sensing, 7*(5), 5133–5159. https://doi.org/10.3390/rs70505133

Polcyn, F. C., Brown, W. L. and Sattinger, I. J. (1970). *The Measurement of Water Depth by Remote Sensing Techniques*. Report No. 8973-26-F [Preprint]. Ann Arbour, MI, USA: Willow Run Laboratories of the Institute of Science and Technology, the University of Michigan.

Stumpf, R. P., Holderied, K. and Sinclair, M. (2003). Determination of water depth with high-resolution satellite imagery over variable bottom types. *Limnology and Oceanography, 48*(1part2), pp. 547–556. https://doi.org/10.4319/LO.2003.48.1_PART_2.0547

Taylor, J. R. (1997) An Introduction to Error Analysis: *The Study of Uncertainties in Physical Measurements* (2nd ed). University Science Books.

TC (2023). *Oceans Protection Plan.* Transport Canada, Government of Canada, Canada. https://tc.canada.ca/en/corporate-services/transparency/briefing-documents-transport-canada/2023/current-topics/oceans-protection-plan (last accessed 18 August 2025).

Warren, M. A., Simis, S. G. H., Martinez-Vicente, V., Poser, K., Bresciani, M., Alikas, K., Spyrakos, E., Giardino, C. and Ansper, A. (2019). Assessment of atmospheric correction algorithms for the Sentinel-2A MultiSpectral Imager over coastal and inland waters. *Remote Sensing of Environment, 225*, pp. 267–289. https://doi.org/10.1016/J.RSE .2019.03.018

Authors' biographies

René Chénier is a manager at the Canadian Hydrographic Service (CHS), where he oversees the Geodesy, Geomatics, and Remote Sensing groups. Over his 17 years with CHS, he established the organization's Remote Sensing Centre of Expertise (RSCoE) and has led numerous initiatives advancing marine and coastal mapping capabilities. His expertise includes Satellite-Derived Bathymetry (SDB), Interferometric Synthetic Aperture Radar (InSAR), polarimetry, geometric modeling, photogrammetry, digital elevation modeling, and AI-based image classification. His work also spans ship detection and monitoring, hydrography, cartography, coastal erosion assessment, and habitat mapping.



René Chénier

Genevieve George is a remote sensing professional working with the Remote Sensing Centre of Expertise at the Canadian Hydrographic Service (CHS). Her work at the CHS focuses primarily on operational satellite derived bathymetry. She has broad expertise in imagery analysis across multiple sensor types and applications, with a particular emphasis on applying machine learning techniques to extract, model, and interpret geospatial data.



Genevieve George

Loretta Abado has worked with the Canadian Hydrographic Service (CHS) since 2014 within the Remote Sensing Centre of Expertise (RSCoE). Her work focuses on the application of geomatics and remote sensing to support hydrographic operations. She contributes to the development and operationalization of remote sensing workflows that support safe navigation.



Loretta Abado

Khalid Omari received the Ph.D. and M.Sc. degrees in remote sensing from the Ottawa–Carleton Geoscience Centre, University of Ottawa, Canada, in 2009 and 2002, respectively. He worked for 14 years as a Remote Sensing Scientist at the Canada Centre for Remote Sensing (CCRS), Natural Resources Canada, later part of the Canada Centre for Mapping and Earth Observation (CCMEO). He is currently a Remote Sensing Scientist with the Canadian Hydrographic Service (CHS), Fisheries and Oceans Canada (DFO), where he develops and applies Earth observation–based methodologies and products for hydrographic applications. His research interests include SAR polarimetry and interferometry, as well as optical multispectral and hyperspectral remote sensing. His doctoral research focused on radiative transfer modeling in vegetation canopies and retrieval of biophysical and biochemical parameters from hyperspectral data.



Khalid Omari

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PEER-REVIEWED ARTICLE

The potential of Inuit communities to map the Canadian Arctic nearshore

Authors

Mathieu Rondeau[1], Gabriel Montpetit-Allard[1], Yan Bilodeau[1], Jérémie Lemarchand[1] and Michel Breton[1]

Abstract

Nearshore hydrographic surveying in the Canadian Arctic remains challenging, resulting in persistent charting gaps and high concern navigation risks. This paper introduces Community-Sourced Bathymetry, an approach engaging Inuit communities to conduct targeted, systematic bathymetric surveys using standard navigation instruments and applying basic hydrographic principles. Results from Inuit-led surveys demonstrate that the collected data compare favorably with historical Canadian Hydrographic Service single-beam echo sounder datasets still largely used in Arctic navigation products. By leveraging local presence and Inuit Traditional Knowledge, this approach provides a promising, scalable solution to enhance Arctic nearshore mapping, improve safety, and strengthen community involvement in hydrography.

Keywords

Community-Sourced Bathymetry (CoSB) · Crowdsourced bathymetry (CSB) · Inuit communities · Canadian Arctic nearshore · Satellite-Derived Bathymetry (SDB) · navigation safety

Resumé

Les levés hydrographiques côtiers dans l'Arctique canadien continuent de poser des défis, qui se traduisent par des lacunes persistantes dans la cartographie et des risques de navigation élevés. Cet article présente la « bathymétrie participative », une approche qui fait appel aux communautés inuites pour réaliser des levés bathymétriques ciblés et systématiques à l'aide d'instruments de navigation standard et en appliquant des principes hydrographiques de base. Les résultats des levés menés par les Inuits montrent que les données recueillies se comparent favorablement aux jeux de données historiques du Service hydrographique canadien, obtenus à l'aide d'échosondeurs monofaisceau qui sont encore largement utilisés dans les produits de navigation arctiques. En s'appuyant sur la présence locale et les savoirs traditionnels inuits, cette approche offre une solution prometteuse et évolutive pour améliorer la cartographie côtière arctique, renforcer la sécurité et consolider l'implication des communautés dans l'hydrographie.

✉ Mathieu Rondeau · mathieu.rondeau@dfo-mpo.gc.ca

[1] Department of Fisheries and Oceans Canada (DFO), Canadian Hydrographic Service (CHS), Ottawa, Ontario, Canada

Resumen

Los levantamientos hidrográficos costeros en el Ártico canadiense siguen siendo un desafío, con el resultado de lagunas persistentes en la cartografía y riesgos para la navegación muy preocupantes. Este artículo presenta la Batimetría de Origen Comunitario, un enfoque que involucra a las comunidades inuit para realizar levantamientos batimétricos específicos y sistemáticos usando instrumentos normales de navegación y aplicando principios básicos de hidrografía. Los resultados de los levantamientos dirigidos por los inuit demuestran que los datos recogidos son mejores que los conjuntos de datos históricos con ecosondas monohaz del Servicio Hidrográfico Canadiense, que siguen utilizándose ampliamente en los productos de navegación del Ártico. Aprovechando la presencia local y los Conocimientos Tradicionales Inuit, este enfoque proporciona una solución prometedora y escalable para mejorar la cartografía costera del Ártico, aumentar la seguridad, y reforzar la participación de la comunidad en la hidrografía.

1 Introduction

Large portions of Canada's Arctic waters remain poorly surveyed – or not surveyed at all (HDACoE, 2025; IHO, 2026). Limited surveying and charting capacity, combined with the vastness of the Canadian Arctic, requires the Canadian Hydrographic Service (CHS) to prioritize its efforts in areas where navigation risk is expected to be highest (Chénier et al., 2022; DFO, 2025), particularly along commercial shipping routes. This corridor focused strategy has proven effective in supporting marine traffic, although many nearshore areas remain to be surveyed. This situation is clearly illustrated in the IHO ARHC *Arctic Hydrographic Risk Assessment 2025 update* (Devereaux et al., 2025) which classifies the overall navigation risk within Canada's Arctic EEZ as low to medium in the main shipping corridors, but as high in the coastal waters (Fig. 1).

These gaps have direct implications for nearshore navigation safety, environmental protection, and community resilience – issues that are becoming increasingly critical as maritime traffic and resource development expand across the region.

Hydrographers widely recognize that no single technology can address all the challenges inherent to hydrographic surveying (Cooper, 2021; Goodrich, 2025), particularly in complex environments such as the Arctic (NOAA, 2016). International best practices, including those promoted by the International Hydrographic Organization (IHO), S-44 Standards (IHO, 2024b), B-12 and B-13 publications (IHO, 2022, 2024a), emphasize the need for a multi-technology approach to achieve adequate coverage and data quality in remote and dynamic regions.

Currently, the Canadian Hydrographic Service (CHS) can rely on a range of technologies and methods for Arctic charting, including:

- Multibeam echosounders (MBES) for high-resolution surveys in areas where underkeel clearance is critical;
- Uncrewed surface vehicles (USVs) to act as force multipliers and increase coverage capability;
- Bathymetric LiDAR for shallow-water surveys;
- Satellite-derived bathymetry (SDB) for broad-scale reconnaissance and danger to navigation detection;
- Crowdsourced bathymetry (CSB) to leverage voluntary contributions from vessels of opportunity.

While these approaches collectively improve coverage, they face notable limitations. MBES and LiDAR

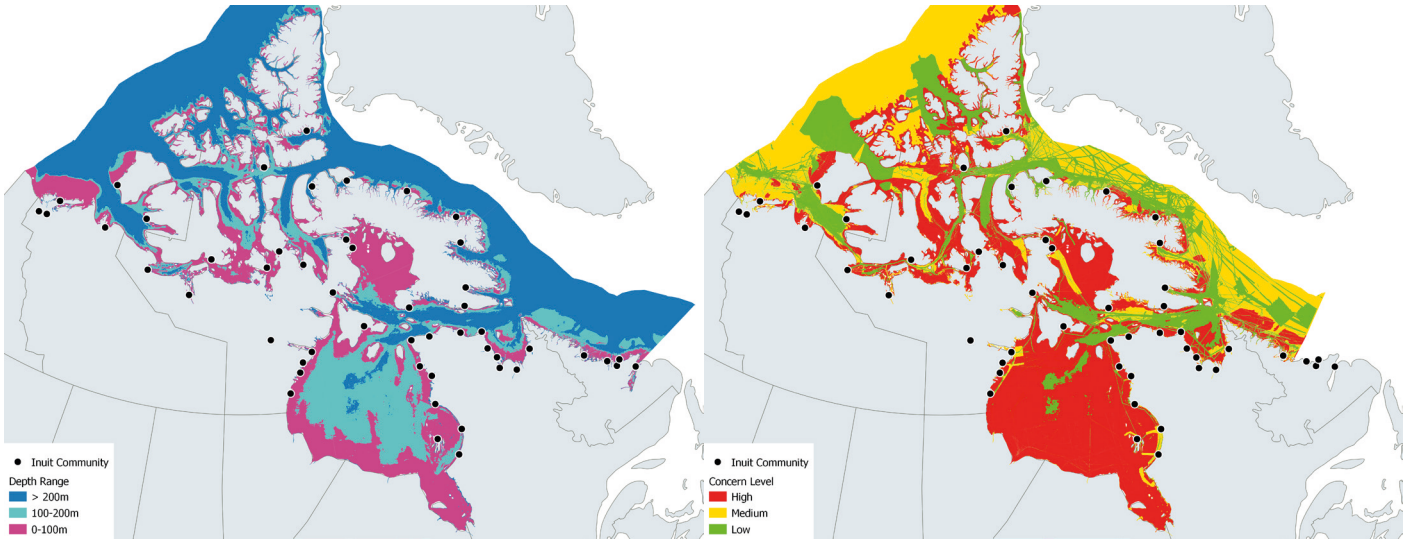


Fig. 1 Canadian Arctic EEZ illustrated according to depth range (left) and to potential concern for navigation (right).

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involve high operational costs and complex mobilization requirements, challenges that are amplified in the Arctic with limited infrastructure for deployments (e.g. ports and airstrips). USVs present attracting advantages in terms of efficiency and operational safety (Bazowsky et al., 2021). However, challenges related to deployment complexity, regulatory constraints, cybersecurity risks, and limitations in autonomous decision-making persist (de Andrade et al., 2025). SDB and CSB show promise (Knudby, 2025 for SDB; Jencks et al., 2024 for CSB), but both are affected by uncertainties that remain difficult to quantify, leading hydrographic offices to restrict their use (Dolou et al., 2020 for SDB; Hains, 2024 for CSB). What other options haven't hydrographic organizations explored for hydrographic surveys in the nearshore of remote areas? What if motivated communities through their attachment to the land they live on and with using simple hydrographic equipment could represent the "True" force multiplier?

This paper introduces Community-Sourced Bathymetry as a promising addition to the Arctic hydrography toolbox. This new approach, developed in the following section, involves engaging Inuit communities, already established across Inuit Nunangat (Inuit homeland in Canada), to conduct bathymetric surveys in areas of interest using standard navigation instruments and applying basic hydrographic principles. In an era where hydrography is increasingly driven by technological innovation, this pragmatic approach – aligned with international trends toward participatory science and local capacity building – helps address gaps left by conventional technologies while supporting Inuit aspirations for active involvement in Inuit Nunangat charting, a foundational layer for future development and policy decisions (ITK, 2023).

2 Method

The Community-Sourced Bathymetry approach stems from work carried out under the CHS Community Hydrography Program (DFO, 2026; Rondeau et al., 2024) which has generated strong interest and engagement within Inuit communities specifically.

This approach shares common ground with crowdsourced bathymetry in that it relies on standard instruments and involves non-experts in hydrography. However, it goes further by emphasizing community engagement and capacity building, and directing deployments toward priority areas that are poorly surveyed or entirely unsurveyed.

The International Hydrographic Organization defines crowdsourced bathymetry (CSB) in its B-12 publication (IHO, 2022) as *the collection and sharing of depth measurements from vessels, using standard navigation instruments, while engaged in routine maritime operations.*

This definition offers certain advantages that are retained in the proposed approach, such as the use of standard navigation instruments and the principle that recognizes and encourages the contribution of bathymetric data from non-institutional sources. However, collecting bathymetric data during routine maritime operations presents clear limitations, as the observed collection patterns are suboptimal from a hydrographic perspective. First, CSB platforms often generate substantial measurements "noise". Causes can be attributed to: bottom tracking loss due to high speed or sudden depth change, cavitation under transducer, sensor interference or poorly adjusted sonar parameters. Second and more importantly, data collection tends to follow the main navigation routes and concentrate in areas where charting products already exist, leaving critical gaps in unsurveyed regions. In Canada, most of the CSB data available in the IHO Data Centre for Digital Bathymetry (DCDB) are located along the St-Lawrence River, the Great Lakes corridor and the Juan de Fuca Strait, leaving the Arctic largely untouched except for a single contribution in the Northwest Passage – which further illustrates the spatial bias toward major navigation routes mentioned earlier – and a few additional datasets on the northeastern coast of Baffin Island (Fig. 2).

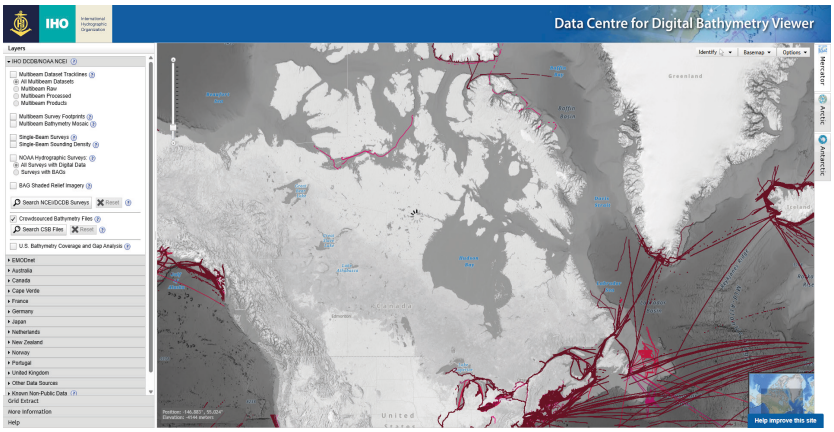


Fig. 2 CSB data available in the IHO DCDB for Canadian waters[1]. Note the very few contributions in the Canadian Arctic specifically.

Community-Sourced Bathymetry therefore proposes adapting the IHO definition by shifting from opportunistic data collection to directed data collection (Fig. 3). Community-Sourced Bathymetry can be defined as *the collection of depth measurements from community vessels, using calibrated standard navigation instruments and following basic hydrographic principles while engage in dedicated survey operations.*

The Community-Sourced Bathymetry approach can be broken down into six main operational tasks:

1. Support and capacity building. Assess local capacity and needs, outfit community boats with standard navigation instruments and data loggers, measure lever-arms – with particular attention to the sonar's draft measurement – and train the local survey crews.

[1] https://www.ncei.noaa.gov/maps/iho_dcdb/ (last accessed 15 January 2026).

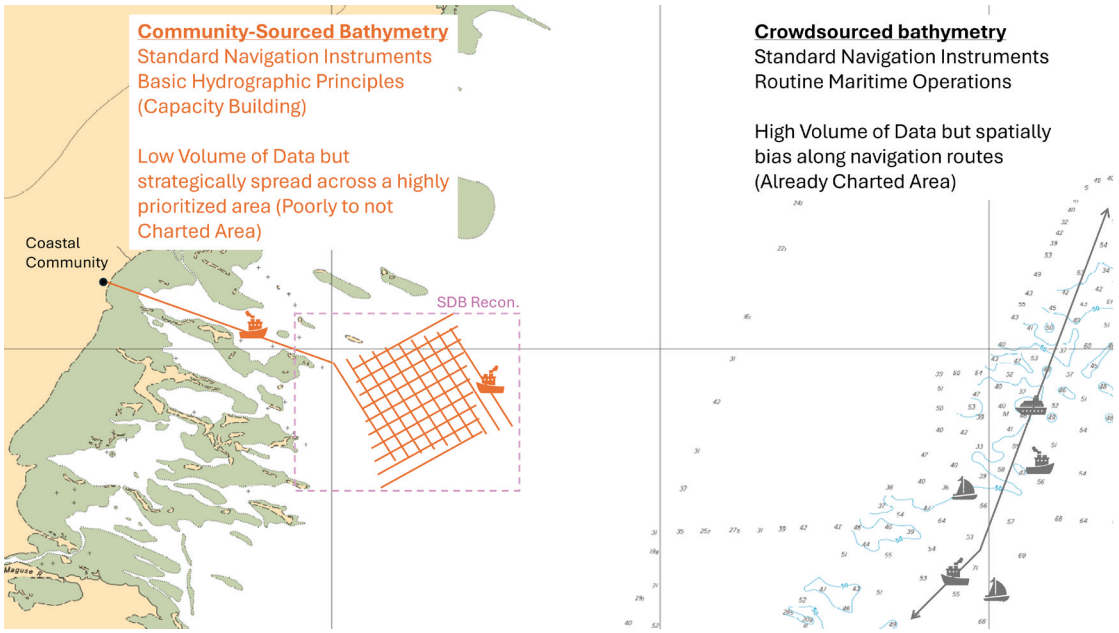


Fig. 3 Conceptual schema showing the distinction between crowdsourced bathymetry and Community-Sourced Bathymetry.

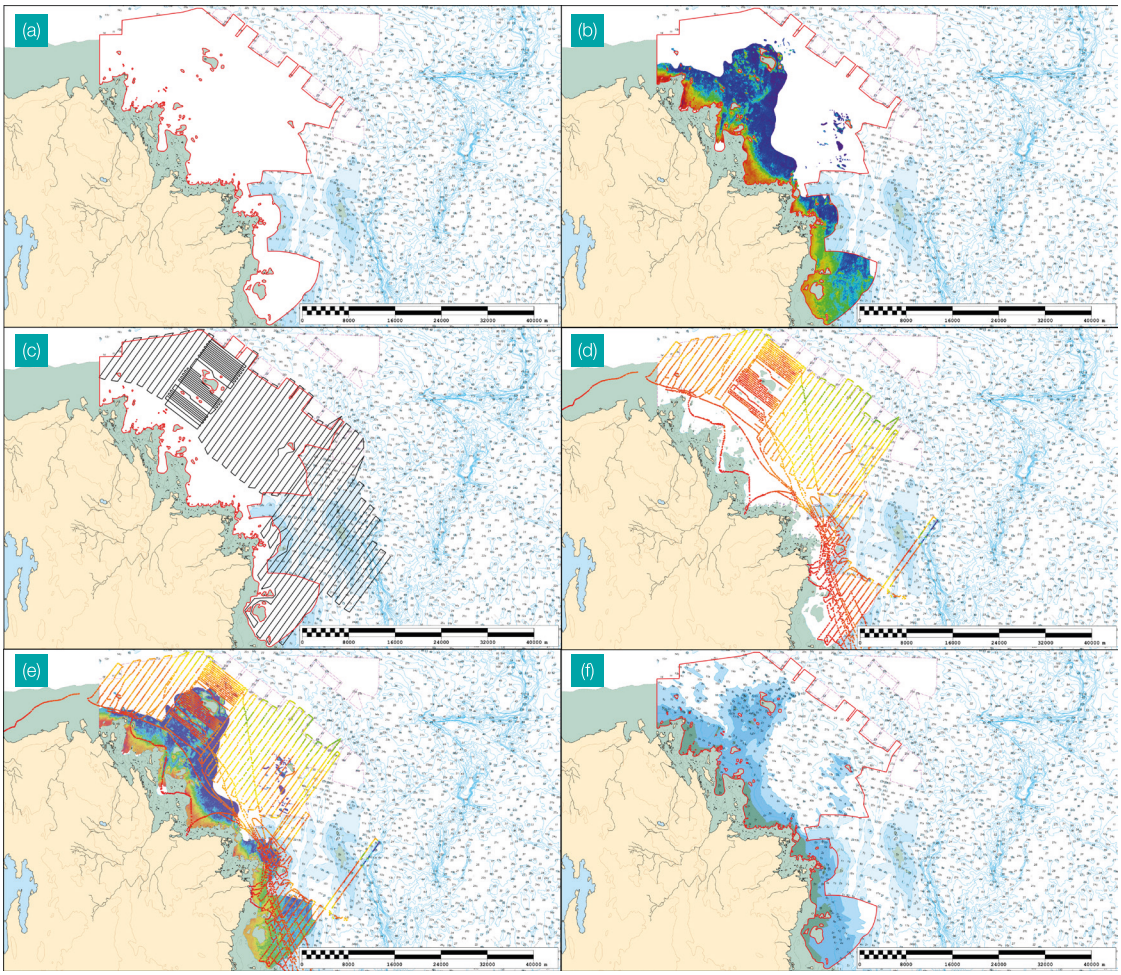


Fig. 4 (a) Area of interest outlined in red (240 km2) shown as unsurveyed/uncharted on the CHS official product; (b) SBD reconnaissance survey; (c) Risk-assessed systematic survey grid; (d) Bathymetric data collected by the two local survey crews; (e) SDB and Community-Sourced Bathymetry overlaid; (f) Community map overlaid on the CHS official product.

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Table 1 Datasets characteristics.

Attribute	Community-Sourced Bathymetry datasets	CHS historical single-beam datasets
Geographical extent	Canada	Canadian Arctic
Depth range	0–100 m	0–100 m
Survey period	2023–2025	1952–2014
Technique of positioning measurement	Integrated GNSS receiver in "off-the-shelf" bathymetric equipment (fish finder)	Miscellaneous (sextant, LORAN A & LORAN C, Decca, Mini Ranger, Microfix, GNSS to name a few)
Technique of sounding measurement	"Off-the-shelf" bathymetric equipment (fish finder)	Single-beam echosounder
Shoal detection by SDB ahead of survey	Yes	No
Shoal examination (star pattern) during survey	No	Yes
Total submitted to the peer-consistency (*n* datasets)	19	586
Total passed the peer-consistency (*n* datasets)	13	359

2. Survey planning and preparation. Task an SDB[2] reconnaissance survey over the areas of interest, identify shallow hazards (dangers to navigation), and design tailored, risk-assessed (informed by SDB) systematic survey grids adapted to expected depth variability and boats capabilities.
3. Community-Sourced Bathymetry data collection. Conduct bathymetric data collection over the areas of interest, following the systematic survey grids at an appropriate survey speed.
4. Bathymetric data processing and qualification. Perform tidal/water-level reduction[3], filter outliers, assess Total Vertical Uncertainty (TVU) per-sounding[4].
5. SDB calibration using Community-Sourced Bathymetry (optional). Adjust and refine the initial SDB depth model (from Step 2) using the validated *in situ* bathymetric data collected by the local survey crews[5].
6. Quality evaluation and integration. Assess data quality using peer-comparison tools, verify consistency with existing datasets, populate metadata, and integrate validated data into navigational products.

Below is an overview of how the Community-Sourced Bathymetry approach was applied in the Asuqaaq area at the mouth of the Koksoak River by two survey crews from the Inuit community of Kuujjuaq (QC) (Fig. 4).

3 Data

Over the past three years, projects have been initiated by the CHS Community Hydrography Program. Dataloggers have been logging a significant amount of bathymetric data – some collected opportunistically (passage survey as define by the IHO) during transit between communities or while traveling for harvesting, fishing and hunting, and some collected systematically (systematic survey as define by the IHO) in specific areas. All data were processed and transformed into community maps, which were disseminated to the communities through Transport Canada's Enhanced Maritime Situational Awareness App (TC, 2025a) and the Arctic Eider Society's SIKU App (Segal et al., 2025). The practicality and accessibility of the approach have resonated within Inuit communities.

Among all the data collected since 2023, four use cases illustrate remarkably well the Community-Sourced Bathymetry approach defined previously: Paulatuk (NT), Inukjuak (QC), Kuujjuaq (QC) and Umiujaq (QC). In these communities, Inuit crews were able to collect data from predefined survey line patterns.

As described in the method, local survey crews used small community boats outfitted with "off-the-shelf" bathymetric equipment (fish finders). Teams were asked to follow predefined line patterns, maintain speed under 10 knots, monitor sonar signal loss and restrain data acquisition in adverse sea conditions (Fig. 5).

Although they are not hydrography experts, the bathymetric data collected by the four Inuit crews, once processed and assessed, compare favorably with single-beam echo sounder data collected by CHS in the 1990s.

4 Results

To demonstrate that data collected in the 2020s by non experts using "off-the-shelf" bathymetric equipment (fish finders) and applying basic hydrographic principles can compare in terms of quality with data collected in the 1990s by CHS, a quantitative study, presented below, was conducted.

The study involves submitting to a peer consistency assessment, (1) the Community-Sourced Bathymetry (CoSB) datasets (*n* = 19) produced since the launch

[2] At CHS, SDB activities are overseen by the internal Remote Sensing Centre of Expertise.

[3] Processing is performed using a dedicated tool developed at CHS (Bilodeau, 2025), which is made available as open-source.

[4] TVU assessment is performed using a dedicated calculation developed in collaboration with University of New-Brunswick (Muthusamy et al., 2025).

[5] Community-Sourced Bathymetry and SDB are complementary. Community-Sourced Bathymetry provides the ground-truth measurements needed to validate and calibrate SDB in areas where uncertainty is otherwise difficult to assess, while SDB complements Community-Sourced Bathymetry by extending spatial coverage between survey lines in shallow waters (up to ~15 m).

Table 2 Statistics of average consistency with MBES reference for CoSB and CHS CATZOC B SBES datasets.

	RMSE	MAE	Weighted mean	Std. dev.
CoSB	0.81	0.60	+0.18	1.27
CHS CATZOC B	2.32	0.95	-0.53	1.66

of the Community Hydrography Program (2023), as well as (2) historical single-beam (SBES) surveys (*n* = 586) collected in the Canadian Arctic nearshore (0-100m depth range) by CHS since the 1950s.

To this end, a systematic quantitative analysis was carried out based on a peer comparison script. This script evaluates each submitted dataset by comparing it with reference surveys. A reference survey is defined as one that:

1. overlaps (even partially) with the dataset being evaluated;overlaps (even partially) with the dataset being evaluated;
2. was conducted using a multibeam echosounder (MBES);
3. has been assigned a Category of Zone Of Confidence (CATZOC) A1 or A2 as defined in the IHO, S-68 Standards (IHO, 2025); and
4. is validated for integration into official charts.

All datasets were reduced to chart datum prior to comparison to ensure vertical consistency. Reference MBES surveys are stored as gridded surfaces, whereas CoSB and SBES datasets consist of point soundings. The comparison is therefore performed by matching each evaluated sounding to the corresponding depth value from the MBES reference grid. Surface differencing was conducted using Teledyne CARIS Base Editor software, with the MBES grid defining the spatial reference framework. Horizontal matching tolerance is thus implicitly controlled by the grid resolution.

For each dataset, depth differences between evaluated soundings and reference surfaces were computed and summarized by key statistics such as the mean of differences, median of differences, and standard deviation of differences. The distribution of residuals provides an empirical estimate of overall consistency.

The characteristics of the datasets that passed the peer comparison step (i.e., those for which at least one reference survey was identified) are presented in Table 1.

Among the datasets submitted to the peer-consistency assessment, 13 Community-Sourced Bathymetry datasets and 359 CHS historical single-beam datasets show overlap with MBES reference surveys. The quantitative consistency analysis conducted shows that Community-Sourced Bathymetry datasets exhibit a level of agreement with the MBES reference that places them in the 61th percentile of the CHS historical datasets when classified from 1 (very poor fit) to 100 (very good fit) (Fig. 6). On a historical perspective, when CHS single-beam datasets are split by decade (1950s–2010s), the results indicate that Community-Sourced Bathymetry surveys outperform CHS single-beam surveys from the 1950s-80s, match the performance of 1990s CHS single-beam surveys, but underperform compared to CHS single-beam surveys conducted since 2000s (Fig. 7). On a data quality perspective, when CHS single-beam datasets are split by CATZOC (B, C, D), the results indicate that Community-Sourced Bathymetry surveys demonstrate



Fig. 5 (a) Locations of the four use cases: Paulatuk (NT), Inukjuak (QC), Kuujjuaq (QC) and Umiujaq (QC); (b) Community boat in Kuujjuaq (QC); (c) Survey line pattern displayed on a community boat's fish-finder; (d) WIBL[6] bathymetric datalogger.

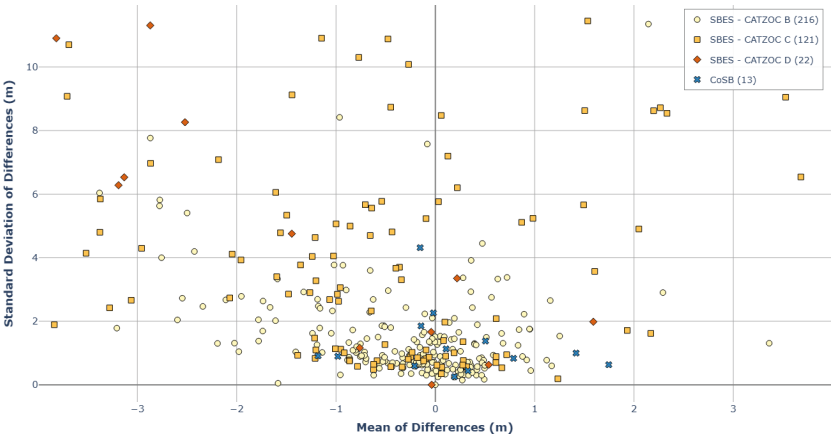


Fig. 6 Scatter plot for CHS single-beam datasets (SBES), split by CATZOC, alongside Community-Sourced Bathymetry datasets (CoSB). The figure is intentionally zoomed to the CoSB data extent; as a result, portions of the CHS SBES datasets lie outside the displayed area.

[6] The Wireless Inexpensive Bathymetry Logger (WIBL) project was initially developed at The Center for Coastal and Ocean Mapping/NOAA-UNH Joint Hydrographic Center at the University of New Hampshire, with grant support from NOAA. See project web page https://wibl.ccom.unh.edu/index.html (last accessed 23 April 2026).

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performances consistent with the range of CHS SBES CATZOC B surveys (Figs. 8 and 9). This comparison is based solely on the "Depth accuracy" criterion, from among the broader set of criteria defined in the IHO S-68 Guidelines for CATZOC allocation.

Table 2 summarizes the key statistics to support comparison between Community-Sourced Bathymetry and CHS CATZOC B single-beam datasets. The error statistics show that Community-Sourced Bathymetry agrees more closely with the reference depths than CHS CATZOC B datasets, both in overall accuracy and consistency. Community-Sourced Bathymetry has a lower Root Mean Square Error (RMSE) (0.81) and lower Mean Average Error (MAE) (0.60), indicating smaller typical vertical differences and fewer large mismatches than CHS CATZOC B datasets (RMSE 2.32, MAE 0.95). The fact that CHS CATZOC B's RMSE is much larger than its MAE suggests the presence of occasional outliers (since RMSE penalizes large deviations more strongly). The weighted mean reflects systematic bias in the signed residuals. Community-Sourced Bathymetry's +0.18 indicates a slight tendency toward deeper depths than the reference, while CHS CATZOC B's -0.53 indicates a tendency toward shallower depths. Finally, the standard deviation confirms that Community-Sourced Bathymetry residuals are more tightly clustered (1.27) than CHS CATZOC B datasets (1.66), meaning Community-Sourced Bathymetry is not only more accurate on average, but also more consistent across the area.

The quantitative analysis presented in this study is subject to several limitations that warrant explicit consideration.

First, the evaluation framework assumes that the reference datasets – MBES surveys categorized as CATZOC A1/A2 and qualified as validated – are treated as a high-confidence reference standard. Under this assumption, all discrepancies identified by the peer comparison tool are attributed solely to the dataset under evaluation. This premise is inherently imperfect, particularly in Arctic environments, where temporal advances in positioning systems and sonar technology, refinement of water level separation models, and the presence of dynamically changing seabed conditions introduce uncertainties that limit the absolute reliability of historical MBES data. As such, these reference datasets, while of high quality, cannot be considered fully invariant benchmarks.

Second, the volume of Community-Sourced Bathymetry data available for analysis remains relatively modest (13 datasets). Although the results indicate a positive and encouraging trend in dataset quality, achieving stronger statistical robustness will require an increase in both the number and geographic diversity of community sourced surveys.

Third, the analysis intentionally does not apply weighting based on the number of soundings contributing to each comparison. Accordingly, a dataset evaluated using only two soundings contributes equally to the final synthesis (Figs. 6–8) as a dataset evaluated with 10,000 soundings. This methodological choice was made to avoid introducing subjective weighting biases that would systematically favor more recent surveys – typically characterized by higher sounding density – over older datasets from the 1950s–1960s–1970s. While unweighted aggregation simplifies interpretation and avoids temporal bias, it does reduce sensitivity to dataset specific robustness.

Despite these limitations, the analysis offers a first-order assessment of the data holdings available in remote Canadian Arctic regions. By adopting a conservative but consistent evaluation framework, the comparison offers a sound basis for understanding the relative performance of Community-Sourced Bathymetry and CHS historical surveys.

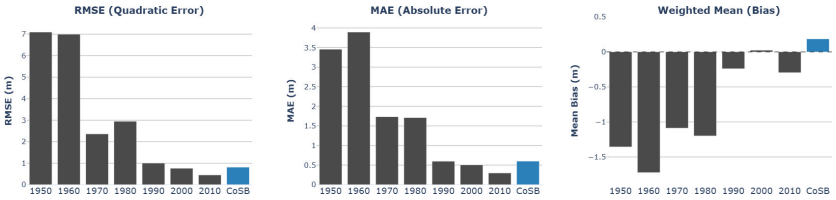


Fig. 7 Key statistics for CHS single-beam datasets (SBES), split by decade, alongside Community-Sourced Bathymetry datasets (CoSB).

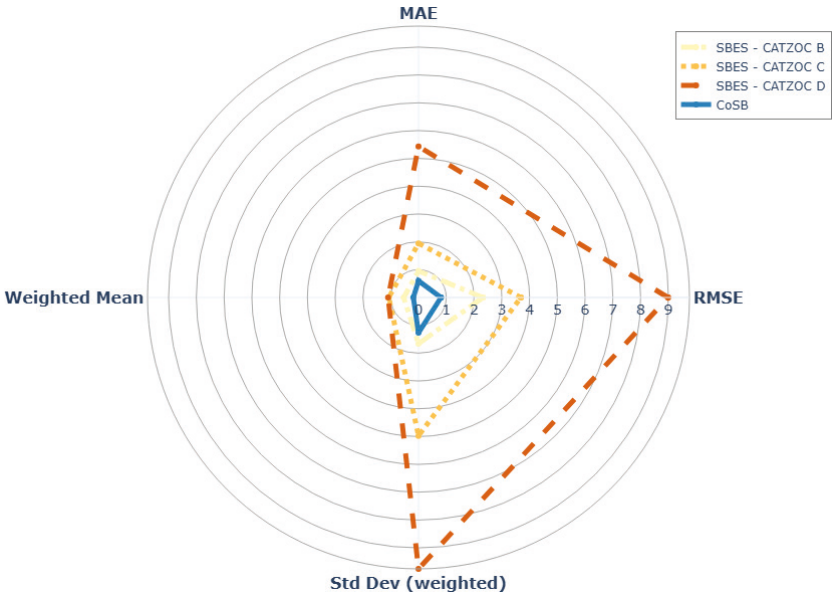


Fig. 8 Radar plot for CHS single-beam datasets (SBES), split by CATZOC, alongside Community-Sourced Bathymetry datasets (CoSB).

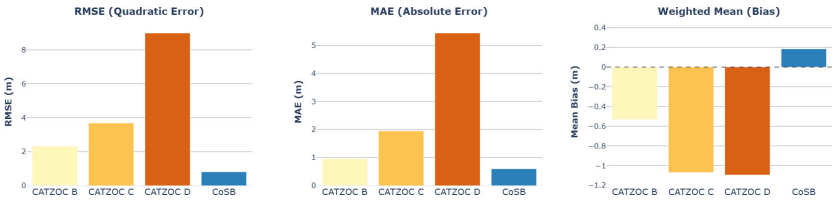


Fig. 9 Key statistics for CHS single-beam datasets (SBES), split by CATZOC, alongside Community-Sourced Bathymetry datasets (CoSB).

5 Discussion

Inuit have lived in and occupied Inuit Nunangat since

time immemorial. Inuit Tapiriit Kanatami (ITK) has recently articulated the vision of Inuit for involvement in Arctic sovereignty, security, and defence (ITK, 2025). Specifically for the maritime Arctic, Inuit express their desire to play a central role: to be consulted, involved in priority-setting, and have local knowledge recognized and valued. They seek safe access for harvesting, effective monitoring, and robust search and rescue (SAR) capabilities, all of which require improved charting of the nearshore.

In the Canadian Arctic, CHS's charting approach focuses on navigation corridors to support commercial shipping, such as sea-lift, to resupply northern communities. Within these corridors, charting quality, as defined in the IHO, S-67 Standards (IHO, 2020), is good (CATZOC A1–A2) based on modern multibeam bathymetric data. Outside the corridors, however, charting quality is typically lower (CATZOC C or D), relying on historical bathymetric data collected over many decades using a range of evolving techniques – from sextant and leadline to GNSS and single beam echosounder – but always with a focus on identifying and examining shoals to support navigation safety.

While the proposed Low Impact Shipping Corridors (LISC) co-developed by Transport Canada and CHS with Inuit communities (Dawson et al., 2019; TC, 2025b) represent an important step toward enhancing safety of community resupply (sealift) and commercial shipping, they primarily focus on established maritime transit routes. As a result, several community-relevant needs remain outside the current scope of the LISC framework, including:

- Search and rescue (SAR) operations in the nearshore
- Safe inter-community marine transit
- Local economic development (e.g. fishing, hunting)
- Establishment and management of marine protected areas
- Environmental response (e.g. oil spill)

The Arctic nearshore – used heavily for fishing, hunting, and inter-community transit – is vital for Inuit coastal communities and other Arctic water users (e.g. Commercial shipping sector, Canadian Coast Guard and Canadian Coast Guard Auxiliary, Department of National Defence, Royal Canadian Navy, Transport Canada, Parks Canada, Scientists, Fisheries industry, Cruise tourism operators, and Recreational boaters). Better knowledge of nearshore seafloor could:

- Enhance Arctic navigation safety
- Increase community resilience (i.e. socially, economically, environmentally)

Inuit in Canada have shown strong interest in participating in seafloor mapping initiatives (ITK, 2023). Four of the 51 communities in Inuit Nunangat have already demonstrated their capacity to collect bathymetric data favorably comparable to CHS historical single beam echo sounder datasets acquired in the 1990s, including at distances of up to 100 km from

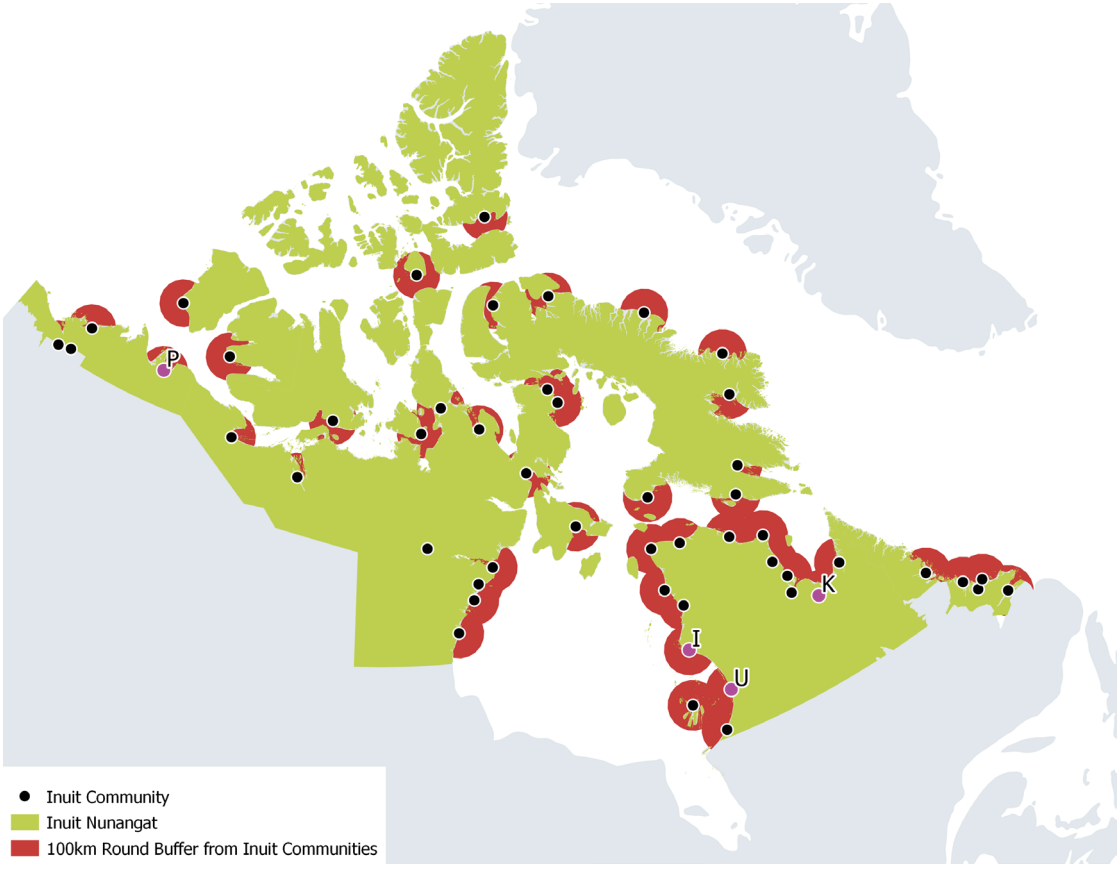


Fig. 10 Extent of areas in Inuit Nunangat reachable from Inuit communities within a 100 km travel range and suitable for implementation of the Community-Sourced Bathymetry approach. The communities of Paulatuk (NT), Inukjuak (QC), Kuujjuaq (QC) and Umiujaq (QC) are shown in pink.

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their home communities. If all communities across Inuit Nunangat were to deploy community boats equipped with standard navigation instruments following the Community-Sourced Bathymetry approach described earlier, up to 16 % of Canada's coastal zone within the 0–200 m depth range could be mapped up to a CATZOC B quality level (Fig. 10). This increased coverage would reduce the potential concern for navigation in these areas from high to medium. It is important to note, however, that achieving this level of coverage in practice would depend on several factors, including logistical feasibility and local capacity to implement and sustain such initiatives across all communities. The figure should therefore be viewed as an aspirational estimate rather than a guaranteed outcome.

The governance model surrounding the involvement of Inuit communities in supporting coastal mapping in the Arctic region has not been examined in this study. The focus here was solely on demonstrating the potential – both in terms of data quality and coverage capability – of the Community-Sourced Bathymetry approach. Questions related to the distribution of roles and responsibilities, funding and capacity building for survey teams, as well as data control and data sharing, will need to be addressed in future work.

6 Conclusion

This study highlights the potential of Inuit communities to contribute meaningfully to Arctic nearshore mapping through the Community-Sourced Bathymetry approach. Using common, commercially available navigation instruments and applying basic hydrographic principles – i.e., measuring sensor offsets (with particular attention to sonar draft), following systematic survey grids, operating at appropriate survey speeds (<10 kt), and applying tidal or water-level reductions – Inuit survey crews produced bathymetric data comparable to CHS historical single-beam surveys (1990s) still used in many Arctic charting products.

This demonstrates that locally operated vessels, when supported with training, planning tools, and appropriate quality control procedures, can play a role in addressing long standing charting gaps. Beyond the technical results, the approach strengthens local capacity, supports Inuit priorities for safety, sovereignty, and environmental stewardship, and fosters deeper collaboration between CHS and northern communities.

While expanding the number and geographic distribution of surveys would be essential to reinforce statistical robustness, the early results are promising. Community-Sourced Bathymetry offers a scalable, cost effective, and community driven model that can enhance Arctic hydrography and increase the resilience and safety of those who rely on these waters.

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References

Bazowsky, D., Mallace, D., Day, M. and MacKenzie, R. (2021). Autonomous Survey in Northern Environments. *The International Hydrographic Review, 25*. https://ihr.iho.int/articles/autonomous-survey-in-northern-environments (last accessed 23 April 2026).

Bilodeau, Y. (2025). *CHS-CSB-Processing: Tools for processing crowdsourced bathymetry (CSB) data for the Canadian Hydrographic Service*. https://doi.org/10.5281/zenodo.17534827

Chénier, R., Abado, L. and Jirovec, A. (2022). CHS priority planning tool – A GIS to prioritize data gaps. *The International Hydrographic Review, 28*, 238–242. https://doi.org/10.58440/ihr-28-n13

Cooper, B. (2021). Effectively Mapping and Charting of Remote Locations with Satellites, Lasers and Acoustics. *The International Hydrographic Review, 26*. https://ihr.iho.int/articles/effectively-mapping-and-charting-of-remote-locations-with-satellites-lasers-and-acoustics/ (last accessed 23 April 2026).

Dawson, J., Carter, N., Van Luijk, N., Parker, C., Weber, M., Cook, A., Grey, K. and Provencher, J. (2019). Infusing Inuit and local knowledge into the Low Impact Shipping Corridors: An adaptation to increased shipping activity and climate change in Arctic Canada. *Environmental Science & Policy, 105*, 19–36. *https://doi.org/10.1016/j.envsci.2019.11.013*

de Andrade, E. M., Sales, J. S. and Fernandes, A. C. (2025). Operative Unmanned Surface Vessels (USVs): A Review of Market-Ready Solutions. *Automation, 6*(2), 17. https://doi.org/10.3390/automation6020017

Devereaux, D., Murphy, J. and Buesseler, B. (2025). *Arctic Hydrographic Risk Assessment 2025 Update*. 15th Conference of the Arctic Regional Hydrographic Commission (ARHC), Anchorage & Nome, Alaska, USA, 8–10 September 2025.

Dolou, H., Laporte, J., Avis, J. and Arino, O. (2020). Thirty years of satellite derived bathymetry – The charting tool that hydrographers can no longer ignore. *The International Hydrographic Review, 24*, 129–154. https://ihr.iho.int/articles/thirty-years-of-satellite-derived-bathymetry-the-charting-tool-that-hydrographers-can-no-longer-ignore/ (last accessed 23 April 2026).

DFO (2025). *About the Canadian Hydrographic Service*. Department of Fisheries and Oceans Canada (DFO), Government of Canada, Canada. https://www.charts.gc.ca/

help-aide/about-apropos/index-eng.html#legal (last accessed 23 April 2026).

DFO (2026). *Community hydrography*. Department of Fisheries and Oceans Canada (DFO), Government of Canada, Canada. https://www.dfo-mpo.gc.ca/science/hydrography-hydrographie/opp-ppo/index-eng.html (last accessed 7 January 2026).

Goodrich, K. (2025). Beyond either/or: integrating hydrographic technologies for a data-driven future. *Hydro International*. https://www.hydro-international.com/content/article/beyond-either-or-integrating-hydrographic-technologies-for-a-data-driven-future (last accessed 1 October 2025).

Hains, D., Keating, S. G., Rathnayake, C., Obura, V., Sharma, S. and Hall, S. (2024). Citizen hydrospatial sciences – To csB or not to csB, that is the question! *The International Hydrographic Review, 30*(1), 162–170. https://doi.org/10.58440/ihr-30-1-n02

HDACoE (2025). *CHS Bathymetric Gap Analysis 2025*. Hydrographic Data Access Centre of Expertise, Canadian Hydrographic Service, Canada.

IHO (2020). *Mariners' Guide to Accuracy of Depth Information in Electronic Navigational Charts (ENC)* (1st ed.). IHO Special Publication S-67, International Hydrographic Organization, Monaco. https://iho.int/uploads/user/pubs/standards/S-67/S-67%20Ed%201.0.0%20Mariners%20Guide%20to%20Accuracy%20of%20Depth%20Information%20in%20an%20ENC_EN.pdf (last accessed 23 April 2026).

IHO (2022). *Guidance to crowdsourced bathymetry* (3rd ed.). IHO Publication B-12, International Hydrographic Organization, Monaco. https://iho.int/uploads/user/pubs/bathy/B_12_CSB-Guidance_Document-Edition_3.0.0_Final.pdf (last accessed 23 April 2026).

IHO (2024a). *Guidance to Satellite-derived Bathymetry* (1st ed.). IHO Publication B-13, International Hydrographic Organization, Monaco. https://iho.int/uploads/user/pubs/bathy/B_13_Ed100_032024.pdf (last accessed 23 April 2026).

IHO (2024b). *Standards for Hydrographic Surveys* (ed. 6.2.0). IHO Special Publication S-44, International Hydrographic Organization, Monaco. https://iho.int/uploads/user/pubs/standards/s-44/S-44_Edition_6.2.0_adopted.pdf (last accessed 23 April 2026).

IHO (2025). *Guidelines and Recommendations for Hydrographic Offices for the Allocation of CATZOC/QOBD Values from Survey Data*. IHO Special Publication S-68, International Hydrographic Organization, Monaco. https://iho.int/uploads/user/pubs/standards/S-68/S-68_Guidelines_Allocation_of_CATZOC_Ed_1.0.0.pdf (last accessed 23 April 2026).

IHO (2026). *Status of Hydrographic Surveying and Charting Worldwide*. IHO Capacity Building Publication C-55, International Hydrographic Organization, Monaco. https://iho.int/en/iho-c-55 (last accessed 23 April 2026).

ITK (2023). *The oceans that we share: Inuit Nunangat Marine Policy Priorities and Recommendations*. Inuit Tapiriit Kanatami, Ottawa, Canada. https://itk.ca/wp-content/uploads/2023/03/20230322-Marine-Policy-Paper-FINAL-SIGNED.pdf (last accessed 23 April 2026).

ITK (2025). *An inuit vision for Arctic sovereignty, security and defence*. Inuit Tapiriit Kanatami, Ottawa, Canada. https://www.itk.ca/wp-content/uploads/2025/06/An-Inuit-Vision-for-Arctic-Sovereignty-Security-Defence.pdf (last accessed 23 April 2026).

Jencks, J. and Baron, B. J. (2024). CSB as part of the modern hydrographic toolbox. *The International Hydrographic Review, 30*(1), 150–160. https://doi.org/10.58440/ihr-30-1-n03

Knudby, A. (2025). Satellite imagery for hazard detection: Better use of satellite imagery could help prevent groundings in the Canadian Arctic. *The International Hydrographic Review, 31*(2), 30–43. https://doi.org/10.58440/ihr-31-2-a13

Muthusamy, P., Church, I., Rondeau, M., Bilodeau, Y. and Breton, M. (2025). Crowd-Sourced Bathymetry vertical uncertainty calculation per sounding. *Abstracts of the ICA, 10*, 1–2. https://doi.org/10.5194/ica-abs-10-209-2025

NOAA (2016). *Arctic charting: Mapping a new frontier*. National Oceanic and Atmospheric Administration, U.S. Department of Commerce, USA. https://www.noaa.gov/explainers/arctic-charting-mapping-new-frontier (last accessed 23 April 2026).

Rondeau, M., Breton, M., Montpetit-Allard, G., Leger, M., Bilodeau, Y. and Kasudluak, J. (2024). From volunteer ping to community map - The CHS' Community Hydrography Program. *The International Hydrographic Review, 30*(1), 64–77. https://doi.org/10.58440/ihr-30-1-a07

Segal, R., Sudlovenick, C., Heath, J., Warner, E., Beale, S. and Chapman, M. (2025). Mapping with SIKU – The Indigenous Knowledge App for environmental data access, land safety, and knowledge sharing across the North. *Abstracts of the ICA, 10*, 1–2. https://doi.org/10.5194/ica-abs-10-255-2025

TC (2025a). *Expanding the Enhanced Maritime Situational Awareness program*. Transport Canada, Government of Canada, Canda. https://tc.canada.ca/en/campaigns/protecting-our-coasts-oceans-protection-plan/stronger-partnerships-indigenous-coastal-communities/expanding-enhanced-maritime-situational-awareness-program#about-enhanced (last accessed 23 April 2026).

TC (2025b). *Northern Low-Impact Shipping Corridors Initiative*. Transport Canada, Government of Canada, Canda. https://tc.canada.ca/en/campaigns/protecting-our-coasts-oceans-protection-plan/stronger-partnerships-indigenous-coastal-communities/northern-low-impact-shipping-corridors-initiative (last accessed 23 April 2026).

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Authors' biographies

Mathieu Rondeau holds a bachelor's degree in surveying engineering from l'École Supérieure des Géomètres et Topographes (Le Mans, France) and a master's degree in geomatics sciences from Laval University (Quebec, Canada). From 2009 to 2018, he worked for the Interdisciplinary Centre for the Development of Ocean Mapping (Canada), where he gained most of his expertise in hydrographic surveying. Since 2018, he has been employed by the Canadian Hydrographic Service. For the past four years, he has been an integral member of the Community Hydrography Program team, supporting coastal communities in the collection and use of bathymetric data.



Mathieu Rondeau

Gabriel Montpetit-Allard began his career as environment and wildlife technician in the private sector. He later obtained a bachelor's degree in physical geography from the Université du Québec à Rimouski. From 2006 to 2018, he gained professional experience in operational sciences in the private and academic sectors. He then joined the Canadian Hydrographic Service team in 2019. Since 2023, he supervises the bathymetric data acquisition and community outreach unit of the Community Hydrography Program. Through this program, the Community Hydrography team seeks to support coastal communities in their goals to collect, process and use bathymetric data.



Gabriel Montpetit-Allard

Yan Bilodeau, holding a Bachelor's degree in Geography from the Université du Québec à Montréal, joined the Canadian Hydrographic Service in 2017 as a multidisciplinary hydrographer. In 2019, he transitioned into the role of a geomatics specialist within the Geomatics and Technical Support team, focusing on automation projects and contributing to the development of bathymetric data processing and integration pipelines. Since 2023, Yan has been an integral member of the Community Hydrography Program team, dedicated to assisting coastal communities across Canada in collecting and utilizing bathymetric data.



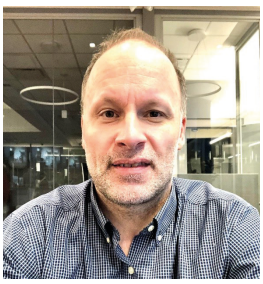
Yan Bilodeau

Jérémie Lemarchand holds a PhD in Earth Sciences and a DESS in Geomatics from the Université du Québec à Montréal. He began his career in hydrography and marine geomatics in 2018, working in the LDGIZC coastal geomorphology laboratory at the Université du Québec à Rimouski. In 2023, he joined the Canadian Hydrographic Service as a member of the Community Hydrography Program team. His work focuses on data processing and support for data acquisition, with an emphasis on meeting community objectives.



Jérémie Lemarchand

Michel Breton has 15 years of experience with the Canadian Hydrographic Service (CHS). Michel initially worked as multidisciplinary hydrographer surveying and charting the west coast of Canada. Over time, a knack for innovation and data management led him onto projects meant at improving data integration in the organization. Since 2019, Michel has been involved in the digital transformation initiative at the CHS, with S-100 implementation, and more recently with crowdsourced bathymetry data. Michel is currently managing the Community Hydrography Program, a program designed to enable coastal communities in Canada to collect and utilize bathymetric data. Michel is representative for Canada on the International Hydrographic Organization (IHO) Crowdsourced Bathymetry working Group (CSBWG).



Michel Breton

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The 12th Conference of the IHO–IAG Advisory Board on the Law of the Sea – foreword to selected conference contributions in IHR


Luigi Sinapi

It is a pleasure and an honour, in my capacity as Director of the International Hydrographic Organization (IHO) and as a member of the IHO delegation to the 12th Conference of the IHO–IAG Advisory Board on the Law of the Sea (ABLOS), to introduce this selection of conference contributions published in The International Hydrographic Review (IHR).

Held in Doha on 7–8 October 2025, and organised in association with the Qatari Standing Committee of the Convention on the Law of the Sea, the 12th ABLOS Conference convened under a unifying and timely theme: *Is UNCLOS Fit for Purpose in Modern Times? Achievements, Challenges and Future Pathways*. More than four decades after the adoption of the United Nations Convention on the Law of the Sea (UNCLOS), the conference provided an exceptional forum for reflecting on its continuing relevance, its adaptability, and the growing demands placed upon it by scientific, technological, environmental, and geopolitical change.

The breadth and depth of the conference programme reflected this reality, reaffirming UNCLOS as the foundational legal framework for ocean governance while engaging with its application across climate change, maritime security, emerging technologies and infrastructure as well as its social and cultural dimensions. These discussions highlighted both the resilience of the Convention and the growing complexity of its implementation in practice.

A strong emphasis was placed on the intersection between law, science, and technology, particularly in relation to the expanding ecosystem of ocean data and observation systems. Advances in hydrography, satellite systems, autonomous platforms, artificial intelligence, and data analytics are transforming how maritime spaces are observed, measured, and governed under UNCLOS. However, these innovations also bring forward important questions of data sharing, privacy, liability, and the need for harmonised international standards, especially as the interface between private sector data and public policy imperatives becomes more pronounced.

The conference also underscored the importance of robust regional and international cooperation frameworks in tackling these challenges, as illustrated by the work of institutions such as the ROPME Sea Area Hydrographic Commission and the CIESM in the Mediterranean and Black Sea, both present during the Conference.

A key message is the central role of technical considerations in the effective implementation of UNCLOS. Maritime delimitation, hydrographic standards, geospatial data integration, and the scientific understanding of ocean space are not ancillary elements but lie at the heart of the Convention's practical operation. These developments nonetheless unfold within its legal framework, which governs how scientific findings are translated into legally relevant determinations, how maritime zones are established, and how ocean space and activities are regulated.

The selected papers published in this issue of IHR reflect these core themes and illustrate the vital contribution that hydrographic and oceanographic knowledge makes to contemporary Law of the Sea discourse.

Several contributions explore how data, its quality, governance, and legal treatment, has become central to modern ocean governance. Andrey Chernov's analysis of evidence and monitoring requirements for alternative fuel bunkering highlights how decarbonisation policies depend on reliable ocean observation systems and clear accountability frameworks. Eva van

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Heukelom examines the growing tension between national legal protections for fisheries data and international cooperation obligations under UNCLOS, a challenge made sharper by the rapid expansion of AI driven monitoring tools. Laura Meyer, Adam Leadbetter, and Peter Burger focus on unlocking private sector ocean data as a global public good, identifying the BBNJ Agreement as an opportunity to extend data sharing practices from national waters to the High Seas.

Other papers underscore the importance of integrated observation and standards in protecting the marine environment. Emily Charry Tissier demonstrates how combining satellite technologies, biological monitoring, and emerging ocean standards can significantly strengthen the protection of marine megafauna across jurisdictions. Tihao Zeng addresses the so called "ocean observation paradox", examining how UNCLOS obligations, climate change impacts, and the emerging plastics treaty converge around the need for coherent monitoring and reporting regimes.

The issue also highlights enduring legal, policy and regulatory challenges that demand both clarity and technical expertise. Tullio Scovazzi's contribution reminds us of the synergies of implementation of UNCLOS with other international instruments and families of international law to ensure effective protection of underwater cultural heritage. Ayo Olugbode's examination of Nigeria's blue economy policy illustrates how national implementation of integrated ocean governance, supported by hydrographic capacity, marine spatial planning, and institutional coordination, remains key to translating international norms into practical national outcomes.

Taken together, these contributions exemplify the intellectual spirit of the 12th ABLOS Conference: critical yet constructive, interdisciplinary in approach, and firmly oriented toward practical solutions. They reinforce several key messages that emerged from the discussions in Doha. First, UNCLOS remains the foundational instrument underpinning the legal order for the seas and oceans, it must however be applied in an evolutive manner that reflects contemporary realities, including climate change and the expanding use of the underwater space. Second, authoritative, timely, and interoperable marine geospatial information is no longer optional – it is essential for legal certainty, environmental stewardship, maritime safety, and sustainable



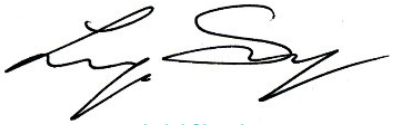
Impressions from 12th ABLOS Conference, Doha, Qatar.

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development. Third, cooperation across disciplines, sectors, and regions is indispensable if we are to avoid fragmentation, regulatory uncertainty, or unequal access to ocean knowledge.

For the IHO, these discussions closely align with our mission to support States in the provision of hydrographic services and standards that enable safe navigation, protect the marine environment, and underpin sound ocean governance. ABLOS, as a unique joint body of the IHO and the IAG, plays in this regard a crucial role in not only convening legal, technical, and scientific communities through conferences but also reflecting on the technical aspects of the Law of the Sea.

It is my hope that this collection in IHR will not only document the outcomes of the 12th ABLOS Conference but also serve as a resource and inspiration for policymakers, legal scholars, hydrographers, and scientists alike. By sustaining an open, informed, and inclusive exchange between law and ocean science, we can help ensure that UNCLOS and the broader system of ocean governance remain fit for purpose in the face of the unprecedented challenges of our time.



Luigi Sinapi
Director and Secretary-General Elect, IHO

CONFERENCE PAPER

Nigeria's blue economy and ocean governance

Author
Ayo Olugbode[1]

Preamble

The following work was presented at the 12th ABLOS Conference, 7–8 October 2025, Doha, Qatar in the oral session *UNCLOS: fit for purpose in modern times.*

Abstract

Sustainable ocean governance is essential for advancing the blue economy by balancing economic growth, environmental protection, and social equity. Global frameworks such as United Nation's Conference on Laws of the Seas (UNCLOS) and Sustainable Development Goal 14 guide nations in managing marine resources, yet many struggle to translate policies into practice due to institutional fragmentation and limited technological capacity. Using Nigeria as a case study, this paper examines the alignment of national blue economy initiatives with international standards, the effectiveness of institutional coordination, and progress in Marine Spatial Planning. It identifies legal gaps, data limitations, and enforcement challenges, and recommends targeted reforms to strengthen implementation and advance ocean governance.

Keywords
blue economy · hydrography · marine spatial planning · ocean governance · policy implementation

1 Introduction

Nigeria is endowed with vast maritime assets that confer on its undeniable maritime credentials within Africa. Bordered by the Atlantic Ocean along the Gulf of Guinea, the nation's maritime environment defines a sovereign territory of about 5,040 square nm, and Exclusive Economic Zone (EEZ) of about 84,000 square nm and an extended Continental Shelf of about 147,000 square nm which is about one third of the total land mass of Nigeria. Additionally, the nation is blessed with the 9th largest delta in the world, covering almost 20,000 square nm and transverse numerous internal navigable rivers. Its inland waterways span over 10,000 kilometres, with about 3,000 kilometres navigable, linking coastal ports to major inland trade hubs. Nigeria's maritime environment is home to huge reserves of living and nonliving natural resources such as fish, shrimps, oil and gas as well as manganese noodles. This rich endowment offers enormous opportunities across diverse sectors, including shipping and maritime transport, fisheries and aquaculture, coastal and cruise tourism, marine biotechnology, offshore renewable energy, and seabed mineral exploration.

Despite these maritime assets, historically exploitation of Nigeria's ocean resources has been sub-optimal, hindered by governance deficits, weak institutional coordination, and limited investment in maritime infrastructure, technologies, data base, human capital, marine science and modern methodologies. Over the years, the Federal Government of Nigeria (FGN) has developed diverse laws, policies and strategies to improve sea-use such as the *Sea Fisheries Act (1992), Cabotage Act (2003), and Merchant Shipping Act (2007), NIMASA Act 2007, and the National Maritime Transport Policy 2021*. It has also continuously ratified international maritime conventions and protocols that bring the nation to speed in the maritime world (Edward, 2023). While these instruments sought to regulate discrete aspects of the maritime sector, they lacked needed cohesion to drive sustainable sea- use. Indeed, without intention, some of these instruments resulted in overlapping mandates and unhelpful inter-agency

✉ Ayo Olugbode · ayo.olugbode@nha.gov.ng
[1] National Hydrographic Agency, Abuja, Nigeria

competition, resource conflicts, as well as missed opportunities for economic diversification and environmental stewardship.

Recognizing these structural gaps and policy inconsistencies, the FGN has had a longstanding aspiration to produce a comprehensive maritime policy and strategy to drive sea-use in furtherance of maritime security and development objectives. This aspiration resulted in the National Maritime Strategy (NMS) of 2023 and lately the National Policy on Marines and Blue Economy (NPMBE) of 2025 which speaks directly to the strategic exploitation of the blue economy. The attainment of the blue economy objectives requires an aggressive and coordinated policy implementation framework. Additionally, the implementation of the blue economy policies requires concerted and integrated factor inputs including deliberate ocean governance approaches. The pertinent questions are: what is the status of blue economy policy implementation in Nigeria; and what is the state of overall ocean governance in Nigeria in furtherance of the blue economy objectives?

2 Basic concepts

The primary instinct here is to present the basic concepts of the three variables in the paper, namely blue economy, ocean governance, and Policy Implementation. This is to create clarity, aid understanding, ensure consistency, and promote essential values. These variables are: blue economy, ocean governance and policy implementation.

Blue economy. The import of blue economy varies across institutions and jurisdictions. While the European Union (EU) views it as a sectoral economic space, Small Island Developing States (SIDS) focus on using the blue economy to support Sustainable Development Goals (SDGs) (Argueta, 2024). These differences reflect a broader tension between resource exploitation and ecosystem stewardship. However, the World Bank, defines blue economy as "the sustainable use of ocean, sea, and coastal resources for economic growth, improved livelihoods, and jobs, while preserving the health of ocean ecosystems" (World Bank, 2017). In this paper, the blue economy is a policy-driven framework that seeks to harness ocean and coastal resources to drive sustainable economic growth, promote social inclusion, and safeguard marine ecosystems. It encompasses diverse ocean-related sectors such as fisheries and aquaculture, shipping and port services, marine bio-technology, tourism, renewable energy, and seabed exploration and mapping. Significantly, implementation of blue economy is aided by deliberate ocean and maritime governance, among other critical inputs.

Ocean governance. Ocean governance refers to the collective system of legal frameworks, institutional mechanisms, policies, norms, and decision-making processes that guide and regulate human interaction with the ocean. According to the United Nations, "it involves the regulation and administration of the ocean's uses, aiming to maintain biodiversity, mitigate climate change impacts, and promote sustainable livelihoods" (UNEP, n.d.). In this paper, ocean governance is conceived as the enabling architecture of laws and regulations, specialized institutions and mechanisms as well as constructive stakeholder engagements that ensure ocean resources are sustainably managed, equitably shared, and protected for future generations. It provides the foundation and amenable operational environment for effective implementation of blue economy policies.

Policy implementation. Policy implementation is viewed within the framework of the recursive policy circle as enunciated by Lasswell (1956) that comprises key elements such as agenda setting; policy formulation; decision making; implementation; Performance Measurement and Evaluation (PME); and lastly, feedback and review. Policy implementation is the structured process of interaction between the goalsetting and actions geared towards achieving them. The imperatives of policy implementation are to effectively translate policy goals to concrete action through clear objectives, stakeholder engagements, robust planning, effective resource allocation, strong institutional capacity and continuous adaptation to changing contexts. The standard rubric for policy implementation includes: availability of relevant policy statements; implied/express tasks therefrom; requisite structure for implementation; detailed requirements, which may include financial, material, human capacity, additional regulations and stakeholder networks, mechanisms for application of policy provision and policy PME.

3 The practice of blue economy amongst nations

Several regional blocks, groups of nations and individual nations have developed comprehensive policies/strategies that provide clear aspirations, specific objectives, institutional coordination frameworks, and funding mechanisms for the blue economy.

European Union (EU). The EU launched its Blue Growth Strategy in 2012, integrating ocean sectors such as renewable energy, aquaculture, coastal tourism, and marine biotechnology under a unified policy platform. The EU model is anchored on the Marine Strategy Framework Directive, which mandates ecosystem-based management of marine waters.

Small Island Developing States (SIDS). The SIDS such as Seychelles and Mauritius have become global frontrunners, embedding environmental sustainability at the core of their blue economy policies. Mauritius for example developed an Ocean Economy Roadmap in 2012, that is envisioned to transform the country into a global maritime and blue economy hub by developing sectors such as fisheries, maritime transport, marine tourism, renewable ocean energy, and marine biotechnology while

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ensuring sustainability in the management of ocean resources (Cervigni & Scandizzo, 2017). Seychelles similarly launched a blue economy roadmap in 2018 that linked Marine Spatial Planning (MSP) with innovative financing mechanisms, such as blue bonds and debt-for-nature swaps, to fund marine conservation and fisheries management Commonwealth Secretariat, 2018).

Asian Maritime Nations (AMN). The AMN have embraced ambitious blue economy agenda. For instance, China's blue economy development plan (2012) and Indonesia's ocean policy (2017) both prioritize marine industrialization, port infrastructure, fisheries modernization, and ocean technology development. These approaches emphasize strong state-led coordination, significant investment in marine science and technology, and extensive public-private partnerships.

African Union. At the continental level, the African Union provides a broad policy framework to foster increased wealth creation from Africa's oceans and seas by developing sustainable thriving blue economy in a secure and environmentally sustainable manner. The *2050 African Integrated Maritime Strategy* (AU, 2012) is designed to address Africa's maritime challenges and harness the potentials of its blue economy. It encourages other sub-regional blocks to draw down from its basic philosophy, principles and objectives.

Economic Community of West African States (ECOWAS). ECOWAS launched the ECOWAS Integrated Maritime Strategy (EIMS) in 2014. The EIMS was aimed at promoting a prosperous, safe, and peaceful ECOWAS Maritime Domain (EMD) for all its people that will allow environmentally sustainable development and maritime wealth creation based on efficient management and good governance.

Individual nations. Based on this supra-national guidance, several African nations have implemented blue economy policy frameworks. Some of these are as follows:

- Kenya launched its blue economy implementation committee in 2018 and has integrated ocean-based sectors into national development plans, emphasizing port development, fisheries, and maritime safety.
- South Africa implemented *Operation Phakisa: Oceans Economy* in 2014, which sets measurable targets for job creation and GDP contribution from marine sectors while embedding ecosystem protective measures.
- Established a Ministry of Fisheries and Marine Resources with an explicit mandate to coordinate blue economy sectors, underpinned by comprehensive marine ecosystem assessments.

Common implementation features and lessons. There are some common features and lessons drawn from the blue economy experiences of regional blocks and nations discussed above. These include the following:

- High-level political anchoring: blue economy policies are located within central national development plans, ensuring sustained political attention and budgetary commitment.
- Integrated ocean governance structures: Dedicated inter- ministerial coordinating bodies or agencies oversee implementation, avoiding institutional fragmentation.
- Marine Spatial Planning (MSP) is widely used to balance competing uses of marine space such as fishing, shipping, conservation, and energy, while reducing conflicts.
- Robust data and monitoring systems: Investment in hydrographic, oceanographic, and geospatial data systems supports evidence-based decision-making.
- Innovative financing: Blue bonds, climate funds, and public-private partnerships mobilize capital for maritime infrastructure and conservation.
- Stakeholder inclusion: Community participation and public-private collaboration increase legitimacy, acceptability and sustainability of initiatives.

4 Overview of blue economy policy development in Nigeria

Drawing from longstanding aspiration for a policy instrument to promote effective sea use and the blue economy as well as international stimulus, Nigeria set up an Inter-Ministerial Committee to develop a comprehensive National Maritime Strategy (NMS). The Ministries involved were: Transport (MoT), Defence (MoD), Justice (MoJ), Agriculture and Rural Development (MoARD), Environment (MoE), Communications and Digital Economy (MoCDE), Foreign Affairs (MoFA), and Internal Affairs (MoIA) as well as Departments/Agencies such as Nigerian National Petroleum Corporation Limited (NNPCL), Nigerian Ports Authority (NPA), Nigeria Maritime Administration and Safety Agency (NIMASA), Shippers Council of Nigeria (SCN), Department of Fisheries (DoF), Nigerian Navy (NN), and Nigeria Police Force (NPF).

The NMS was signed in 2022 and launched by President Muhammadu Buhari GCFR in May 2023. The vision of NMS 2022 is "to achieve Nigeria's economic prosperity, growth and development through the sustainable use of the nation's maritime resources in a safe and secure environment". The core principles were: protection of strategic maritime interest; promotion of economic wellbeing; promotion of social freedoms; promotion of environmental sustainability; promotion of global citizenship; and the need for both domestic and international collaborations.

The six pillars of NMS 2022 were:

1. To promote an amenable legal and regulatory framework in Nigeria's maritime environment.
2. To promote effective Ocean and Maritime Governance in Nigeria.
3. To promote the development of a blue economy in Nigeria.

4. To promote environmental sustainability in Nigeria's maritime environment.
5. To promote effective Communication and Information Technology system in Nigeria's maritime environment.
6. To promote a viable security and defence system in Nigeria's maritime environment.

NMS 2022 represents a multi-thematic and multistakeholder effort to promote maritime economic prosperity, growth and development in a safe, and secure environment in a sustainable manner. Significantly, it included an Implementation Plan that recognized diverse but mutually reinforcing roles of stakeholders. For instance, the MoJ was to develop Pillar 1 on legal/regulatory framework; the MoT was to develop Pillar 2 on ocean/maritime governance; NIMASA was to develop Pillar 3 on blue economy; and NN was to develop Pillar 6 on security.

After the democratic transition in 2023, the government of President Bola Ahmed Tinubu GCFR prioritized the blue economy and established a full-fledged Ministry of Marines and Blue Economy (MoMBE). It then commenced the development of a capstone national policy on marines and blue economy, which was approved in 2025. The policy has a vision to "make Nigeria a global leader in sustainable marine and blue economy practices" and its Mission is "to sustainably harness Nigeria's rich marine and coastal resources, fostering economic growth and development while ensuring the conservation of our marine ecosystems". The NPMBE promotes core functions of the blue economy in the areas of: Maritime Trade and Transportation (including port infrastructure and services, shipbuilding and repairs as well as maritime safety and security); Fisheries and Aquaculture; Marine Resources and Industries; Energy and Environmental Sustainability; Blue Tourism and Recreation as well as Maritime Education and Training.

5 Implementing blue economy in Nigeria

Recognising that the NPMBE is a major turning point in sea-use in Nigeria, the FGN has made concerted efforts to implement the blue economy policy in various ways. These are as follows:

Regulations. Establishment of a 4-year Policy Implementation Plan that spans from 2023 to 2027, based on 4 strategic actions. These are: strengthening blue governance; enhancing port infrastructure; promoting blue economy investments; and transforming port operations.

Structure. A key requirement of blue economy policy implementation is the establishment of a viable implementation structure. In the Policy, the President is the overall head of the blue economy initiative. He shall be assisted by the Policy Advisory Council (PAC) in the discharge of the objectives of the policy. The PAC shall be chaired by the Honourable Minister of Marines and blue economy and have representatives of participating MDAs, private sector and development partners as members. At the core of the implementation is the Policy Implementation Steering Committee (PISC) which will receive countrywide guidance from a Sub-national Coordination Committee (SNCC). The PISC is to be chaired by the Permanent Secretary of the FMMBE, with membership from the Ministry and external consultants. These entities constitute the implementation structures for the NPMBE.

Mechanisms. In furtherance of the blue economy, the FGN has lately initiated some critical measures. These include the digitalization of port systems and the introduction of a centralized platform for maritime single window. These measures are expected to reduce bottlenecks, improve transparency and efficiency, reduce cost of doing business, facilitate trade and boost economic growth.

Financing and indigenous capacity development. Recognizing that local operators struggle with funding for vessel acquisition; the implementation plan prioritizes financing schemes such as the Cabotage Vessel Financing Fund (CVFF) in furtherance of one of the key objectives of the Cabotage Act 2003. Indeed, the disbursement of the first tranche of CVFF was expected to commence in August 2025. The plan also stresses human capital development through specialized training, research partnerships, and seafarer capacity enhancement.

Stakeholder collaboration and public-private partnerships. The MMBE has lately emphasized the importance of collaboration among government agencies, private investors, coastal communities, and academia in furtherance of blue economy policy implementation. In particular, Private Public Partnerships (PPPs) are seen as vital in financing port infrastructure, offshore energy, and environmental protection projects.

Sustainability and environmental protection. The blueprint for blue economy implementation incorporates measures for marine spatial planning, biodiversity conservation, and pollution control. Emphasis is placed on balancing economic exploitation with ecological sustainability, aligning Nigeria with the UN Sustainable Development Goal 14 (Life Below Water).

6 Implementing ocean governance in Nigeria

Ocean governance in Nigeria is motivated by the need to make better use of knowledge, skills, aptitudes and available resources to promote economy efficiency and initiate better priority setting in support of blue economy. Some of these initiatives in ocean governance include, maritime governance and institutions, maritime domain awareness, role of hydrography, marine spatial planning.

Maritime Governance and Institutions. In furtherance of ocean governance, the FGN has promoted the delineation of maritime governance institutions under various ministries such as the Ministries of Marine and Blue Economy, Defence, Finance and Budget Planning. Typical examples of such maritime

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governance institutions are NIMASA, NPA, NIWA, NN, National Hydrographic Agency (NHA) and Nigerian Customs Service (NCS) among others. Still on maritime governance, the FGN is actively promoting national and regional maritime collaborations to achieve maritime safety and security. In particular, it is actively strengthening maritime partnerships in the Gulf of Guinea (GoG) and promoting joint exploration of maritime resources in the GoG in furtherance of the blue economy.

Maritime domain awareness. To promote Nigeria's Maritime Domain Awareness, the NN already operates the Falcon Eye, a maritime surveillance system used to monitor and protect the nation's EEZ and territorial waters. In addition to the Falcon Eye, the FGN has caused the activation of other enhanced surveillance systems such as the Automatic Identification System (AIS), Vessel Monitoring System (VMS) and satellite monitoring. These technologies are expected to improve safety, reduce insurance premiums, and combat insecurity such as Illegal, Unreported and Unregulated (IUU) fishing and piracy in furtherance of the blue economy.

Role of hydrography. The universal role of hydrography in ocean governance is aptly captured by the exploits of the National Hydrographic Agency (NHA) in Nigeria. Established by the NHA Act 2021, the NHA is now the foremost hydrographic agency in Nigeria. It has taken over the erstwhile responsibilities of the NN Hydrographic Office as the sole authority for the conduct of hydrographic surveys and production of nautical charts in Nigeria. Driven by the mantra of the International Hydrographic Organisation (IHO) that "there can be no sustainable use of the oceans without adequate knowledge of the seas", the NHA has conducted numerous hydrographic surveys across Nigeria and adjoining waters resulting in the production of globally available paper and electronic nautical charts. Clearly, the NHA promotes navigational safety, environmental stewardship, and maritime sustainability in furtherance of ocean governance and the blue economy objectives of the nation.

Marine Spatial Planning. Nigeria has initiated MSP primarily through pilot projects in economically and environmentally sensitive coastal areas such as Lagos and Niger Delta. These MSP initiatives employ hydrographic and geospatial data supplied by the NHA to identify and delimit marine zones for various uses, including commercial shipping lanes, fishing grounds, oil and gas exploration areas, conservation zones and tourism sites. The planning process integrates stakeholder consultations spanning local communities, industry actors, and governmental entities to enhance broad- based ownership.

7 Challenges and prospects of blue economy and ocean governance in Nigeria challenges

Some challenges faced by investors, stakeholders and key players in the Nigerian blue economy sector include the following:

Need for inter-agency coordination. A key issue and seemingly obvious challenge in blue economy implementation is the manifest need for coordinating diverse (and sometimes disparate) activities of several institutions in the maritime environment. For instance, critical functions such as maritime safety and security, and both licensing and revenue collection are currently within the purview of multiple institutions. While admitting the role of the FGN, in recent times, to promote crosscutting communications, a lot more still needs to be done, to ensure understanding of institutional differences, effective collaboration, inclusivity and working partnerships.

Human capacity gaps. Nigeria's blue economy comprise diverse sectors such as fisheries, aquaculture, marine transport, hydrography, offshore oil and gas exploration and coastal tourism. The sustainable development of these sectors hinges not only on technological advancement but also on the human capital that ordinarily drives innovation, sustained industrial practices/culture and foster inclusive growth. Current human capacity gaps are due to factors such as lopsided education curriculum, and inadequate training infrastructure. Significantly, there is also a disconnect between training and practice associated with the absence of a designated national carrier. Consequently, the main goals of the Cabotage Act 2003 to reserve domestic shipping for Nigerian-flagged, owned and crewed vessels are not being met at the expense of the blue economy

Environmental degradation. The Nigerian maritime environment suffers enormous degradation arising from several factors. These include institutional weaknesses associated with inadequate coordination between regulatory bodies and stakeholders; as well as ineffectual implementation of the Environmental Impact Assessment (EIA) Act of 1992 associated with inadequate monitoring and penalties for violation. The situation creates enormous social, economic, technical and environmental challenges for blue economy investors.

Data sharing challenges. The absence of a comprehensive framework for data-sharing significantly limits integrated marine management capabilities in Nigeria. In this regard, agencies such as NIMASA, NIWA, Nigerian Institute for Oceanography and Marine Research (NIOMR) and NHA collect and maintain crucial marine data according to their specific mandates. However, despite law empowering the NHA as the sole depository of such data in Nigeria, inter-agency rivalry, sharing this information with other relevant agencies or stakeholders like local fishing communities or oil and gas companies becomes a major hurdle.

Prospects. Despite the challenges impeding the optimization of blue economy and ocean governance, there are credible prospects that this initiative will succeed in Nigeria. This optimism stems from the following factors:

Political will and priority. For the first time in Nigerian history, the FGN is showing strong political will in

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promoting optimal sea-use particularly blue economy imperatives. In furtherance of this high-level political anchoring, the FGN has prioritized and shown genuine commitment to implement its blue economy agenda.

International instruments. Various international instruments and agenda point to the drawdown of blue economy initiatives by developing nations including Nigeria. These drives include the United Nations Sustainable Development Goal Number 14 (SDG 14 on Life below Water), and the impetus by the World Bank, and World Economic Forum. There are also the International Maritime Organisation (IMO) initiatives on safe, secure and environmentally sound shipping, as well as the Paris Agreement on environmental protection and marine protected areas among others.

Decade of Ocean Science. The Decade of Ocean Science for Sustainable Development 2021 – 2030 declared by the United Nations could propel a renewed focus on maritime data science including hydrography in furtherance of ocean governance and blue economy.

Regional IC-ENC office. In June 2025, NHA received the approval of the International Centre for Electronic Nautical Charts (IC- ENC) to establish the West African Regional Office and Training Centre in Nigeria. This status can boost Nigeria's blue economy credentials. In particular, it can enhance maritime safety, leading to reduced marine insurance premiums, and increased port throughput; stimulate private-sector investments, and create direct and indirect employment in marine technologies, chart production, vessel operations, and training services.

African Continental Free Trade Agreement (AfCFTA). The AfCFTA promises a single African market for 55 countries with real prospects for the blue economy; intra-African trade; job creation; economic development; and poverty reduction.

International maritime security. Buoyed by the realities of the Regional Security Complex Theory, and expected advantages of common security approaches, there are genuine prospects that blue economy in Nigeria could benefit from improved regional maritime security.

8 Strategies for improving blue economy implementation in Nigeria

The strategic outlook for Nigeria illustrates both the challenges and huge promise of transitioning to sustainable blue economy. In view of the diversities inherent in the blue economy, it is advised to apply a multi-layered umbrella strategy. This will allow a broad framework that guides and unifies sub-thematic initiatives and actions under a common vision and purpose. At the same time, it will allow the resolution of specific challenges as articulated below.

Inter-agency coordination. The key to ensuring understanding of institutional differences, effective collaboration, and working partnerships between diverse maritime organisations would be to adopt an inclusive principle of lex specialis in role implementation of maritime agencies/organisations. This principle mandates that a rule governing specific subject matter overrides a rule governing general matters. It will facilitate sub-sectoral precedence and lead of specific organisations based on their statutes, competences, experience, corporate capacity and overall resource endowments. This is to be fastened together by the collectivism which mandates part of a whole system to act in furtherance of the collective objectives rather than in pursuit of only informed self-interest. Collaboration must also involve communities and the public and the private sector to increase legitimacy, acceptability and sustainability of initiatives.

Human capacity development. Human capacity development in the blue economy must be viewed as a strategic imperative. In the short term, the MMBE must intentionally and aggressively facilitate local and foreign training of key professionals in specific sub-thematic areas of the blue economy. In the medium term, the MMBE and other maritime agencies must facilitate the development of special training institutions and platforms in Nigeria to drive critical mass of Knowledge, Skills and Aptitudes (KSAs) in blue economy management. This is also to include the localization of foreign based institutions and organisations. A typical example here is the approved West African Regional Office and Training Centre of the IC-ENC in Nigeria. In the long term, there must be a deliberate effort to designate or establish a national carrier to provide a readily available platform for training and development of industry ready seafarers.

Environmental protection and enforcement. Going forward, and to emplace robust environmental preparedness and resilience, it is suggested that environmental management is undergirded by 2 core principles. These are the principles of *user pays* and *polluter pays*. The first mandates that users and beneficiaries pay for the use and potential running down of natural resources. The second mandates that polluters pay significant cost for degrading and polluting the maritime environment. These principles need to be embedded in national environmental management code as preventive measures to protect biodiversity, manage pollution and ensure environmental sustainability of the environment. They are to be applied alongside international conventions such as the MARPOL.

Effective data management. Going forward, the FGN need to embark on good investment in hydrographic, oceanographic, and geospatial data systems to support evidence-based decision-making. Indeed, the already existing legal or policy framework for mandatory repository of such geospatial data with the NHA should be implemented, in addition to effective data sharing amongst agencies and the archiving of such data for future ocean governance and blue economy.

9 Conclusion

Nigeria's experience demonstrates both the promise and the challenges of transitioning from fragmented maritime policies to a coherent blue economy

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framework anchored on ocean governance. The establishment of the Ministry of Marine and Blue Economy and the adoption of the 2025–2034 national policy mark important milestones in this evolution. However, persistent gaps in institutional coordination, legal frameworks, data infrastructure, and enforcement capacity highlight that policy formulation alone is insufficient. Rather, effective implementation, guided by robust governance and supported by technological innovation, remains the central determinant of success.

At the global level, Nigeria's case underscores a broader lessons for developing maritime nations. First is that sustainable blue economic growth depends on embedding ocean governance as the core principle for policy delivery. Secondly, integrated governance, inclusive stakeholder participation, and international cooperation provide the pathways to bridge the divide between aspiration and practice. If these elements are consolidated, Nigeria and other coastal states can transform their maritime endowments into engines of economic diversification, climate resilience, and long-term sustainability.

References

Argueta, K. (2024). *The blue economy: A historic opportunity for SIDS*. United Nations Development Program, New York, USA. https://www.undp.org/blog/blue-economy-historic-opportunity-sids (last accessed 3 April 2026).

AU (2012). *2050 Africa's Integrated Maritime Strategy*. African Union Headquarters, Addis Ababa, Ethiopia. https://au.int/sites/default/files/documents/30929-doc-2050_aim_strategy_eng_0.pdf (last accessed 3 April 2026).

Cervigni, R. and Scandizzo, P. (2017). *The Ocean Economy in Mauritius: Making It Happen, Making It Last*. Washington, DC: World Bank.

Commonwealth Secretariat (2018). *Seychelles' Blue Economy: Strategic Policy Framework and Roadmap Charting the Future (2018–2030)*. Commonwealth Secretariat, London, United Kingdom. https://seymsp.com/wp-content/uploads/2018/05/CommonwealthSecretariat-12pp-RoadMap-Brochure.pdf (last accessed 3 April 2026).

Edward, O. (2023). *Federal Government approves ratification of six maritime conventions and protocol*. Nigerian Maritime Administration and Safety Agency, Lagos, Nigeria. https://nimasa.gov.ng/fg-approves-ratification-of-six-maritime-conventions-and-protocols/ (last accessed 3 April 2026).

Lasswell, H. D. (1956). *The decision process: seven categories of functional analysis*. College Park, Maryland: University of Maryland Press, 23pp.

UNEP (n.d.). *Ocean Governance*. United Nations Environmental Programme, Nairobi, Kenya. https://www.unep.org/topics/ocean-seas-and-coasts/regional-seas-programme/ocean-governance (last accessed 3 April 2026).

World Bank (2017). *What is the Blue Economy?* World Bank Group, Washington, DC, USA. https://www.worldbank.org/en/news/infographic/2017/06/06/blue-economy (last accessed 3 April 2026).

CONFERENCE PAPER

Underwater cultural heritage: an international law perspective

Author
Tullio Scovazzi[1]

Preamble

The following work was presented at the 12th ABLOS Conference, 7–8 October 2025, Doha, Qatar in the oral session *Advances in ocean governance*.

Abstract

The present international law regime leaves doubts as regards the objective of protection of the underwater cultural heritage. A provision included in the 1982 treaty of general codification of international law of the sea can be understood in a counterproductive meaning, as implying freedom of fishing for this heritage under a first-come-first-served approach. The 2001 treaty that could specifically ensure the effective protection of the heritage has not yet received sufficiently broad participation by States.

Keywords
underwater cultural heritage · international law · treaty law · admiralty law · looting · State ships or aircraft

1 Introduction

The aqualung, an automatic compressed air diving device, was used for the first time in 1943 and allowed the inventors, Émile Gagnan and Jacques Cousteau, to explore and film underwater. Since then, seabed exploration has taken advantage of more and more advanced and sophisticated technology. To give only two examples, in 1969 the wreck of an aircraft was located in Santa Monica Bay by towing from a ship for ten days a side-looking sonar through dark waters to find patterns of small objects and by plunging television cameras to check the nature of them (Bascom, 1987). The expedition that Robert Ballard organized in 1997 to explore the seabed in an area of the Mediterranean Sea between Italy and Tunisia (Skerki Bank Deep Sea Project), utilised a support ship, a nuclear-powered research submarine of the United States Navy and a remotely operated vehicle (Ballard, 1998).

Technological developments have greatly improved human knowledge of the sea and have facilitated awareness of all historical information to be drawn from underwater cultural heritage. They have increased the interest of the general public for this kind of heritage and widespread appreciation of it. However, at the same time, as the seabed has become more easily accessible, technological developments have determined a new threat for the preservation of underwater cultural heritage.

The greatest exhibition of human civilization lies on the seabed. According to some estimates, in the past centuries almost 5 % of all seagoing ships were lost every year, be it for acts of God, human errors, naval battles or other causes (Throckmorton, 1987). Today the capacity of several States and private entities to use very sophisticated technological means to explore the seabed at increasing depths not only allows access to a unique cultural heritage, but also entails the risk of such heritage being looted or used for private commercial gain under a first-come-first-served approach. Given this general picture, the questions may be asked whether we have an international legal regime addressing underwater cultural heritage and, if so, whether it is sufficient to ensure its protection.

✉ Tullio Scovazzi · tullio.scovazzi@unimib.it
[1] Università degli Studi di Milano-Bicocca, Milan, Italy (retired)

2 The UNCLOS regime

The present international law regime for the protection of underwater cultural heritage (Strati, 1995), as resulting from the United Nations Convention on the Law of the Sea (Montego Bay, 1982)[1], is disappointing, to say the least. Out of 320 articles and nine annexes, the UNCLOS devotes to the subject only two provisions, namely Arts. 149 and 303, that show gaps and contradictions.

Art. 303, para. 1, sets forth a general obligation of protection and cooperation which applies to all archaeological and historical objects, wherever at sea they are found:

"States have the duty to protect objects of an archaeological and historical nature found at sea and shall cooperate for this purpose".

Despite its broad content, some legal consequences can be drawn from this provision. First, a State that knowingly destroys or allows the destruction of objects belonging to underwater cultural heritage can be held responsible for a breach of an international obligation. Second, a State that persistently disregards the requests by other States to negotiate about forms of cooperation aimed at protecting underwater cultural heritage can be held responsible for an internationally wrongful act as well.

As regards the maritime zones falling under the sovereignty or jurisdiction of the coastal State, it is implied in the UNCLOS that the full sovereignty granted to the coastal State within the internal maritime waters and the 12-mile territorial sea also covers underwater cultural heritage. Beyond the territorial sea, Art. 303, para. 2, UNCLOS allows the coastal State to prevent the removal of archaeological and historical objects in the waters between 12 and 24 nautical miles (the so-called archaeological contiguous zone) (Aznar, 2014)[2].

The main problem with Art. 303 is that the UNCLOS does not establish any regime relating to underwater cultural heritage found in the space located between the external limit of the 24-mile contiguous zone and the 200-mile external limit of the exclusive economic zone or continental shelf. The rights granted to the coastal State within this space relate to the exploration and exploitation of its natural resources and cannot be extended to man-made artifacts, such as those belonging to underwater cultural heritage[3]. This legal vacuum greatly threatens the protection of cultural heritage, as it brings into the picture the principle of freedom of the seas that could easily lead to a first-come-first-served approach. Availing himself of this principle, any person on board a ship could explore the exclusive economic zone or the continental shelf adjacent to any coastal State, bring archaeological and historical objects to the surface, become their owner under a domestic legislation (in most cases, the flag State legislation), remove the objects for his or her own benefit and sell them on the market. If this were the case, there would be no guarantee that the objects would be disposed of for public benefit rather than for private commercial purposes and personal gain.

The danger of freedom of fishing for underwater cultural heritage under the UNCLOS regime is multiplied by Art. 303, para. 3, that subjects the whole of Art. 303 to the law of salvage and other rules of admiralty:

"Nothing in this article affects the rights of identifiable owners, the law of salvage or other rules of admiralty, or laws and practices with respect to cultural exchanges".

The mysterious expression "the law of salvage or other rules of admiralty" refers to a body of customary domestic law that, lacking specific legislative provisions, is applied in some countries, in particular the United States. In many countries, the notion of salvage is only related to the attempt to save a ship, or property carried by it, from imminent marine peril. However, United States courts apply it, as a part of the so-called admiralty law, also to ancient sunken ships and to objects removed from wrecks, which, far from being in peril, lay on the seabed, having been lost since many years.

For example, the United States Court of Appeals for the 4th Circuit in the decision *RMS Titanic Inc. v Haver* of 24 March 1999 stated that the law of salvage and the law of finds, which are both parts of admiralty law, constitute a "venerable law of the sea". It is supposed to apply in all the oceans and seas of the world, to have arisen from custom among "seafaring men" and to have "been preserved from ancient Rhodes (900 BCE), Rome (Justinian's Corpus Juris Civilis) (533 CE), City of Trani (Italy) (1063), England (the Law of Oleron) (1189), the Hanse Towns or Hanseatic League (1597), and France (1681), all articulating similar principles"[4]. Coming to the practical result of such an outstanding display of legal erudition, the law of salvage, applying where the owner of the wreck or objects is known, gives the salvor a lien (or right *in rem*) over the object. The law of finds, applying where the owner of the wreck or objects is not known, means that "a person, who discovers a shipwreck in navigable waters that has been long lost and abandoned and who reduces the property to actual or constructive possession,

[1] Hereinafter: UNCLOS.

[2] "In order to control traffic in such objects, the coastal State may, in applying article 33, presume that their removal from the seabed in the zone referred to in that article [= the contiguous zone] without its approval would result in an infringement within its territory or territorial sea of the laws and regulations referred to in that article". In fact, the wording of Art. 303, para. 2, is far from clear.

[3] In 1980, during the negotiations of the UNCLOS, an informal proposal was submitted by seven States (Cape Verde, Greece, Italy, Malta, Portugal, Tunisia and Yugoslavia) to extend the jurisdiction of the coastal State to the underwater cultural heritage found on the continental shelf (doc. C.2/Informal Meeting/43/REV. 3). However, the proposal was not adopted.

[4] In International Legal Materials, 1999, p. 807.

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becomes the property's owner"[5]. In fact, the American model leads to a first-come-first-served or freedom-of-fishing approach based on the destination of underwater cultural heritage for the purpose of personal commercial interest. Private appropriation and sale are the most likely destiny of the removed artefacts which are considered as goods on the market.

The fact remains that such exorbitant, although "venerable", bodies of law are complete strangers in the legislation of the several States that follow a model based on the public interest to preserve the cultural heritage for the general benefit, in particular for research and exhibition purposes. For example, in Italy, according to the 2004 Code of Cultural Properties and Landscape, research in the field of archaeological and cultural properties is reserved for the Ministry for Cultural Properties and Activities or to the public or private subjects who have been authorized by the Ministry. Anyone who fortuitously discovers cultural properties is bound to inform the competent public authority within 24 hours. The removal and taking into custody of the properties are permitted only where there is no other means to ensure their security until the intervention of the public authorities. All the cultural properties found by anyone in the subsoil or on the seabed belong to the State demesne, if immovable, or to the inalienable patrimony of the State, if movable. The finder is entitled to a reward which is paid by the Ministry and cannot exceed one-fourth of the value of the properties (if the properties are found at sea, the reward corresponds to one-third of their value)[6]. The Italian legislation applies within the 12-mile territorial sea and, at least according to some judgments, to ships flying the Italian flag.

Coming back to the UNCLOS, if there is a conflict between the general objective to protect underwater cultural heritage (Art. 303, para. 1), on the one hand, and salvage law and other rules of admiralty, on the other, the latter does prevail (Art. 303, para. 3). This is really astonishing and worsens the picture of Art. 303. Does this provision, while apparently protecting underwater cultural heritage, strengthen a regime which results in the use of much of this heritage for commercial purposes, regardless of its importance from the cultural point of view? Does Art. 303 give an overarching status to a body of rules that cannot provide any effective means for the protection of the heritage in question and could be understood as a covert invitation to the looting of underwater cultural heritage? This doubt is far from being trivial, especially for those countries where national legislation gives priority to the State's duty to preserve cultural heritage for purposes of public interest.

The concerns are not substantially attenuated by the fact that, because of the lack of corresponding concepts, the very words "salvage" and "admiralty" could not be properly translated into languages different from English. In the French and Spanish official texts of the UNCLOS they are rendered with expressions – "droit de récupérer des épaves et (...) autres règles du droit maritime"; "las normas sobre salvamento u otras normas del derecho marítimo" – which imply a broader and quite different meaning[7].

Some prospective remedies for the unsatisfactory regime of the UNCLOS could be drawn from Art. 303, para. 4. It provides that Art. 303 does not prejudice "other international agreements and rules of international law regarding the protection of objects of an archaeological and historical nature". The UNCLOS itself seems to allow the drafting of more specific treaty regimes which can ensure better protection of the underwater cultural heritage, filling the gaps and eliminating the contradictions that it has generated.

The second UNCLOS provision on underwater cultural heritage (Art. 149) deals only with the heritage found in the so-called Area, that is the seabed and ocean floor beyond the 200-mile limit of national jurisdiction. It provides that "all objects of an archaeological and historical nature found in the Area shall be preserved or disposed of for the benefit of mankind as a whole, particular regard being paid to the preferential rights of the State or country of origin, or the State of cultural origin, or the State of historical and archaeological origin".

The provision appears devoid of details that could ensure its practical application. However, it embodies two promising ideas. First, Art. 149 shows a preference for uses of archaeological and historical objects that promote the "benefit of mankind as a whole". Private interests, such as the disposal of the objects for trade and personal gain, are given little weight, if any. Second, some categories of States which have a link with the objects are given preferential rights, although Art. 149 does not specify either the content of these rights or the manner in which they should be harmonized with the concept of "benefit of mankind as a whole". Despite its vague wording, Art. 149 seems in conceptual contradiction with the freedom of fishing regime implied in Art. 303, para. 3.

It is true that the subject of underwater cultural heritage was taken into consideration only in the last period of UNCLOS negotiations, which lasted for about ten years overall. However, the lack of time and the need to bring complex negotiations to an end cannot be seen as a justification for such a contradictory and counterproductive regime.

[5] Ibidem, p. 808.

[6] The reward may be paid either in money or through the cession of part of the properties.

[7] Indeed, the meaning of Art. 303, para. 3, UNCLOS is completely different in the English text, on the one hand, and in the French and Spanish texts, on the other (the Arab, Chinese and Russian official texts should also be checked). This is an interesting instance for the application of Art. 33 of the Convention on the Law of Treaties (Vienna, 1969), relating to the interpretation of treaties authenticated in two or more languages.

3 The CPUCH regime

3.1 General aspects

On 2 November 2001, the Convention on the Protection of the Underwater Cultural Heritage[8] (O'Keefe, 2002; Garabello & Scovazzi, 2003; Aznar, 2004; Dromgoole, 2006; Dromgoole, 2013; Lowther et al., 2025) was adopted in Paris within the framework of the United Nations Educational, Scientific and Cultural Organization (UNESCO). It entered into force on 2 January 2009, after the deposit of the twentieth instrument of ratification or accession. At the time of writing, it has been ratified by 81 States.

The CPUCH applies to "all traces of human existence having a cultural, historical or archaeological character which have been partially or totally under water, periodically or continuously, for at least 100 years"[9]. It can be included among the "other international agreements" which States are allowed to conclude under the already mentioned Art. 303, para. 4, UNCLOS.

The CPUCH, which was the outcome of a complex negotiation, was adopted by vote (87 States in favour, 4 against and 15 abstentions). However, the lack of *consensus* at the moment of its adoption should not be considered as an irreparable flaw. Not only did the great majority of developing countries vote in favour, but also several among the industrialized countries and maritime powers were satisfied with the outcome of the negotiations. Looking at its content, the CPUCH can be understood as a reasonable defence against the results of the contradictory and counterproductive regime of the UNCLOS. The basic defensive tools are the elimination of the undesirable effects of the law of salvage and finds, the exclusion of a "first come, first served" approach for the heritage found in the exclusive economic zone or on the continental shelf and the strengthening of regional cooperation.

3.2 The exclusion of law of salvage and finds

While most countries participating in the negotiations for the CPUCH concurred in rejecting the application of the law of salvage and finds to underwater cultural heritage, a minority of States were not prepared to accept an absolute ban. To achieve a reasonable compromise, Art. 4 provides as follows:

"Any activity relating to underwater cultural heritage to which this Convention applies shall not be subject to the law of salvage or law of finds, unless it: (a) is authorized by the competent authorities, and (b) is in full conformity with this Convention, and (c) ensures that any recovery of the underwater cultural heritage achieves its maximum protection".

This provision is to be understood in connection with Art. 2, para. 7 ("underwater cultural heritage shall not be commercially exploited") and with the Annex, which forms an integral part of the CPUCH. In particular, under Rule 2 of the Annex:

"The commercial exploitation of underwater cultural heritage for trade or speculation or its irretrievable dispersal is fundamentally incompatible with the protection and proper management of underwater cultural heritage. Underwater cultural heritage shall not be traded, sold, bought or bartered as commercial goods".

While not totally excluding the application of law of salvage and law of finds, the CPUCH regime has the practical result of preventing all the undesirable effects of the application of these kinds of rules. Undisclosed activities and freedom of fishing for archaeological and historical objects are clearly banned.

3.3 Jurisdiction in the Exclusive Economic Zone

The majority of the States participating in the negotiations were ready to extend the jurisdiction of the coastal State to underwater cultural heritage found in the exclusive economic zone or on the continental shelf. However, a minority of States assumed that the extension of the jurisdiction of coastal States beyond the limit of the territorial sea would have altered the delicate balance embodied in the UNCLOS between the rights and obligations of the coastal State and those of other States. As a compromise, the CPUCH provides for a three-step procedural mechanism (reporting, consultations and urgent measures), which involves the participation of all the States linked to the heritage.

As regards reporting, the CPUCH bans secret activities or discoveries. States Parties must require their nationals or vessels flying their flag to report activities or discoveries to them. If the activity or discovery is located in the exclusive economic zone or on the continental shelf of another State Party, the CPUCH sets forth two alternative solutions:

"(i) States Parties shall require the national or the master of the vessel to report such discovery or activity to them and to that other State Party;

(ii) alternatively, a State Party shall require the national or master of the vessel to report such discovery or activity to it and shall ensure the rapid and effective transmission of such reports to all other States Parties"[10].

States Parties must also notify the Director-General of UNESCO who must promptly make the information available to all States Parties.

As regards consultations, the coastal State is bound to consult all States Parties which have declared their interest in being consulted on how to ensure the effective protection of the underwater cultural heritage in question. The CPUCH provides that any State Party may declare such an interest and that this "declaration shall be based on a verifiable link, especially a cultural, historical or archaeological link,

[8] Hereinafter: CPUCH.

[9] Art. 1, para. 1, a.

[10] Art. 9, para. 1, b.

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to the underwater cultural heritage concerned"[11]. The coastal State is entitled to co-ordinate the consultations, unless it expressly declares that it does not wish to do so, in which case the States Parties having declared an interest in being consulted shall appoint another coordinating State.

As regards urgent measures, the CPUCH provides as follows:

"Without prejudice to the duty of all States Parties to protect underwater cultural heritage by way of all practicable measures taken in accordance with international law to prevent immediate danger to the underwater cultural heritage, including looting, the Coordinating State may take all practicable measures, and/or issue any necessary authorizations in conformity with this Convention and, if necessary prior to consultations, to prevent any immediate danger to the underwater cultural heritage, whether arising from human activities or any other cause, including looting. In taking such measures assistance may be requested from other States Parties"[12].

The right of the coordinating State to adopt urgent measures is an important aspect of the CPUCH regime. It would have been contradictory to subordinate a right to act urgently to the conclusion of consultations that are normally expected to last for some time. It would also have been illusory to grant this right to the flag State, considering the risk of activities carried out by vessels flying a flag of convenience. The CPUCH clearly provides that in coordinating consultations, taking measures, conducting preliminary research and issuing authorizations, the coordinating State acts "on behalf of the States Parties as a whole and not in its own interest"[13]. Any such action cannot in itself constitute a basis for the assertion of any preferential or jurisdictional rights. It is regrettable that, despite all the efforts to reach a reasonable compromise, a consensus could not be achieved on the CPUCH as a whole, because of the fear of some maritime powers that the right to adopt urgent measures could be seen as an instance of "creeping" coastal State jurisdiction.

The procedural mechanism envisaged in the CPUCH has been put in effect for the first time in the case of the submarine heritage of the Skerki Bank. Located at the western entrance of the Sicilian Channel and connecting the western and eastern Mediterranean basins, the Skerki Bank has been since ancient times one of the busiest shipping routes in the world. Rocky elevations reaching almost the surface of the sea and invisible to navigators make it a particularly dangerous seaway and the place where hundreds of ships have been wrecked. In 2018, Italy notified the discovery of ancient and modern shipwrecks in the area of the Skerki Bank, located on the continental shelf of Italy and Tunisia. Seven other Mediterranean States (Algeria, Croatia, Egypt, France, Morocco, Spain and Tunisia), declared their interest in being consulted and a Coordination Committee was established. In 2022, an international underwater archaeological mission under the aegis of UNESCO was organized, using a French research vessel[14]. The results of the mission confirm that the area in question is full of historical, archaeological and geographical information (UNESCO, 2023). Moreover, the mission can be seen as a model to be replicated, *mutatis mutandis*, in other seas of the world within the CPUCH framework.

3.4 Sunken State ships and aircraft

The question of sunken State ships and aircraft, including warships, was much discussed during the negotiations for the CPUCH. Some States took the position that no special regime should be granted to such ships and aircraft. According to other States, the flag State retains title indefinitely to its sunken craft, wherever it is located, unless title has been expressly abandoned or transferred by it.

While the UNCLOS does not deal with this question, the CPUCH makes a distinction, depending on where such heritage is located. In the exclusive economic zone or on the continental shelf, "no activity directed at State vessels and aircraft shall be conducted without the agreement of the flag State and the collaboration of the Coordinating State"[15]. On the contrary,

"within their archipelagic waters and territorial sea, in the exercise of their sovereignty and in recognition of general practice among States, States Parties, with a view to cooperating on the best methods of protecting State vessels and aircraft, should inform the flag State Party to this Convention and, if applicable, other States with a verifiable link, especially a cultural, historical or archaeological link, with respect to the discovery of such identifiable State vessels and aircraft"[16].

The hortatory character of this provision ("should inform") has attracted the criticism by States which are in favour of the indefinite retention of title by the flag State on State craft.

Notably, in deciding a case to which the CPUCH was not applicable, the United States District Court for the Middle District of Florida, Tampa Division

[11] Art. 9, para. 5. The concept of "verifiable link" is not defined in the CPUCH (incidentally, it would be very difficult to draft any definition in this regard).

[12] Art. 10, para. 4

[13] Art. 10, para. 6.

[14] Tunisia acted as coordinating States for the part of the mission taking place on the Tunisian continental shelf and Italy for the part of the mission taking place on the Italian continental shelf.

[15] Art. 10, para. 7.

[16] Art. 7, para. 3.

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(order of 22 December 2009) and the United States Court of Appeals for the Eleventh Circuit (judgment of 21 September 2011) found that the frigate *Nuestra Señora de las Mercedes*, which sunk in 1804 during a battle with a British squadron, was a State ship belonging to Spain. Consequently, the ship and its cargo enjoyed sovereign immunity from United States jurisdiction (Aznar, 2019; Scovazzi, 2019).

4 Specific agreements

The CPUCH devotes one of its provisions to bilateral, regional or other multilateral agreements:

1. States Parties are encouraged to enter into bilateral, regional or other multilateral agreements or develop existing agreements, for the preservation of underwater cultural heritage. All such agreements shall be in full conformity with the provisions of this Convention and shall not dilute its universal character. States may, in such agreements, adopt rules and regulations which would ensure better protection of underwater cultural heritage than those adopted in this Convention.
2. The Parties to such bilateral, regional or other multilateral agreements may invite States with a verifiable link, especially a cultural, historical or archaeological link, to the underwater cultural heritage concerned to join such agreements"[17].

The provision paves the way to a multiple-level protection of underwater cultural heritage. The key to coordination between treaties applicable at different levels is the criterion of "better protection" (or "added value"), in the sense that regional and sub-regional treaties are concluded to ensure a better level of protection than that granted by treaties adopted at a more general level.

Some specific agreements have so far been concluded between coastal States and States interested in protecting wrecks of particular importance for their national historical and cultural heritage. These kinds of agreements, which are not prejudiced by the UNCLOS or the CPUCH, establish forms of cooperation between States interested in the protection of the underwater cultural heritage.

Reference can be made in this regard to the 1972 Agreement between the Netherlands and Australia concerning Old Dutch Shipwrecks, namely the *Batavia*, the *Vergulde Draeck*, the *Zuytdorp* and the *Zeewijk*, which sank respectively in 1629, 1656, 1712 and 1727 and have been found on the Australian continental shelf; to the 1989 Exchange of notes between the United Kingdom and South Africa concerning the *HMS Birkenhead*, sunk in 1852 in the vicinity of the South African coast; to the 1989 Agreement between the United States and France concerning the Wreck of the *CSS Alabama*, lost in battle in 1864 and found within the French territorial sea (Acquaviva, 2002); to the 1997 Memorandum of understanding between the United Kingdom and Canada on the shipwrecks *HMS Erebus* and *HMS Terror*, lost in 1846 during the attempt by Sir John Franklin to search for the North-West Passage; and to the 2003 Agreement between France and the United States of America regarding the wreck of the *La Belle*, which sank in 1686 off the coast of Texas. The multilateral 2003 Agreement concerning the shipwrecked vessel *RMS Titanic*, concluded by Canada, France, the United Kingdom and the United States, relating to the well-known British liner that sunk in 1912 and was discovered in 1985, has entered into force in 2019 only for the last two States.

References

Acquaviva, G. (2002). The Case of the Alabama - Some Remarks on the Policy of the United States towards Underwater Cultural Heritage". In G. Camarda and T. Scovazzi (Eds.), *The Protection of Underwater Cultural Heritage - Legal Aspects*, p. 31). Giuffrè, Milano.

Aznar, M. (2004), *La protección internacional del patrimonio cultural subacuático – Con especial referencia al caso de España.* Tirant, Valencia.

Aznar, M. (2010). Treasure Hunters, Sunken State Vessels and the 2001 UNESCO Convention on the Protection of Underwater Cultural Heritage. *International Journal of Marine and Coastal Law*, p. 209.

Aznar M. (2014). The Contiguous Zone as an Archaeological Maritime Zone. *International Journal of Maritime and Coastal Law*, p. 1.

Ballard, R. (1998). *The Discovery of the Titanic*. Warner, New York;

Bascom, W. (1987). Deepwater Salvage and Archaeology. In P. Throckmorton (Ed.), *The Sea Remembers – Shipwrecks and Archaeology,* p. 9. Barnes & Noble, New York.

Dromgoole, S. (2006). *The Protection of the Underwater Cultural Heritage – National Perspectives in Light of the UNESCO Convention 2001*. Martinus Nijhoff, Leiden:

Dromgoole, S. (2013). *Underwater Cultural Heritage and International Law*. Cambridge University Press, Cambridge.

Garabello, R. and Scovazzi, T. (2003). *The Protection of the Underwater Cultural Heritage: Before and After the 2001 UNESCO Convention*. Martinus Niijhoff, Leiden.

Lowther, J., Sellick, J. and Williams, M. (2025). *The Protection of the Underwater Cultural Heritage - National Approaches and Perspectives*. Brill / Nijhoff, Leiden.

O'Keefe, P. (2002). *Shipwrecked Heritage: A Commentary on the UNESCO Convention on Underwater Cultural Heritage*. Institute of Art & Law, Leicester;

Scovazzi, T. (2019). Sunken Spanish Ships before American Courts. *International Journal of Maritime and Coastal Law*, p. 245.

Strati, A. (1995). *The Protection of the Underwater Cultural*

[17] Art. 6.

https://doi.org/10.58440/ihr-32-1-c02

Heritage: An Emerging Objective of the Contemporary Law of the Sea. Nijhoff, Leiden.

Throckmorton P. (1987). Diving into the Past. In P. Throckmorton (Ed.), *The Sea Remembers – Shipwrecks and Archaeology*, p. 222. Barnes & Noble, New York.

UNESCO (2023). *International Underwater Archaeological Mission under the Aegis of UNESCO Convention for the Protection of the Underwater Cultural Heritage – Autonomous Projects on the Skerki Bank (Tunisian Continental Shelf) and in the Footsteps of Ballard-McCann in the Sicilian Channel (Italian Continental Shelf).*

CONFERENCE PAPER

Ocean observation paradox: UNCLOS, climate change and the future plastics treaty

Author
Tihao Zeng[1]

Preamble

The following work was presented at the 12th ABLOS Conference, 7–8 October 2025, Doha, Qatar in the oral session *Advances in ocean governance.*

Abstract

This paper explores the ocean observation paradox undermining global marine plastic governance. While the 2024 ITLOS Climate Change Advisory Opinion affirms a stringent due diligence obligation under UNCLOS Part XII to monitor transboundary pollution according to best available science, UNCLOS Part XIII structurally hinders these efforts. Continuous autonomous systems of ocean observation are physically essential to monitor plastics across the ocean but remain structurally incompatible with rigid coastal State consent regimes in the EEZ. Resolving this jurisdictional friction requires carving out certain ocean monitoring activities from traditional Marine Scientific Research. The emerging Plastics Treaty could embed pragmatic, notification-based exemptions to operationalize the science necessary for effective environmental compliance and litigation.

Keywords
ocean observation · plastic pollution · Plastics Treaty · marine scientific research · law of the sea · UNCLOS · GOOS

1 Introduction

Marine plastic pollution, intrinsically linked to the fossil fuel economy and climate change, has precipitated a severe global environmental crisis. Recognizing this, the 2024 Advisory Opinion by ITLOS affirmed that States possess a stringent due diligence to protect the marine environment using the best available science. Fulfilling this mandate requires continuous, coordinated ocean observation to track the pathways, degradation and accumulation dynamics of marine plastics. However, a profound legal paradox paralyzes these efforts: while UNCLOS Part XII demands proactive monitoring, the rigid Marine Scientific Research consent regimes of UNCLOS Part XIII actively hinder it. Because modern autonomous monitoring systems drift unpredictably across Exclusive Economic Zones, they are not well fit in with static coastal State consent rules. To unpack this observation paradox, this paper first presents the plastics-climate nexus and evolving State due diligence obligations under ITLOS. It then establishes the scientific needs of the Integrated Marine Debris Observing System as a core tracking mechanism. Subsequent analysis highlights the jurisdictional friction between the physical realities of ocean boundary currents and states sovereignty. Finally, the paper evaluates Part XIII's administrative bottlenecks, particularly the six-month advance notification requirement and assesses pragmatic workarounds like the Argo examples, concluding with a

✉ Tihao Zeng · tihao.zeng@graduateinstitute.ch
[1] Université de Genève, Geneva, Switzerland

call for specific operational carve-outs together with the future Plastics Treaty to support emerging environmental litigation and compliance mechanisms.

2 Plastics production, pollution, and the climate nexus

The crisis of marine plastic pollution has precipitated a multifaceted global emergency, incrementally degrading marine ecosystems, endangering human health, and inflicting devastating socioeconomic costs. Plastics, defined technically as materials containing high polymers that can be shaped during processing, and often compounded with chemical additives (ISO, 2013, n.d.), dominate anthropogenic marine litter primarily due to their extreme environmental persistence. Driven by exponential production and inadequate waste management, these synthetic materials accumulate across all marine compartments, from coastlines and the sea surface to the pelagic water column and the deep seafloor. The scale of this accumulation is so vast that researchers refer to the present epoch as the 'Plasticene', marked by a distinct depositional layer of synthetic debris in the geological record (Haram et al., 2020).

Once in the marine environment, plastics undergo complex physical and chemical degradation, fragmenting from visible macroplastics into microplastics (particles smaller than 5 mm) and nanoplastics (Andrady, 2015). This fragmentation continuously releases both secondary plastic particles and embedded toxic additives into the surrounding ecosystem (Fotopoulou & Karapanagioti, 2017). The resulting ecological damage is twofold: macroplastics inflict direct physical trauma on marine megafauna through entanglement and ingestion, while micro- and nanoplastics infiltrate trophic webs. These microscopic particles act as vectors for persistent organic pollutants, transferring toxins through the food chain to human populations, correlating with severe health risks such as metabolic disorders and potential carcinogenic effects (UNEP, 2016, 2021, 2022b). Beyond these biological impacts, marine plastic pollution imposes catastrophic economic burdens, with global annual losses primarily devastating the fisheries, tourism, and maritime navigation sectors, which estimated between USD 6 billion and 19 billion in 2018 (UNEP, 2021).

This pollution originates from a complex matrix of land- and sea-based sources. Terrestrial leakage, exacerbated by the export of waste to regions with inadequate infrastructure, enters the ocean via surface runoff, riverine transport, wastewater discharges, and atmospheric deposition. Simultaneously, sea-based sources, notably abandoned, lost, or discarded fishing gear (ALDFG) accounts for approximately 10 % of floating marine debris, which directly pollutes critical habitats, particularly in fragile ecosystems like the Arctic (UNEP, 2021). Fundamentally, however, the material source of this pollution is inextricably linked to fossil fuel extraction and climate change. Global plastic production, which doubled to 460 million metric tons between 2000 and 2019, is projected to nearly triple by 2060 (OECD, 2022). Because 99 % of synthetic plastics are derived directly from fossil feedstocks, their extraction and manufacturing account for immense greenhouse gas (GHG) emissions (UNEP, 2022b).

Consequently, plastic pollution functions as a potent threat multiplier, compounding climate-induced ecological stressors such as ocean acidification, warming, and sea-level rise. By degrading critical habitats like coral reefs and mangroves, plastic debris actively impairs ecosystem resilience, diminishing the natural capacity of coastal environments to withstand climate extremes (Deshpande et al., 2020; UNEP, 2021). Recognizing the indivisibility of these intertwined environmental crises, recent international jurisprudence has progressively interpreted treaty and customary obligations in light climate change which is linked to the plastics crisis. In its landmark 2024 Advisory Opinion, the International Tribunal for the Law of the Sea (ITLOS) affirmed that anthropogenic greenhouse gases (GHGs) emissions constitute 'pollution of the marine environment' under the United Nations Convention on the Law of the Sea (UNCLOS) (ITLOS, 2024; UN, 1982, 2023). Crucially, ITLOS clarified that Part XII of UNCLOS imposes a stringent due diligence obligation upon States to mitigate such transboundary pollution using the 'best available science' (ITLOS, 2024; Ford et al., 2022; Qiu et al., 2025).

Given the climate-plastic nexus, fulfilling this stringent due diligence obligation requires regulatory means that transcend traditional, siloed sectoral boundaries (Hubert, 2023; IOC, 2021). Because marine plastic pollution is inherently diffuse and transboundary, effective governance relies globally upon robust, harmonized data collection. Consequently, there is a growing consensus among scientific and policy communities regarding the imperative for an integrated global observation system capable of tracking plastic flows systematically across atmospheric, terrestrial, aquatic, and biological compartments (Bank et al., 2021). Deploying such a systemic framework is essential to establish the statistical baselines required to quantify the crisis, attribute pollution to specific sources, and evaluate the efficacy of mitigation strategies (Maximenko et al., 2021; Rayner et al., 2019). Ultimately, sustained and standardized ocean observation serves as the scientific foundation upon which all coordinated international marine governance must be built.

3 Scientific and physical bases of ocean observation for plastics

Before analyzing the legal regimes applicable to ocean observations, it is helpful to first understand its physical and technical basis. Some definitional clarifications are conducive to delineate the scope of discussion. In a narrow technical sense, ocean

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observation refers to the routine collection of oceanographic data across all maritime zones, capturing parameters such as temperature, pressure, currents, salinity, and wind (Roach, 2007). Seen more broadly, for example the EuroSea initiative conceptualizes ocean observation as a holistic 'value chain of marine knowledge' (Jolly et al. 2021; Reilly et al., 2022). In this framework, observation is not merely the extraction of raw data, but a fully integrated system connecting the initial deployment of platforms and sensors to modeling, forecasting, and the delivery of end user services. In practice, the term ocean observation usually encompasses this entire cycle of measurement, analysis, and data dissemination designed to foster economic value in the blue economy and deliver essential information for sustainable development (Wegelein, 2005; Yu, 2022a; Reilly et al., 2022). Within this context, *data* denotes the unprocessed factual representations of the physical world, whereas *information* refers to the analyzed and interpreted forms of data that are utilized by end users such as governments, port authorities, and environmental agencies, in order to guide governance, mitigate risks, or enforce treaty compliance (ITC, 2001; Reilly et al., 2022).

The ocean observing system worldwide is inherently decentralized, composed of multiple networks and platforms operated at global, regional, and national scales. Conceptually, it functions as an integrated framework comprising inputs based on societal or scientific demands (such as climate obligations or treaty requirements), observing processes executed by various platforms and sensors, and outputs delivered as data products, trend indicators, and hotspot alerts (IOC Task Team, 2012). Despite those observing platforms are fragmented across different jurisdictions and institutions, their activities are increasingly managed as integrated systems to maximize efficiency, avoid duplication, and ensure cross-domain coverage of physical, biogeochemical, and biological variables (Tanhua et al., 2019).

A central coordinating body is the Global Ocean Observing System (GOOS), established in 1991 under the Intergovernmental Oceanographic Commission (IOC) of UNESCO. Supported by partnerships with the World Meteorological Organization (WMO) and the Group on Earth Observations (GEO), GOOS defines standards, sets observing priorities, and coordinates a vast network of ship-based, fixed-point, and autonomous platforms globally. According to the GOOS Status Report 2025, the system's recent expansion has been heavily driven by technological innovations in autonomous networks, such as the Argo profiling array, which now exceeds 4,000 active floats, and the integration of emerging platforms like uncrewed surface vehicles. These autonomous advancements help offset declines in traditional ship-based observations caused by global budget constraints, while new public-private partnerships, such as the '10,000 Ships for the Ocean' initiative, increasingly leverage the commercial maritime industry to expand observing capacity (GOOS, 2025). The concerned activities should be considered as part of GOOS 'as long as the sampled data and the products and forecasts are distributed rapidly' to end users such as business, government, or regulatory authorities (Bork et al., 2008).

Despite these ongoing advancements and the active integration of biological and ecosystem variables, GOOS reports that the global network remains structurally 'subcritical'. The system possesses limited resilience to financial or geopolitical disruptions, depends heavily on a few major state contributors, and suffers from critical supply chain vulnerabilities. Introducing the tracking of marine plastic pollution into this already fragile framework presents unique physical, biological, and chemical complexities that challenge traditional oceanographic monitoring (Ryder, 2003; GOOS, 2025). Marine debris varies significantly in its chemical composition, encompassing diverse polymers and additives, as well as in physical properties such as size, shape, and buoyancy. Crucially, approximately 50 % of commercial plastics, such as polyethylene terephthalate (PET) and polyvinyl chloride (PVC), are intrinsically heavier than seawater and sink to the seafloor, effectively eluding surface monitoring. Furthermore, even buoyant microplastics are notoriously difficult to accurately quantify. Standard surface net tows typically capture only the top one meter of the water column, missing deeper layers where plastics are drawn down by biological aggregation, biofouling, and physical processes such as Langmuir circulation. Because of these highly variable transport and degradation dynamics, an estimated 66.7 % of ocean plastics remain currently unmonitorable under existing observation frameworks (Isobe & Iwasaki, 2022).

To overcome this fragmentation and bridge the massive data gaps in plastics monitoring, GOOS, GEO Blue Planet, and UNEP Global Partnership on Plastic Pollution and Marine Litter (UNEP-GPML) have jointly proposed the Integrated Marine Debris Observing System (IMDOS, 2023, 2025). IMDOS operates as an overlay designed to harmonize existing, disparate observation networks' data into a coherent and interoperable framework. This integration includes modelling, *in situ* observations such as water-following drifters and subsurface Argo floats that mimic the vertical movement of debris in pelagic ecosystems, with the synoptic, broader capabilities of remote sensing satellites as well as citizen science. These automated data streams are further augmented by numerical models that optimize field observations and citizen science initiatives, which expand contributions from coastal communities. Given that plastic waste accounts for more than 80 % of the total marine debris, IMDOS acts as a core system in addressing marine plastic pollution (Maximenko et al., 2019; Maximenko et al., 2021). To operationalize this mission, the IMDOS Steering Committee recently

formalized eleven dedicated Task Teams spanning thematic data collection, technical coordination, and policy engagement (GEO Blue Planet, 2025).

Following the recent second part of the fifth session of the Intergovernmental Negotiating Committee to develop an international legally binding instrument on plastic pollution, including in the marine environment (INC-5.2) negotiations, an important direction for monitoring emphasizes a comprehensive life-cycle approach divided into three complementary streams: plastics in the economy (production and trade), plastics in waste (collection and recycling), and plastics in the environment. While IMDOS is most directly relevant to the environmental monitoring stream in specifically addressing marine leakages, its efforts must be designed in close coordination with economic and waste monitoring. This ensures data interoperability across the full plastic life cycle through harmonized indicators, comparable units, and integrated datasets routed through centralized hubs like the UNEP-GPML digital platform. To solidify this role, IMDOS has established a dedicated 'UN Global Plastics Treaty' Task Team (TT10) aimed at actively engaging the INC process, positioning IMDOS as the unified system for marine debris monitoring methodologies, and encouraging the creation of a centralized repository aligned with the treaty's objectives. However, a critical hurdle remains: IMDOS currently operates without a clear legal mandate from an international commitment or an UN organization, making the acquisition of such a mandate and sustained financial commitments a priority for effective treaty implementation (GEO Blue Planet, 2025).

The operational backbone of this integration is the Essential Ocean Variables (EOVs) developed by GOOS. EOVs are defined as the minimal, agreed-upon set of variables whose sustained measurement is indispensable for understanding ocean changes and informing policy (IOC Task Team, 2012). As the emerging plastics treaty ambitions to address the full life cycle of plastics, ocean observation systems must trace both upstream inputs and downstream impacts (UNEP, 2022). To achieve this, a dedicated Marine Plastics EOV is currently at the pilot stage under the guidance of GOOS and IMDOS. The EU-funded EuroSea project (Deliverable D1.5) formally conceptualizes this as 'the first in a new class of EOVs which help the GOOS address the need to monitor human impacts' rather than strictly natural phenomena (Palacz et al., 2022). Deliverable D1.5 provides the foundational EOV Specification Sheet, establishing a Common Sampling Protocol (CSP) aligned with GESAMP Working Group 40 guidelines that augments existing ocean observing approaches to elevate the readiness level of marine debris monitoring globally (EuroSea, 2022; GESAMP, 2019). The scope of this EOV encompasses specific sub-variables, including floating macroplastic patches, size-fractioned microplastics, shoreline litter, seafloor debris, plastics in biota, and polymer identification through chemical markers.

Beyond the dedicated Marine Plastics EOV, effective monitoring requires the adaptation of existing biological, biogeochemical, and physical variables. Within the Biogeochemistry EOV for Particulate Matter, microplastics are now actively conceptualized as a subclass of suspended particulate matter (Erni-Cassola et al., 2024). Established sampling techniques for particulate organic and inorganic matter such as optical sensors are being adapted to include plastic particle counts, mass, and polymer composition (Othman et al., 2023). Simultaneously, remote sensing under the Ocean Colour EOV is contributing to macroplastic observation. Recent studies utilizing Sentinel-2 and Landsat high-resolution multispectral imagery have demonstrated that aggregated floating macroplastic patches can be detected using spectral unmixing techniques (Papageorgiou et al., 2022; Cerra et al., 2025). Finally, mature physical EOVs such as surface and subsurface currents, wind stress, sea state, sea surface height, and sea-ice extent, remain highly relevant, as they directly govern the transport pathways, degradation dynamics, and accumulation zones of plastics across the global ocean (Maximenko et al., 2019; Maximenko et al., 2021; EuroSea, 2022).

4 UNCLOS and Part XII obligations

UNCLOS Part XII establishes the comprehensive framework for marine environmental protection. Article 192 imposes a general, overarching obligation on all States to protect and preserve the marine environment. This is operationalized through Article 194, which mandates States to take all measures necessary to prevent, reduce, and control pollution from 'any source'. The general obligation of Article 192 is further accompanied by two main categories of procedural obligations: cooperation (Articles 197–201) and monitoring and assessment (Articles 204–206). To ensure compliance and understand environmental impacts, Articles 204 and 206 specify the requirements for States to continuously monitor the risks and effects of pollution and to conduct environmental impact assessments (EIA) when there are reasonable grounds to believe planned activities may cause substantial pollution or significant harmful changes (Dupuy & Viñuales, 2018).

According to Article 1(1)(4) of UNCLOS, 'pollution of the marine environment' is defined as the introduction by humans, directly or indirectly, of substances or energy into the marine environment that results in deleterious effects. In its 2024 Advisory Opinion (Case No. 31), the ITLOS broke this definition down into three cumulative criteria: (1) identification of a substance or energy; (2) introduction by humans; and (3) actual or likely harm. Relying extensively on the 'best available science' from the Intergovernmental Panel on Climate Change (IPCC), particularly the Sixth Assessment Report (AR6) and the Special Report on the Ocean and Cryosphere (IPCC, 2019, 2023), the

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Tribunal determined that anthropogenic GHGs constitute marine pollution. Accordingly, ITLOS ruled that Article 194 imposes a stringent due diligence obligation on States to mitigate such pollution, emphasizing that necessary measures must be determined objectively based on the best available science (ITLOS, 2024). This conveys a clear message: protecting the marine environment from complex, transboundary stressors require proactive, science-based governance (Hubert, 2023).

The ITLOS precedent has profound implications for the governance of marine plastic pollution. As 99 % of synthetic plastics are derived from fossil fuels and their production is inextricably linked to GHG emissions, the stringent due diligence standard and the mandate to utilize the best available science directly apply to regulating the full life cycle of plastics. To fulfill their due diligence obligations under Part XII, States are legally obliged to cooperate in good faith to implement robust ocean observation systems that generate baseline, attribution, and compliance data. Integrating new marine technologies for ocean observations, such as smart sensors, remote satellite imaging, and autonomous underwater vehicles (AUVs), may increasingly be understood as a necessity to meeting this due diligence and cooperation obligation.

However, deploying these observing elements raises jurisdictional friction. While States are mandated to monitor pollution under Part XII, Marine Scientific Research (MSR) under UNCLOS Part XIII remains subject to strict coastal State consent regimes, balancing research freedom with coastal sovereignty (Caflisch & Piccard, 1978; Stephens & Rothwell, 2016). The physical reality of ocean dynamics exacerbates this legal uncertainty. Exclusive Economic Zones (EEZs) and continental shelves encompass approximately 40 % of the global ocean, yet their scientific importance regarding plastic transport is disproportionately high. Much of the ocean's flow is physically constrained by the bottom and lateral topography found within these margins. Furthermore, due to the Earth's rotation, the strongest near-surface flows are concentrated at western boundaries, while critical upwelling zones and the primary sources of terrestrial run-off (and thus, plastic pollution) dominate eastern boundaries (Ryder, 2003).

Because oceanographic events and pollutant transport operate across multiple cycles of variability that are entirely unconstrained by maritime boundaries, conducting comprehensive marine monitoring is physically impossible without sustained access to these coastal domains. While Part VII of UNCLOS preserves MSR as a freedom on the high seas, monitoring activities within the EEZ are strictly subject to the Part XIII consent regime. Nevertheless, interpretation of and the interaction between Part XII and Part XIII has been discusses in this context (Hubert, 2023).

5 Ocean observation for plastics and marine scientific research

While UNCLOS Part XIII establishes the global regime for MSR, the Convention notably fails to define the term 'marine scientific research' itself (Caflisch & Piccard, 1978; Stephens & Rothwell, 2016). This seemingly intentional ambiguity is a product of compromise during the Third UN Conference on the Law of the Sea that has generated persistent friction between coastal States and researching States (Birnie, 1995). Coastal States generally favor a broad interpretation that subjects most data collection activities in the EEZ to the consent regime of Article 246, viewing them as potentially related to natural resources or national security (Roach & Smith, 2012). Conversely, researching States often distinguish between 'pure' scientific inquiry and 'applied' research, arguing that the routine, automated monitoring of the marine environment falls under the distinct category of operational oceanography and thus outside the restrictive scope of Part XIII entirely (Stephens & Rothwell, 2016; Yu, 2022a).

While Article 243 encourages States and international organizations to cooperate to create favorable conditions for MSR, the core legal obstacle to an integrated global observation system remains the consent regime. Under Article 245, coastal States have exclusive rights to regulate MSR in the territorial sea. In the EEZ and on the continental shelf, Article 246(2) stipulates that MSR shall be conducted with the consent of the coastal State. While this consent should, in 'normal circumstances', be granted for peaceful research (Article 246(3)), coastal States retain the discretion to withhold it if the research is of direct significance for the exploration and exploitation of natural resources (Article 246(5)(a)). Because tracking marine plastics and climate variables relies on continuous, long-term time-series data, this static, project-by-project consent model is operationally ill-suited (Ryder, 2003). The bureaucratic delays inherent in seeking diplomatic clearance for every sensor or float entering a foreign EEZ create massive spatial and temporal gaps in global datasets (Roach & Smith, 2012).

This operational challenge is acutely exemplified by the European Global Ocean Observing System (EuroGOOS), which coordinates monitoring activities across the highly fragmented maritime jurisdictions of the European seas. Because UNCLOS provides no distinct legal exemption for routine operational oceanography, EuroGOOS members face significant legal precarity when deploying autonomous technologies, such as underwater gliders. These autonomous platforms are essential for tracking transboundary pollutants, such as marine plastic debris, across transition regions between open oceans and shelf seas. However, their unpredictable drift patterns inevitably cross multiple maritime boundaries, rendering them fundamentally incompatible with existing static jurisdictional frameworks. Recent assessments from the EuroSea initiative shows that this incompatibility is

further exacerbated by the fact that Member States possess 'no explicit requirement for consistent interpretation and implementation of international rules' regarding ocean observation (van Doorn & Veloso, 2023). It emphasized that the primary operational bottleneck is UNCLOS Article 248, which requires researching States to submit detailed information to seek coastal State consent at least six months in advance of an observing campaign within a foreign EEZ. Furthermore, if a coastal State does not react by the day the project commences, UNCLOS Article 252 dictates that consent is merely implied, a mechanism that creates 'unnecessary unpredictability for planning marine scientific research' for unpredictably drifting autonomous fleets (van Doorn & Veloso, 2023). To resolve this administrative friction, EuroSea advocates for a harmonized EU-level ocean observing policy, applying the principle of subsidiarity. Specifically, this includes the adoption of standardized clearance request forms and the establishment of a centralized Marine Scientific Research Clearance Office in each Member State, which could act as a single point of contact to effectively compress the diplomatic clearance timeframe from six months to a single month (van Doorn & Veloso, 2023).

Historically, the international scientific community has attempted to bypass these bottlenecks through non-legally binding instruments. Recognizing the incompatibility of Part XIII with free-floating equipment, the IOC and its Advisory Body of Experts on the Law of the Sea (ABE-LOS) formulated Draft Practical Guidelines aiming to build mutual trust through notification procedures for profiling floats (IOC, 1999). While providing certain stability and clarity, these guidelines remain incomplete: they omit emerging technologies like gliders, fail to regulate devices drifting from one foreign EEZ directly into another, and ultimately still build upon the restrictive UNCLOS Part XIII consent regime (Bork et al., 2008). An alternative legal pathway is the application of UNCLOS Article 247, which provides a simplified, implied consent regime for MSR conducted under the auspices of a competent international organization like the IOC. Yet, applying mandatory six-month advance notification and four-month no-objection period to individual, unpredictably drifting platforms remains highly impractical (IOC, 2005). To function effectively for autonomous fleets, this notification timeline would need to apply to an overall project's inception rather than individual float border-crossings. Ultimately, as historical debates over the Ocean Data Acquisition Systems (ODAS) Draft Convention demonstrated, UNCLOS Part XIII was simply not designed for autonomous ocean observation platforms, leaving their legal governance firmly anchored in uncertainty (Bork et al., 2008). Despite the critical global need for operational oceanography to track climate change and transboundary plastic pollution, coastal States remain reluctant to modify the existing MSR consent regime, leaving the legal governance of autonomous ocean observation platforms in uncertainty.

Nevertheless, the 'Argo approach' offers a pragmatic legal precedent for the future. The Argo program, which maintains thousands of profiling floats globally, operates under IOC Resolution XX-6. It utilizes a notification scheme rather than a strict consent mechanism: researching States notify coastal States of deployments, and if a float drifts into an EEZ, the coastal State can request that data be withheld from the public domain or shared only with them (Ryder, 2003; Yu, 2022b). This approach balances the 'due regard' obligation of Article 58 with the scientific imperative for global coverage. For marine plastics observation, adopting a similar 'notification and transparent data' framework, potentially to be formalized under the new Plastics Treaty or subsequent decisions, could legitimize the use of IMDOS assets in EEZs without abrogating coastal State rights (Stephens & Rothwell, 2016). The routine, automated collection of oceanographic data using autonomous platforms is arguably distinct from traditional MSR (Ryder, 2003; Yu, 2022a). Yet, while frameworks like WMO Resolution 45 (Cg-18; WMO, 2019) support the free operation of certain observing platforms in the EEZ by excluding meteorological tracking from the Part XIII regime, the legal boundary for environmental and plastic tracking remains highly blurred (Yu, 2022b). Furthermore, as the deployment of Maritime Autonomous Surface Ships (MASS) and AUVs expands for pollution tracking, clarifying their legal status and navigational rights under UNCLOS is essential (Venancio, 2025; Xing, 2024; Zou & Telesetsky, 2021). Addressing these jurisdictional ambiguities is paramount, as continuous, unhindered ocean observation is the foundational mechanism through which States can actually operationalize their environmental due diligence obligations under UNCLOS.

6 Conclusion

Sustained and standardized ocean observation serves as the indispensable scientific foundation upon which coordinated marine governance of marine plastics could effectively take place. As this paper has demonstrated, the physical complexities of marine plastic pollution demand a continuous, globally integrated monitoring framework like the IMDOS. Yet, the efficacy of such systems is severely compromised by the legally stringent consent regime of UNCLOS Part XIII. The coastal State consent, particularly the six-month advance notification requirement under Article 248, is operationally incompatible with the unpredictable drift patterns of autonomous gliders and profiling floats essential for modern oceanography (Bork et al., 2008). Consequently, the international community is caught in an observation paradox: legally compelled by Part XII and the ITLOS due diligence standard to monitor transboundary pollution, yet legally restricted from accessing the critical 40 % of the ocean contained within the EEZ.

Beyond informing international policy, the data

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generated by these observation systems serves as evidentiary ground for emerging environmental litigations. In the realm of climate change, recent judicial decisions including that of the ITLOS as well as by several domestic courts rely extensively on the 'best available science' compiled by the IPCC. This reliance on empirical data is now extending to a rapidly growing wave of plastics litigation, where stakeholders increasingly seek to hold States accountable for due diligence failures and corporate entities liable for ecological harm and public nuisance (Beresford et al., 2022). Currently, such litigation is heavily constrained by the scientific difficulty of proving complex causation and source attribution within dynamic ocean currents (Swiss Re, 2025). But advancements have been made. For example, the Court of Appeal of Rouen unprecedentedly convicted a vessel of marine pollution based solely on satellite detection in 2025 (CLS, 2025; FNE, 2025). By tracing the lifecycle pathways of polymers from terrestrial leakage to pelagic sinks and precisely quantifying microplastic accumulation, an unhindered observational framework like IMDOS would provide the objective metrics necessary to attribute transboundary harm, establish legal liability, and enforce compliance.

Resolving this friction requires moving beyond the rigid interpretation and application of MSR. While existing workarounds like UNCLOS Article 247 remain impractical for free-floating platforms, the 'Argo approach' based on deployment notification and transparent data sharing rather than explicit prior consent may prove pragmatic for a broader application. As negotiations for the Global Plastics Treaty continue, policymakers must embed specific legal carve-outs for operational ocean monitoring, ensuring that the rigid jurisdictional limits of the 20th century do not blind the science required to save the oceans in the 21st.

References

Andrady, A. L. (2015). Persistence of plastic litter in the oceans. *Marine Anthropogenic Litter*, 57–72. Springer.

Bank, M. S., Swarzenski, P. W., Duarte, C. M., Rillig, M. C., Koelmans, A. A., Metian, M., Wright, S., Provencher, J. F., Sanden, M., Jordaan, A., Wagner, M., Thiel, M. and Ok, Y. S. (2021). Global plastic pollution observation system to aid policy. *Environmental Science & Technology*, *55*, 7770–7775. https://doi.org/10.1021/acs.est.1c00818

Beresford, N., Brook, N., Carrigan, D., Haas, K., Kassing, D., Pies, C., Studdert, J. and Verdam, H. (2022). *The price of plastic pollution: Social costs and corporate liabilities (Annex 2: Liability risks arising from the manufacture, distribution, use and disposal of plastics)*. Minderoo Foundation. https://cdn.minderoo.org/content/uploads/2022/10/13131231/The-Price-of-Plastic-Pollution-Annex-2.pdf (last accessed 31 March 2026).

Birnie, P. (1995). Law of the sea and ocean resources: Implications for marine scientific research. *International Journal of Marine and Coastal Law, 10*(2), 229–251.

Bork, K., Karstensen, J., Visbeck, M. and Zimmermann, A. (2008). The Legal Regulation of Floats and Gliders—In Quest of a New Regime? *Ocean Development & International Law, 39*(3), 298–328. https://doi.org/10.1080/00908320802235338

Caflisch, L. and Piccard, J. (1978). The legal régime of marine scientific research and the Third United Nations Conference on the Law of the Sea. *Zeitschrift für ausländisches öffentliches Recht und Völkerrecht, 38*, 848–901.

Cerra, D., Auer, S., Baissero, A. and Bachofer, F. (2025). Detection and Monitoring of Floating Plastic Debris on Inland Waters From Sentinel-2 Time Series. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 18*, 1122–1138. https://doi.org/10.1109/JSTARS.2024.3502796

CLS (2025). *A victory for the oceans: CLS expertise establishes a legal precedent*. CLS, for Earth from Space, Ramonville Saint-Agne, France. https://maritime-intelligence.groupcls.com/a-victory-for-the-oceans-marine-pollution-legal-precedent/ (last accessed 31 March 2026).

Deshpande, P. C., Philis, G., Brattebø, H. and Fet, A. M. (2020). Using Material Flow Analysis (MFA) to generate the evidence on plastic waste management from commercial fishing gears in Norway. *Resources, Conservation & Recycling, 5*, 100024. https://doi.org/10.1016/j.rcrx.2019.100024

Dupuy, P.-M. and Viñuales, J. E. (2018). *International Environmental Law* (2nd ed.). Cambridge University Press.

Erni-Cassola, G., Dolf, R. and Burkhardt-Holm, P. (2024). Microplastics in the water column of the Rhine River near Basel: 22 months of sampling. *Environmental Science & Technology, 58* (12), 5491–5499. https://doi.org/10.1021/acs.est.3c08364

FNE (2025). *Pollution maritime : Affaire Guardians la détection par satellite retenue comme nouveau moyen de preuve*. France Nature Environnement Normandie, Rouen, France. https://www.fne-normandie.fr/2025/04/25/pollution-maritime-affaire-guardians-la-detection-par-satellite-retenue-comme-nouveau-moyen-de-preuve/ (last accessed 31 March 2026).

Ford, H. V., Jones, N. H., Davies, A. J., Godley, B. J., Jambeck, J. R., Napper, I. E., Suckling, C. C., Williams, G. J., Woodall, L. C. and Koldewey, H. J. (2022). The fundamental links between climate change and marine plastic pollution. *Science of The Total Environment, 806*, 150392. https://doi.org/10.1016/j.scitotenv.2021.150392

Fotopoulou, K. N. and Karapanagioti, H. K. (2017). Degradation of Various Plastics in the Environment. In H. Takada and H. K. Karapanagioti (Eds.), *Hazardous Chemicals Associated with Plastics in the Marine Environment* (Vol. 78, pp. 71–92). Springer International Publishing. https://doi.org/10.1007/698_2017_11

GEO Blue Planet (2025). *1st IMDOS Steering Committee meeting: Meeting report*. https://geoblueplanet.org/wp-content/uploads/2024/10/250108-IMDOS-SC-meeting_report_vf.pdf (last accessed 31 March 2026).

GESAMP (2019). *Guidelines for the monitoring and assessment of plastic litter in the ocean* (P. J. Kershaw, A. Turra and F. Galgani, Eds.). (Reports and Studies GESAMP No. 99). United Nations Environment Programme.

GOOS (2025). *Global Ocean Observing System status report 2025* (GOOS Report No. 310). GOOS Secretariat, OceanOPS, GOOS Observations Coordination Group. https://www.ocean-ops.org/goosreport/ (last accessed 31 March 2026).

Haram, L. E., Carlton, J. T., Ruiz, G. M. and Maximenko, N. A. (2020). A Plasticene Lexicon. *Marine Pollution Bulletin, 150*,

110714. https://doi.org/10.1016/j.marpolbul.2019.110714

Hubert, A.-M. (2023). Marine scientific research and the protection of the seas and oceans. In R. Rayfuse, A. Jaeckel and N. Klein (Eds.), *Research Handbook on International Marine Environmental Law* (pp. 385–408). Edward Elgar Publishing.

IMDOS (2023). *Strategy Document*. Integrated Marine Debris Observing System. https://imdos.org/files/page_files/32/imdos-strategy-endorsednov23.pdf (last accessed 31 March 2026).

IMDOS (2025). *Navigating the Global Plastics Treaty: The Role of IMDOS*. Integrated Marine Debris Observing System. https://imdos.org/news/inc5-2 (last accessed 31 March 2026).

IOC (1999). *The Argo Project* (Resolution XX-6). The Intergovernmental Oceanographic Commission (IOC) of UNESCO, Paris, France. https://unesdoc.unesco.org/ark:/48223/pf0000120502 (last accessed 31 March 2026).

IOC (2005). *Procedure for the application of Article 247 of the United Nations Convention on the Law of the Sea by the Intergovernmental Oceanographic Commission of UNESCO* (Annex to Resolution XXIII-8). The Intergovernmental Oceanographic Commission (IOC) of UNESCO, Paris, France. https://www.jodc.go.jp/info/ioc_doc/Governing/145407e.pdf (last accessed 31 March 2026).

IOC (2021). *Ocean knowledge for a sustainable ocean economy: Synergies between the Ocean Decade and the outcomes of the Ocean Panel* (The Ocean Decade Series, 17; IOC/2021/ODS/17). The Intergovernmental Oceanographic Commission (IOC) of UNESCO, Paris, France. https://unesdoc.unesco.org/ark:/48223/pf0000375969 (last accessed 31 March 2026).

IOC Task Team (2012). A *Framework for Ocean Observing* (IOC/INF-1284 rev 2). The Intergovernmental Oceanographic Commission (IOC) of UNESCO, Paris, France. https://unesdoc.unesco.org/ark:/48223/pf0000211260 (last accessed 31 March 2026).

IPCC (2019). *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. M. Weyer, Eds.). Cambridge University Press. https://doi.org/10.1017/9781009157964

IPCC (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Core Writing Team, H. Lee and J. Romero, Eds.). IPCC. https://www.ipcc.ch/report/ar6/syr/ (last accessed 31 March 2026).

ISO (2013). *Plastics — Vocabulary* (ISO Standard No. 472:2013). International Organization for Standardization, Geneva, Switzerland. https://www.iso.org/standard/44102.html (last accessed 31 March 2026).

ISO (n.d.) *ISO/TC 61: Plastics*. International Organization for Standardization, Geneva, Switzerland. https://www.iso.org/committee/49256.html (last accessed 31 March 2026).

Isobe, A. and Iwasaki, S. (2022). The fate of missing ocean plastics: Are they just a marine environmental problem? *Science of the Total Environment, 825*, 153935. https://doi.org/10.1016/j.scitotenv.2022.153935

ITC (2001). *Principles of Remote Sensing*. International Institute for Aerospace Survey and Earth Sciences.

ITLOS (2024). *Request for an advisory opinion submitted by the Commission of Small Island States on Climate Change and International Law* (Advisory Opinion, Case No. 31). International Tribunal for the Law of the Sea, Hamburg, Germany.

Jolly, C., Jolliffe, J., Postlethwaite, C., and Heslop, E. (2021). Value chains in public marine data: A UK case study. *OECD Science, Technology and Industry Working Papers*, No. 2021/11, OECD Publishing, Paris. https://doi.org/10.1787/d8bbdcfa-en

Liblik, T., Karstensen, J., Testor, P., Alenius, P., Hayes, D., Ruiz, S., Heywood, K. J., Pouliquen, S., Mortier, L. and Mauri, E. (2016). Potential for an underwater glider component as part of the Global Ocean Observing System. *Methods in Oceanography, 17*, 50–82. https://doi.org/10.1016/j.mio.2016.05.001

Maximenko, N., Corradi, P., Law, K. L., Van Sebille, E., Garaba, S. P., Lampitt, R. S., Galgani, F., Martinez-Vicente, V., Goddijn-Murphy, L., Veiga J. M., Thompson, R. C., Maes, C., Moller, D., Löscher, C. R., Addamo, A. M., Lamson, M. R., Centurioni, L. R., Posth, N. R., Lumpkin, R., Vinci, M., Martins, A. M., Pieper, C. D., Isobe, A., Hanke, G., Edwards, M., Chubarenko, I. P., Rodriguez, E., Aliani, S., Arias, M., Asner, G. P., Brosich, A., Carlton, J. T., Chao, Y., Cook, A.-M., Cundy, A. B., Galloway, T. S., Giorgetti, A., Goni, G. J., Guichoux, Y., Haram, L. E., Hardesty, B. D., Holdsworth, N., Lebreton, L., Leslie, H. A., Macadam-Somer, I., Mace, T., Manuel, M., Marsh, R., Martinez, E., Mayor, D. J., Le Moigne, M., Molina Jack, M. E., Mowlem, M. C., Obbard, R. W., Pabortsava, K., Robberson, B., Rotaru, A.-E., Ruiz, G. M., Spedicato, M. T., Thiel, M., Turra, A. and Wilcox, C. (2019). Toward the Integrated Marine Debris Observing System. *Frontiers in Marine Science, 6*, 447. https://doi.org/10.3389/fmars.2019.00447

Maximenko, N., Palacz, A. P., Biermann, L., Carlton, J., Centurioni, L., Crowley, M., Hafner, J., Haram, L., Helm, R. R., Hormann, V., Murray, C., Ruiz, G., Shcherbina, A., Stopa, J., Streett, D., Tanhua, T., Wright, C. and Zabin, C. (2021). An integrated observing system for monitoring marine debris and biodiversity. *Oceanography, 34*(4), 52–59. https://doi.org/10.5670/oceanog.2021.supplement.02-22

OECD (2022). *Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options*. OECD Publishing, Paris.

Othman, A. M., Elsayed, A. A., Sabry, Y. M., Khalil, D. and Bourouina, T. (2023). Detection of sub-20 µm microplastic particles by attenuated total reflection Fourier transform infrared spectroscopy and comparison with Raman spectroscopy. *ACS Omega, 8*(11), 10071–10081. https://doi.org/10.1021/acsomega.2c07998

Palacz, A., Telszewski, M., Tanhua, T. and Heslop, E. (2022). *Marine plastics EOV and common sampling protocol* (EuroSea Deliverable D1.5). EuroSea. https://doi.org/10.3289/eurosea_d1.5

Papageorgiou, D., Topouzelis, K., Suaria, G., Aliani, S. and Corradi, P. (2022). Sentinel-2 Detection of Floating Marine Litter Targets with Partial Spectral Unmixing and Spectral Comparison with Other Floating Materials (Plastic Litter Project 2021). *Remote Sensing, 14*(23), 5997. https://doi.org/10.3390/rs14235997

Qiu, W., Wu, B. and Tai, T. H. (2025). Judicialization and legal implications of international maritime governance in the context of climate change: Insights from ITLOS Advisory Opinion No. 31. *Frontiers in Marine Science, 12*, 1640148. https://doi.org/10.3389/fmars.2025.1640148

Rayner, R., Jolly, C. and Gouldman, C. (2019). Ocean observing and the blue economy. *Frontiers in Marine Science, 6*(330), 1–6.

https://doi.org/10.58440/ihr-32-1-c06

Reilly, K., Ros, S., MacManus, C., Manson, S., Cortes, J., Garcia, J. R. and Villa, J. (2022). *Report on economic value of ocean observations* (EuroSea Deliverable D8.6). EuroSea. https://doi.org/10.3289/eurosea_d8.6

Roach, J. A. (2007). Defining scientific research: Marine data collection. In M. H. Nordquist et al. (Eds.), *Law, Science & Ocean Management* (pp. 541–574). Martinus Nijhoff Publishers.

Roach, J. A. and Smith, R. W. (2012). *Excessive Maritime Claims* (3rd ed.). Martinus Nijhoff Publishers.

Ryder, P. (2003). *A possible migration from marine scientific research to operational oceanography in the context of the United Nations Convention on the Law of the Sea (UNCLOS)*. Environmental Information Services.

Stephens, T. and Rothwell, D. (2016). Marine scientific research. In D. Rothwell, A. Oude Elferink, K. Scott and T. Stephens (Eds.), *The Oxford Handbook of the Law of the Sea* (pp. 559–581). Oxford University Press.

Swiss Re. (2025). *Plastics: a new wave of litigation?* Swiss Re Institute. https://www.swissre.com/institute/research/sonar/sonar2025/plastics-new-wave-litigation.html (last accessed 31 March 2026).

Tanhua, T., McCurdy, A., Fischer, A., Appeltans, W., Bax, N., Currie, K., DeYoung, B., Dunn, D., Heslop, E., Glover, L. K., Gunn, J., Hill, K., Ishii, M., Legler, D., Lindstrom, E., Miloslavich, P., Moltmann, T., Nolan, G., Palacz, A., Simmons, S., Sloyan, B., Smith, L. M., Smith, N., Telszewski, M., Visbeck, M. and Wilkin, J. (2019). What We Have Learned From the Framework for Ocean Observing: Evolution of the Global Ocean Observing System. *Frontiers in Marine Science, 6*, 471. https://doi.org/10.3389/fmars.2019.00471

UN (1982). *United Nations Convention on the Law of the Sea* (adopted 10 December 1982, entered into force 16 November 1994). 1833 U.N.T.S. 397. United Nations, New York, USA. https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf (last accessed 31 March 2026).

UN (2023). *Agreement under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction* (A/CONF.232/2023/4). United Nations, New York, USA.

UNEP (2016). *Marine plastic debris and microplastics* (UNEP/EA.2/Res.11). UN Environment Programme, Nairobi, Kenya.

UNEP (2021). *From pollution to solution: A global assessment of marine litter and plastic pollution*. UN Environment Programme, Nairobi, Kenya.

UNEP (2022a). *Resolution 5/14: End plastic pollution: Towards an international legally binding instrument* (UNEP/EA.5/Res.14). UN Environment Programme, Nairobi, Kenya.

UNEP (2022b). *Plastics science: Note by the secretariat* (UNEP/PP/INC.1/7). UN Environment Programme, Nairobi, Kenya.

van Doorn, R. and Veloso, P. F. (2023). *Report on the use of legal frameworks for ocean observing systems* (EuroSea Deliverable D1.7). EuroSea. https://doi.org/10.3289/eurosea_d1.7

Venancio, D. S. (2025). Challenges in defining the legal status of Autonomous Underwater Vehicles (AUVs). *Ocean Development & International Law, 56*(3), 1–20. https://doi.org/10.1080/00908320.2025.2531164

Wegelein, F. H. T. (2005). *Marine Scientific Research: The Operation and Status of Research Vessels and Other Platforms in International Law*. Martinus Nijhoff Publishers.

WMO (2019). *Resolution 45 (Cg-18)*. World Meteorological Organization, Geneva, Switzerland.

Xing, W. (2024). Contemplating Maritime Autonomous Surface Ships (MASS) under the international law on ship-source pollution. *Marine Pollution Bulletin, 207*, 116884.

Yu, C. (2022a). *Marine Scientific Research and the Regulation of Modern Ocean Data Collection Activities under UNCLOS*. Brill Nijhoff.

Yu, C. (2022b). Operational oceanography as a distinct activity from marine scientific research under UNCLOS? – An analysis of WMO Resolution 45 (Cg-18). *Marine Policy, 143*, 105131.

Zou, K. and Telesetsky, A. (2021). *Marine scientific research, new marine technologies and the law of the sea*. Brill Nijhoff.

CONFERENCE PAPER

Balancing national legal protections of fisheries data and UNCLOS obligations in the age of AI

Author
Eva van Heukelom[1]

Preamble

The following work was presented at the 12th ABLOS Conference, 7–8 October 2025, Doha, Qatar in the oral session *New technologies and maritime security*.

Abstract

Fisheries are an essential ocean industry, generating billions annually and supporting the livelihoods of millions worldwide. Effective management depends on governments' ability to collect and analyse fisheries data, including vessel movements, catch, and ownership information. This article examines the international legal frameworks that mandate such data collection, alongside national legal protections that may restrict data sharing beyond public authorities. It considers whether these limitations are justified, given the inherently transboundary nature of fisheries and the need for cross-border data exchange, particularly in efforts to combat illegal, unreported and unregulated (IUU) fishing.

Keywords
keyword fisheries · UNCLOS · fisheries transparency · fisheries data · AI · data protection · privacy

1 Introduction

Ask any fisheries inspector what matters most for effective management, and they will tell you: you cannot manage what you cannot see. In fisheries, "seeing" means having timely, reliable information on where, when, and how vessels are fishing, and what they are catching. This visibility underpins States' monitoring, control and surveillance (MCS) systems and is essential to meeting the obligation under the United Nations Convention on the Law of the Sea (UNCLOS) to conserve living marine resources on the basis of the best scientific evidence available and to maintain stocks at levels capable of producing maximum sustainable yield (UN, 1982, art. 61). Yet the legal framework that structures much of ocean governance was negotiated in a pre digital, paper based world, long before satellite tracking, real time databases, or artificial intelligence (AI) could be imagined as routine tools. At the same time, governments have rapidly expanded domestic regimes for personal data protection, privacy, and commercial confidentiality, creating a complex landscape for sharing the very data that modern, AI enabled fisheries management depends on.

This article explores how national legal protections for fisheries related data, particularly personal data and commercially sensitive information, interact with States' obligations under the law of the sea to manage fisheries responsibly and cooperatively. It focuses on data generated by technologies such as the Automatic Identification System (AIS), Vessel Monitoring Systems (VMS), remote electronic monitoring (EM), satellite imagery, and electronic logbooks, which together provide a granular picture of human activity at sea. The aim is not to provide a doctrinal legal treatise, but to offer a clear understanding of the main legal tensions and to outline practical approaches for designing data systems and sharing

✉ Eva van Heukelom · eva@naturaljustice.nl
[1] Natural Justice, Noord-Brabant, Netherlands

arrangements that both respect domestic protections and support international obligations, including those embedded in UNCLOS and related instruments.

This article is based on the presentation of Eva van Heukelom at the ABLOS 12th Conference in Qatar. It was titled "Balancing National Legal Protections of Fisheries Data & UNCLOS Obligations in the Age of AI" and it is based on her PhD research at the Law of the Sea Department at the Universität Hamburg under supervision of Prof. Dr. Alexander Proelß.

2 Law of the sea in a pre digital world

UNCLOS was negotiated between 1973 and 1982 and is often described as the "constitution for the oceans" (UN, 1982). It distributes rights and duties between coastal States, flag States, and the international community across distinct maritime zones, including the territorial sea, exclusive economic zone (EEZ), and the high seas. Within the EEZ, coastal States have sovereign rights for exploring, exploiting, conserving, and managing living resources, coupled with duties to ensure that these resources are not over exploited and are conserved on the basis of the best scientific evidence available (UN, 1982, art. 61). UNCLOS itself, however, is striking for what it does not say: it contains no express references to 'fisheries data', 'AIS', 'VMS', or 'artificial intelligence'. When it was being drafted, fisheries management was understood largely in terms of catch reporting, biological surveys, and paper based exchanges between administrations; satellites and digital databases were peripheral, and AI did not yet exist as a tool to support large-scale fisheries data analyses.

It would be misleading to assess UNCLOS's fitness for modern fisheries governance by reading the 1982 text in isolation. Contemporary law of the sea is primarily captured in UNCLOS, together with a set of "implementation agreements". To date, three implementation agreements have entered into force.. First, the 1994 Agreement relating to the implementation of Part XI of UNCLOS addresses deep seabed mining and is less directly connected to fisheries management (UN, 1994). Second, the 1995 Agreement for the Implementation of the Provisions of UNCLOS relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (the Fish Stocks Agreement) significantly develops the obligations related to fisheries (UN, 1995). Third, the 2023 Agreement on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction (the BBNJ Agreement) seeks to fill governance gaps for biodiversity in areas beyond national jurisdiction.

The Fish Stocks Agreement is particularly important in the context of data. Its general principles explicitly recognize that "the timely collection, compilation and analysis of data are fundamental to the effective conservation and management of straddling fish stocks and highly migratory fish stocks" (UN, 1995, Annex I). It clarifies that data should be collected both from fisheries on the high seas and in areas under national jurisdiction and compiled in a way that enables statistically meaningful analysis, including catch and fishing effort statistics as well as "vessel related and other data for standardizing fishing effort," and information on non target and associated species (UN, 1995, art. 1). At the same time, the Agreement acknowledges that "confidentiality of non aggregated data shall be maintained" and specifies that dissemination is subject to the terms on which data have been provided (UN, 1995, Annex I).

Seen together, UNCLOS and the Fish Stocks Agreement articulate a clear expectation: States should collect, analyze, and possibly share fisheries related data in a timely and meaningful manner, including data closely tied to vessel operations, while respecting legitimate confidentiality concerns. The treaties leave the technical modalities, i.e. what technologies to use, how to structure databases, how to process data, largely to States and regional fisheries management organizations (RFMOs). This flexibility is what allows modern tools such as AIS, VMS, EM and AI based analytics to be integrated into MCS systems without revisiting UNCLOS itself. However, the same openness also means that much of the real friction arises from domestic law, not from UNCLOS: from data protection laws, constitutional privacy guarantees, intellectual property laws, administrative confidentiality rules, and transparency or freedom of information legislation.

Beyond the law of the sea, environmental law and international human rights law further reinforce obligations relevant to fisheries data. The growing recognition of the right to a clean and healthy environment, and the link between environmental degradation and the enjoyment of human rights, strengthens arguments that States must manage marine resources in a way that protects both ecosystems and the communities that depend on them. In this way, fisheries data sit at the intersection of multiple bodies of law: law of the sea, environmental protection, human rights, and domestic regulatory frameworks. International human rights instruments such as the International Covenant on Civil and Political Rights (ICCPR) also establish the right to privacy and private life (ICCPR, 1966, art. 17), which feeds into contemporary personal data protection regimes. Therefore, international human rights law provides protections to support the collection, storage, and sharing of fisheries data, but may also limit these due to conflicting interests. It is this interaction that will be explored in further detail in this article.

3 Technologies generating fisheries data

Over the last four decades, fisheries management has shifted from intermittent, low resolution observations to continuous, high resolution streams of digital data. AIS is a maritime tracking technology originally developed to enhance navigational safety and

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collision avoidance by broadcasting vessel identity, position, course, and speed over VHF radio frequencies. Since around 2000, the International Maritime Organization (IMO) has progressively required AIS for vessels above certain tonnage thresholds engaged in international voyages, primarily through the International Convention for the Safety of Life at Sea (SOLAS) (IMO, 1974; Foley et al., 1990; see also relevant IMO instruments). AIS exchanges static data (such as vessel name, IMO number, dimensions, type), dynamic data (position, time stamp, speed over ground, heading), and certain voyage related information (such as destination and estimated time of arrival), although some of the latter are of limited relevance in fishing. From a fisheries perspective, AIS offers high frequency position and motion data that can be used to infer fishing behavior and gear type, but it has known limitations: some (smaller) fishing vessels are exempt; transponders can be switched off or manipulated; and AIS was never designed as an enforcement tool.

In contrast, VMS was developed specifically as a compliance and enforcement tool for fisheries (Paolo et al., 2024). VMS units, often satellite based, transmit vessel position, time, and sometimes speed or heading at regular intervals, typically providing multiple position reports per day with positional accuracy on the order of 100 meters. VMS carriage is usually mandated by fisheries legislation, license conditions, or RFMO measures for vessels above certain sizes or operating in particular fisheries. Unlike AIS, VMS data are generally not publicly accessible; they are transmitted to, and controlled by, fisheries monitoring centers (FMCs) or equivalent authorities, and commonly treated as confidential. For many States, VMS is the backbone of their MCS system and an indispensable source of information for meeting their UNCLOS Article 61 obligations.

Around these two core systems, a suite of complementary technologies has emerged. Remote electronic monitoring (EM) systems combine cameras, sensors, and onboard storage or transmission to document fishing operations, gear use, and catch handling. Satellite imagery, including both optical and synthetic aperture radar (SAR), can detect vessels regardless of whether transponders are active and can be cross referenced against AIS and VMS to identify dark or suspicious activity (Paolo et al., 2024). Electronic logbooks allow captains to submit catch and effort data digitally, improving timeliness and consistency. Together, these systems generate what can be described as fisheries "Key Data Elements" (KDEs): vessel location, date and time of activity; speed and course; vessel identity (including unique vessel identifier, name, and flag); fishing authorizations; gear type and fishing methods; catch quantity and composition; and related ownership and flag histories, including ultimate beneficial ownership.

These KDEs are not merely technical fields in a database. Several of them can overlap with protected categories of information in domestic law. Vessel location, date, and time may constitute personal data where they can be linked to a specific individual, such as the vessel's master. Ownership and beneficial ownership data often include names, contact details, and nationality, which will in practice almost always qualify as personal data. Detailed fishing tracks and patterns may be argued to fall within trade secret protections, particularly where they reveal profitable fishing grounds. Understanding these overlaps is essential to designing lawful data sharing arrangements that still allow States and their partners to use modern tools, including AI or machine learning to better understand what happens at sea and to act on that information.

4 Personal data protection and privacy at sea

In recent decades, many States and regions have adopted comprehensive regimes for personal data protection, driven by concerns over surveillance, digitization, and the ease with which information can be aggregated and repurposed (Humble, 2021). The most influential of these is the European Union's General Data Protection Regulation (GDPR), which defines personal data as "any information relating to an identified or identifiable natural person," explicitly including location data (EU, 2016, art. 4(1); see also Recital 71). The Council of Europe's Convention 108 extend similar principles to a broader group of States. Outside Europe, some jurisdictions have adopted dedicated data protection laws, such as Japan's Act on the Protection of Personal Information (APPI, 2003), while elsewhere protections derive mainly from constitutional rights to privacy or private life, as in the United States.

From a fisheries perspective, the central question is when, and to what extent, vessel tracking data constitutes personal data subject to these regimes. Individuals directly involved in fishing, i.e. masters and crew, could potentially be data subjects where data relates to them or can be used to identify them. Another group of individuals are legal or beneficial owners, whose names or identifiers may appear in licensing and registry data and whose economic interests are tied to vessel operations. Under instruments such as the GDPR, location data can be personal data when it is linked to an identifiable person, and this link may exist if, for example, public registers reveal the name of the master of a specific vessel and continuous VMS or AIS tracks show where that vessel is located at given times. The European Data Protection Supervisor has recognized that monitoring of vessel movements can involve processing personal data as long as the data can be linked to identified or identifiable individuals, including masters, owners, or crew (WP29, 2007).

At the international level, the right to privacy is enshrined in Article 17 of the ICCPR, which states that no one shall be subjected to arbitrary or unlawful

interference with privacy, family, home or correspondence, nor to unlawful attacks on honor and reputation (ICCPR, 1966, art. 17). Case law from human rights bodies and domestic courts has elaborated how this right applies in contexts such as communications surveillance, workplace monitoring, and GPS tracking of vehicles. However, I would argue the fisheries context is distinct. Vessels are generally workplaces rather than private homes, and monitoring via AIS or VMS is typically mandated by law as a condition of engaging in a regulated fishery. In addition, the open fields doctrine in the United States has limited the expectation of privacy in activities conducted in open areas, including at sea, although recent jurisprudence on persistent location tracking has highlighted potential privacy concerns (U.S. Supreme Court, 2012).

In practice, the connection between vessel tracking data and individual privacy is often narrower than stated. Comprehensive crew lists are generally not public, and in many cases only the name of the master or legal owner may be accessible in registers, such as those managed and published online by RFMOs. Nonetheless, in jurisdictions where location is explicitly included in the definition of personal data and where a link to an individual can be established, the publication or sharing of VMS or similar data may engage data protection rules, requiring a lawful basis, respect for purpose limitations, and appropriate safeguards. This creates uncertainty for administrations and for organizations seeking to promote greater vessel tracking transparency for the purposes of enhancing compliance and accountability at sea.

5 Commercially sensitive information and trade secrets

Separate from personal data protections, many jurisdictions recognize legal regimes protecting commercially sensitive information. Confidential business information may encompass any private details that a company keeps secret to maintain competitive advantage, including financial data, marketing strategies, unique processes, and, in the fisheries context, information about fishing grounds and patterns. Trade secrecy typically protects information that has commercial value because it is secret and has been subject to reasonable steps to keep it confidential. In some jurisdictions, fishing corporations have successfully argued that detailed information about fishing locations or techniques constitutes a trade secret and that mandating disclosure or sharing of this data would unlawfully undermine their competitive position.

Administrative law can reinforce these protections. Fisheries authorities often receive detailed data from companies under statutory or contractual obligations, and may treat this data as confidential, limiting dissemination even within government. In some cases, non disclosure agreements (NDAs) are used to reassure industry that data will not be shared beyond the collecting authority. Such NDAs may cover a broad range of fisheries data, from VMS tracks to licensing details and ownership information. While these arrangements can secure industry cooperation, they may also undermine broader policy goals by preventing the use of data for cross agency collaboration, regional cooperation, or public transparency initiatives.

These commercial and administrative protections are sometimes invoked in ways that go beyond what is strictly necessary to protect legitimate business interests. For example, the assertion that any disclosure of fishing locations would destroy the value of fishing rights may be overstated in situations where data could be anonymized, delayed, or otherwise processed to mitigate competitive impacts while still supporting enforcement and research. At the same time, the global nature of fisheries, characterized by transboundary stocks and complex value chains, underscores that over protecting commercial information can facilitate opacity, including the use of flags of convenience, shell companies, and opaque ownership structures that enable IUU fishing and tax evasion.

6 Transparency laws and examples of proactive sharing

In contrast to regimes focused on confidentiality, some States have adopted transparency or access to information laws that facilitate proactive disclosure of government held data, including in the fisheries sector. Norway's Freedom of Information Act (Offentleglova; JD, 2006) and Chile's Transparency Act (Ley de Transparencia; MINSEGPRES, 2008) are prominent examples. These laws require public bodies to facilitate access to information and establish transparency as a default, subject to specified exceptions for privacy, security, and commercial confidentiality.

In practice, Norway routinely publishes VMS based vessel tracking information for its fishing fleet, and Chile provides VMS data to organizations such as Global Fishing Watch, which combine it with AIS and other sources to produce public vessel tracking maps (Global Fishing Watch, n.d.). These practices coexist with robust personal data protection frameworks, such as the GDPR in Norway (EU, 1994, 2018) and constitutional privacy protections in Chile, demonstrating that legal systems can accommodate both privacy and public interest transparency when carefully balanced. They also show that once transparency is embedded in general administrative law, fisheries data can be treated as a form of public information rather than as purely confidential enforcement material.

These examples are not universally replicated. In the European Union, with the same GDPR protections as applicable to Norway, no Member State makes VMS data publicly accessible, often citing confidentiality or data protection concerns. Similarly, in jurisdictions such as Japan or the United States,

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there is no consistent practice of publishing VMS data, although some aggregated or delayed information may be available. The result is a patchwork landscape where the same type of data, i.e. vessel tracks, authorizations, ownership details, is treated as confidential in some States, partially accessible in others, and public in a few instances.

7 UNCLOS obligations and emerging tensions

Against this domestic backdrop, it is important to recall that UNCLOS and related instruments impose international obligations that depend on the availability and, in many cases, the sharing of fishery related data. Article 61 of UNCLOS requires coastal States to ensure that living resources in the EEZ are not endangered by over exploitation and are managed based on the best scientific evidence available; Article 62 requires them to promote optimum utilization (UN, 1982). For straddling and highly migratory stocks, the Fish Stocks Agreement adds more specific data related responsibilities: States are to collect and share catch and effort data, as well as vessel related information, in a form that allows meaningful analysis and cooperative management, including through RFMOs (UN, 1995). The same Agreement recognizes the need to respect confidentiality of non aggregated data and to honor the terms under which data are supplied.

Meeting these international obligations requires States to design MCS systems that collect sufficiently detailed data and to participate in cooperative data exchanges, both domestically (across agencies) and internationally. For instance, restricting port access to vessels engaged in IUU fishing, one of the most effective tools currently available, depends heavily on access to vessel histories, authorization status, and activity patterns, which can be derived from VMS, AIS, and related sources. Similarly, the effective implementation of catch documentation and supply chain traceability schemes, which aim to ensure that buyers do not provide the economic incentive for IUU fishing, hinges on having reliable upstream activity data and being able to integrate it into verification processes. AI based analytics further increase the value of rich, long term data series, as they can reveal patterns of non compliance and guide enforcement resources to high risk vessels and areas.

Domestic legal protections can impede the flow of data needed for these functions. A coastal State may have VMS data capable of supporting advanced AI models to detect high risk behavior and to inform regional cooperation, but its data protection authorities or internal legal advisers may interpret personal data or trade secrecy rules as prohibiting sharing with neighboring States, RFMOs, or civil society partners, particularly in non aggregated form. Port States may wish to use risk profiles generated by third party platforms that combine multiple data sources, yet may find themselves constrained by national confidentiality rules when it comes to contributing their own data to such platforms. Civil society organizations like Global Fishing Watch, SkyTruth, and Trygg Mat Tracking have demonstrated how combining AIS, satellite imagery, registries, and, where available, VMS can enhance transparency and support enforcement, but their access to official VMS data depends entirely on the willingness and legal capacity of States to share.

These tensions do not necessarily mean that UNCLOS is outdated or unfit for purpose. Rather, they reveal that the balance between different legal interests – privacy, commercial confidentiality, transparency, and environmental stewardship – is increasingly being struck at the national level, often without a clear understanding how this interacts with international fisheries obligations. While international law makes clear you cannot invoke national law to justify a failure to perform a treaty obligation (UN, 1969, art. 27), it is not always a given that sharing data beyond an FMC is required to fulfil UNCLOS obligations. Further, national laws frequently lack clear balancing tests for situations where, for example, trade secret protections intersect with environmental or human rights obligations, or where personal data protections must be weighed against the public interest in sustainable resource management. In others, the issue may be less legal than practical: limited administrative capacity, lack of familiarity with international law, or political concerns may inhibit data sharing even where legal avenues exist.

8 Navigating legal protections in practice

The challenge, then, is to navigate domestic legal protections in a way that respects individual rights and legitimate commercial interests while still enabling the data flows needed to fulfil UNCLOS obligations and to harness modern technologies for effective fisheries governance.

One approach is to minimize the extent to which fisheries data fall within the scope of personal data protection laws in the first place. This can be done by removing direct identifiers such as vessel names or unique vessel identifiers from data intended for broader dissemination, thereby attenuating the link between tracks and specific individuals aboard. Aggregating data over time or across fleets can further reduce identifiability, although aggregation may also diminish analytical value, particularly for detecting specific high risk vessels. Anonymization therefore appears to be a more promising strategy than aggregation where the goal is to retain useful granularity; even then, care is needed in small fleets or niche fisheries where re identification risks remain high.

Where personal data protection regimes clearly apply, e.g. States intend to share identified vessel tracks or to link them with public registers, organizations must ensure that data processing has a lawful basis and respects key principles such as purpose limitation and data minimization. Consent from data

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subjects is one possible basis, but in the context of fisheries this may be logistically challenging and legally complex, especially where multiple crew members are involved and power imbalances exist. More promising may be legal bases grounded in the public interest or the exercise of official authority, particularly where domestic law or policy recognizes environmental protection, sustainable resource management, or transparency in natural resource exploitation as legitimate objectives. Some jurisdictions' data protection laws explicitly allow processing and sharing of personal data where necessary for tasks carried out in the public interest, though interpretations vary.

Commercial confidentiality and trade secret concerns can also be addressed through careful design of access regimes and contracts. Tiered access models can ensure that detailed, near real time data are available to core enforcement agencies, while more filtered or delayed data products are shared with regional partners, researchers, or the public. Data sharing agreements can specify permitted uses, protect against misuse by recipients, and recognize the need to safeguard competitive interests while still allowing analysis relevant to IUU fishing, environmental impacts, or supply chain integrity. Experience in jurisdictions such as Norway and Chile suggest that transparency and commercial interests need not be mutually exclusive, particularly when transparency is framed as a component of good governance and as part of the social license to operate.

Finally, technical experts and legal practitioners can work together to support legal and policy development. By clearly articulating what data are needed for particular management or enforcement objectives, what resolution and latency are required, and what safeguards can realistically be implemented, it becomes easier for lawmakers and regulators to craft rules that are both protective and enabling. This includes contributing to guidance within RFMOs, FAO led processes, or regional bodies on standardized, lawful sharing of fisheries data, and highlighting how improved transparency can reduce incentives for flags of convenience, opaque ownership structures, and other enablers of illicit activity at sea.

9 Is UNCLOS fit for purpose?

Returning to the core question whether UNCLOS is fit for purpose in modern times. At least in relation to fisheries and data, the analysis here supports a cautiously affirmative answer. UNCLOS, together with its implementing agreements, embeds a clear expectation that States will manage living marine resources based on sound, timely information, and will cooperate across jurisdictions to conserve and use these resources sustainably. While the Convention does not mention data or technology explicitly, it is sufficiently flexible to accommodate the transition from paper based reporting to satellite based tracking, from manual analyses to AI driven models. The law of the sea is not designed to prescribe the architecture of MCS systems or databases; instead, it sets objectives and allocates responsibilities, leaving the choice of tools and institutional arrangements to States.

Where the system falls short, it is often not because UNCLOS is inherently outdated, but because States have not fully implemented or coordinated the various legal regimes that affect fisheries data – international fisheries obligations, personal data protection, commercial confidentiality, transparency, and human rights. Excessive or unbalanced protections around fisheries data can inadvertently shield IUU fishing and undermine efforts to ensure food security and healthy marine ecosystems.

Conversely, thoughtful alignment of domestic laws with international obligations can enable greater fisheries transparency while still safeguarding individual rights and legitimate business interests.

The oceans are becoming increasingly observable, and AI is amplifying what can be inferred from vessel tracks, catch records, and environmental data. If managed responsibly, these advances can finally allow States to give practical effect to UNCLOS's call for conservation based on the best scientific evidence and for cooperative stewardship of shared marine resources. Achieving this will not require rewriting UNCLOS, but it will require careful work at the interface of law, technology, and policy: understanding the legal status of fisheries data, designing systems that respect both domestic protections and international duties, and maintaining an honest focus on the ultimate objective: healthy oceans and a thriving, lawful fisheries sector.

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References

APPI (2003). *Act on the Protection of Personal Information*. Japan.

EU (1994). *Agreement on the European Economic Area* (OJ C 239/3, 1994; original adopted 1992, entered into force 1994. Council of the European Union. European Union, Brussels.

EU (2016). *General Data Protection Regulation* (2016/679). *Official Journal of the European Union, L119*, 1–88. European Union, Brussels.

EU (2018). Decision of the EEA Joint Committee No 154/2018 of 6 July 2018 amending Annex XI (Electronic communication, audiovisual services and information society) and Protocol 37 (containing the list provided for in Article 101) to the EEA Agreement [2018/1022]. *Official Journal of the European Union, L183*. http://data.europa.eu/eli/dec/2018/1022/oj

Foley, J. D., van Dam, A., Feiner, S. K. and Hughes, J. F. (1990). *Computer Graphics – Principles and Practice* (2nd ed.). Addison Wesley.

Humble, K. P. (2021). International law, surveillance and the protection of privacy. *The International Journal of Human Rights, 25*(1), 1–22.

IMO (1974). *International Convention for the Safety of Life at Sea (SOLAS)*. International Maritime Organization, London, United Kingdom.

JD (2006). *Act relating to the right of access to documents held by public authorities and public undertakings ('Offentleglova')*. Justis- og beredskapsdepartementet (Ministry of Justice and Public Security), Oslo, Norway.

MINSEGPRES (2008). *Ley No. 20.285 sobre Acceso a la Información Pública*. Diario Oficial de la República de Chile, Ministerio Secretaría General de la Presidencia, Santiago, Chile.

Paolo, F. S., Kroodsma, D., Raynor, J., Hochberg, T., Davis, P., Cleary, J., Marsaglia, L., Orofino, S., Thomas, C. and Halpin, P. (2024). Satellite mapping reveals extensive industrial activity at sea. *Nature, 625*, 85–91. https://doi.org/10.1038/s41586-023-06825-8

U.S. Supreme Court (2012). *United States v. Jones*, 565 U.S. 400.

UN (1966). *International Covenant on Civil and Political Rights*. 999 U.N.T.S. 171. United Nations, New York, USA.

UN (1969). Vienna Convention on the Law of Treaties. *United Nations Treaty Series, 1155*, 331.

UN (1982). *United Nations Convention on the Law of the Sea* (adopted 10 December 1982, entered into force 16 November 1994). 1833 U.N.T.S. 397. United Nations, New York, USA. https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf (last accessed 30 March 2026).

UN (1994). *Agreement Relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea*. United Nations, New York, USA.

UN (1995). Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks. *United Nations Treaty Series, 2167*, 3. United Nations, New York, USA.

WP29 (2007). *Opinion 4/2007 on the concept of personal data (WP29)*. Article 29 Data Protection Working Party (WP29), European Union, Brussels.

CONFERENCE PAPER

Evidence requirements for alternative fuel bunkering under decarbonisation rules

Author
Andrey Chernov[1]

Preamble

The following work was presented at the 12th ABLOS Conference, 7–8 October 2025, Doha, Qatar in the oral session *New technologies and maritime security.*

Abstract

Decarbonisation rules are turning bunkering into an evidence problem. Fuel claims now pass through MRV (Monitoring, Reporting and Verification) files, port records, and ocean-observation data. This Note explains the main data sources, where they fail, and why data integrity matters for enforcement, due diligence, and insurance. It uses ammonia bunkering as a hard case because small errors can trigger safety, pollution, and legal exposure. A short caselet shows what an audit-ready evidence package looks like near a sensitive coast. Five practical takeaways suggest how hydrographic and observing communities can support accountable transition.

Keywords
alternative marine fuels · ammonia bunkering · maritime decarbonisation · MRV shipping emissions · fuel chain of custody · law of the sea · liability and compensation

1 Why "bunkering evidence" matters now

Decarbonisation compliance is no longer only about technology. It is also about proof. Regulators and markets increasingly ask two questions. What fuel was used, and what can be shown and verified. The second question is rising fast. When reported figures trigger cost, penalties, or contractual outcomes, evidence quality becomes a legal risk factor.

Three forces drive this shift. First, global policy is moving toward stronger control. The IMO's 2023 GHG Strategy sets a clear direction toward net-zero emissions close to 2050 and calls for faster action (IMO, 2023). Second, regional regimes already convert data into consequences. In the European Union, shipping requires monitoring, reporting, and verification of emissions (European Union, 2015). FuelEU Maritime adds well-to-wake intensity requirements and links fuel choices to compliance records (European Union, 2023a). The EU also expanded the ETS (Emissions Trading System) framework and aligned key parts of its climate rules (European Union, 2023b). In these systems, a wrong number is not a small internal error. It can become a legal and financial event. Third, alternative fuels increase the distance between a physical transfer and the compliance claim. With conventional fuel oil, a bunker delivery note and a representative sample often anchor the story. With low-carbon fuels, the claim can depend on attributes and upstream steps. The evidence becomes layered. Layers create failure points. They also create disputes about who controlled what, who relied on what, and who pays.

Ammonia makes the evidence issue easy to see. Ammonia is discussed as a low or zero carbon option at the point of use, but it is highly hazardous. A minor deviation in transfer control can have immediate safety and environmental implications. A minor deviation in

✉ Andrey Chernov · achernov@sunymaritime.edu
[1] State University of New York Maritime College, New York, U.S.A.

data can also create later enforcement and contractual consequences. LNG can act as a comparator. It shows how fuel-specific issues and emissions accounting questions can shape commercial outcomes. But ammonia is a hard case because public concern is high and the tolerance for uncertainty is low.

For the hydrographic and ocean-observation community, this matters directly. Independent observations do not replace MRV. They can strengthen accountability. They can provide time and location anchors. They can support response decisions. They can also reduce disputes by adding external, time-stamped data that is hard to rewrite after the fact.

2 The evidence stack: what data exists

Bunkering evidence is best understood as an "evidence stack". It has four layers. Each layer has a different owner and a different audit logic. A strong system links the layers with timestamps, custody controls, and clear responsibility.

Layer 1: Regulatory reporting data (MRV and related files). MRV turns fuel use into legally relevant numbers. In the EU, the MRV Regulation establishes how emissions must be monitored, reported, and verified (European Union, 2015). FuelEU Maritime adds further requirements tied to fuel and energy use (European Union, 2023a). These rules push operators to treat data governance as compliance infrastructure. A clean MRV file requires consistent inputs, documented methods, and a traceable record of corrections.

Layer 2: Port and bunkering documents (the transfer record).This layer includes delivery documents, meter records, sampling steps, checklists, and signed logs. Under MARPOL Annex VI practice, bunker delivery notes and fuel oil sampling guidance help create a bridge between fuel supplied and compliance checks (IMO, 2024). For ammonia, operational records also include safety controls and emergency readiness. Measurement method, meter calibration, and custody seals are not "nice to have". They are part of the proof.

Layer 3: Shipboard data (what the ship recorded). This includes tank levels, fuel management system logs, engine control records, alarm logs, and event logs. It can also include VDR (Voyage Data Recorder) time markers for key events. Shipboard data links transfer events to consumption and reporting. It also creates cyber integrity risk. If the data can be edited without trace, its legal value drops.

Layer 4: External observation data (ports, coast, and ocean). This includes AIS tracks, VTS records where available, satellite observations, coastal sensors, metocean data, and water-quality monitoring. External data can validate the time and location of the operation. It can support plausibility checks. It can also support response and post-incident reconstruction if a release is suspected. For sensitive coast operations, currents, tide, and wind can be as important as the transfer log.

Table 1 summarises owners and weak points across the stack. It also highlights where the hydrographic and observing community can add value.

The practical lesson is simple. Decarbonisation creates a multi-source truth environment. No single record will carry the whole burden. A good evidence pack aligns layers, preserves custody, and makes later reconstruction possible.

3 Where evidence fails: three predictable break points

Evidence failures cluster in three places. They are predictable, so they are preventable. Each failure point can turn a technical variance into a legal dispute.

Failure point 1: Certification and fuel attributes. Low-carbon fuels often carry claims about origin, pathway, and lifecycle emissions. For "green ammonia", the compliance value depends on more than chemical composition. It depends on upstream production and chain-of-custody. The risk is not only fraud. It is also mismatch and non-recognition. A certificate can be valid in one system but not accepted in another. A certificate can also become detached from the physical batch if custody controls are weak. When this happens, the ship may face compliance exposure even if the transfer was safe and the fuel was fit for use.

Failure point 2: Custody transfer and measurement at the interface. The transfer interface is a classic dispute zone. Parties argue about what quantity was delivered, what quantity was received, and what method controlled the measurement. Under MARPOL Annex VI sampling practice, representative samples and linked records support compliance checks (IMO, 2024). For ammonia, the measurement and control system can differ from fuel oil routines. Small measurement differences can scale into large reporting differences when they are converted into MRV outcomes. If custody is unclear, allocation becomes unclear. Supplier, owner, charterer, and verifier can all point at each other.

Failure point 3: Onboard reporting and verification integrity. Even if the physical transfer is correct, the reporting layer can fail. Data can be incomplete, inconsistent, or not traceable back to primary records. Verification can also be too procedural. A weak audit trail makes it hard to explain deviations and hard to defend reliance. In regimes that turn reported figures into direct consequences, this becomes a core risk (European Union, 2015; European Union, 2023a). It also affects public confidence. Communities near pilot projects want proof that the operator can detect, report, and correct problems.

These failure points show why ocean-observation inputs matter. Independent data can anchor timing and location. It can support reconstruction. It can also reduce "missing facts" disputes. When facts are clearer, legal allocation is narrower and settlement is faster.

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Table 1 Evidence stack, owners, and vulnerabilities.

Layer	Typical data	Main owner	Common vulnerability	What hydrographic / observing community can support
MRV/reporting	MRV inputs, methods, verification outputs	Operator, verifier	Inconsistent inputs, weak correction log	Reference datasets, clear metadata, time alignment standards
Port/transfer	Delivery docs, meter data, sampling, safety logs	Supplier, port, operator	Custody gaps, unclear quantity method	Port data standards, secure timestamps, coastal risk layers
Shipboard	Tank levels, alarms, VDR markers	Ship operator	Editability, missing calibration trail	Guidance on audit-ready time/position anchoring
External	AIS/VTS, satellite, metocean, water quality	Observing institutions, authorities	Data silos, hard access, weak interoperability	Trusted, time-stamped products; consistent formats; rapid access during incidents

4 Legal accountability: why data integrity changes duties and outcomes

This Note stays at a high level. The goal is clarity for non-lawyers. The central point is that modern environmental governance is built on monitoring and verification. Data integrity shapes whether oversight looks credible and whether enforcement is workable.

At the international level, UNCLOS Part XII sets a general duty to protect and preserve the marine environment (United Nations, 1982). It also addresses monitoring and assessment of risks and effects. In practice, that pushes States toward systems that can observe, assess, and respond using reliable information. Due diligence is not only about having rules on paper. It is also about being able to see what is happening, to record it, and to act on it.

At the regional level, EU MRV formalises the evidence logic. Operators must monitor, report, and verify emissions under a defined system (European Union, 2015). FuelEU Maritime ties fuel use to compliance outcomes that depend on documented records (European Union, 2023a). As these systems mature, the legal risk profile changes. Data becomes economically material. That drives more disputes about reliance and proof. It also drives contract design. Parties add stronger warranties, audit rights, record-keeping duties, and correction protocols because data errors can trigger real costs.

Insurance and claims are shaped by the same logic. Claims handling depends on causation and proof. Evidence quality affects speed and cost. In alternative fuels, the "facts" often include technical and data questions, not only physical events. What was transferred. What was measured. What was recorded. What was verified. Weak records widen disputes. Strong records narrow them. This matters for compensation pathways. It also matters for public trust.

For hydrographic offices and ocean observing institutions, the accountability link is practical. Independent observations can support enforcement and response. They can also support fairness. If there is no release, external data can help show that. If there is a release, external data can help locate and model it. In both cases, observation systems are part of the evidence environment that modern decarbonisation rules increasingly assume.

5 Mini caselet: ammonia bunkering near a sensitive coast

Scenario. A port authorises a pilot ammonia bunkering operation for a coastal vessel. The transfer uses a bunker barge near a sensitive shoreline with fisheries and protected habitat. Public concern is high. The port wants a pilot that is safe and also defensible in evidence terms.

What must exist and be verifiable. Build an "audit-ready pack" using the evidence stack. Keep it time-aligned and tamper-evident.

Plan and thresholds. A documented plan for location, timing, exclusion zones, emergency steps, and clear metocean thresholds for pause or abort. Record what current, tide, and weather data sources were used and when. This matters because conditions shape dispersion and response logic.

Transfer record. Meter readings with calibration evidence. A clear method statement for how quantity is determined. A signed timeline of key steps, including connection, start, stop, and any alarms or interruptions. For ammonia, include safety checks that show control of hazardous conditions. The purpose is reconstruction. Investigators must be able to replay the event.

Shipboard record. Tank levels before and after, relevant alarms, and logs of operational deviations. If digital entries are used, keep access controls and a change log. If records can be edited quietly, they do not support due diligence.

External anchors. AIS tracks and any port traffic records for time and position. Coastal observation data during the operation window, including current and wind information. If a release is suspected, rapid water-quality observations and dispersion modelling become central. Independent data also protects the operator when there is no release.

What happens when evidence is weak. A community odor report or sensor alert can escalate fast. Weak evidence turns response into guesswork. The port may suspend pilots. Private disputes may follow. Parties can argue about what was delivered, what

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was measured, and who controlled the record. In an MRV-driven environment, missing audit trails can turn a manageable variance into long exposure (European Union, 2015; European Union, 2023a).

Short port lens: "port as evidence node" (Singapore as illustration). A major bunkering hub can act as an evidence node because it concentrates port records, traffic monitoring, and data exchange. Singapore is a useful illustration of this idea. The narrow point is that ports can set evidence norms. If a port requires standardised digital bunkering records, secure timestamps, clear custody transfer methods, and interfaces to reporting systems, it can reduce disputes. The caution is also clear. If data governance is weak, the port becomes a bottleneck for trust.

6 Five practical takeaways

Set a minimum evidence pack for alternative fuels. Keep it short and strict. Define required logs, timestamps, custody controls, and method statements. Make it reconstructable.

Use ocean observation as an independent anchor. Provide time-stamped metocean and coastal data that supports planning, response, and later reconstruction. Make access and formats predictable.

Treat custody transfer as a legal control point. Adapt proven discipline from MARPOL Annex VI fuel sampling practice to new fuels (IMO, 2024). Focus on custody, method, and tamper-evidence.

Design MRV integrity like a safety system. Use audit trails, access controls, and anomaly checks. If a number can trigger penalties, it deserves high control.

Make "port as evidence node" a policy goal. Ports can reduce risk by standardising digital records and aligning them with reporting regimes. This also helps public confidence in ammonia pilots.

7 Conclusion

Decarbonisation is building a new accountability environment for shipping. Bunkering is central because it turns physical reality into a compliance claim. For ammonia, the link is sharp. Safe pilots can still fail if they cannot prove what happened. Hydrographic and ocean-observation communities can help by strengthening independent anchors and supporting evidence standards that make the transition governable.

References

European Union (2015). Regulation (EU) 2015/757 of the European Parliament and of the Council of 29 April 2015 on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport, and amending Directive 2009/16/EC. *Official Journal of the European Union*, L 123/55. http://data.europa.eu/eli/reg/2015/757/oj

European Union (2023a). Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC. *Official Journal of the European Union*, L 234/48. http://data.europa.eu/eli/reg/2023/1805/oj

European Union (2023b). Directive (EU) 2023/959 of the European Parliament and of the Council of 10 May 2023 amending Directive 2003/87/EC and Decision (EU) 2015/1814. *Official Journal of the European Union*, L 130/134. http://data.europa.eu/eli/dir/2023/959/oj

IMO (2023). *2023 IMO Strategy on Reduction of GHG Emissions from Ships*. Resolution MEPC.377(80), adopted 7 July 2023. International Maritime Organization, London, United Kingdom. https://www.cdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.377(80).pdf (last accessed 16 February 2026).

IMO (2024). *Guidelines for the sampling of fuel oil for determination of compliance with MARPOL Annex VI*. MSC-MEPC.2/Circ.18, 11 July 2024. International Maritime Organization, London, United Kingdom.

United Nations (1982). United Nations Convention on the Law of the Sea (UNCLOS), adopted 10 December 1982. *UN Treaty Series, 1833*, p. 3.

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CONFERENCE PAPER

Beyond boundaries: mobilising private sector ocean data sharing from national waters to the high seas – an opportunity under the BBNJ agreement

Authors

Laura Meyer[1], Adam Leadbetter[2,3] and Peter Burger[1]

Preamble

The following work was presented at the 12th ABLOS Conference, 7–8 October 2025, Doha, Qatar in the oral session *Ocean observation and cooperation frameworks*.

Abstract

This article examines the critical role of private sector ocean data in advancing sustainable ocean governance from national waters to Areas Beyond National Jurisdiction (ABNJ). Despite its significant value, such data often remains inaccessible due to legal, technical, and contractual barriers. Building on recent policy developments, including the BBNJ Agreement, the Ocean Decade and IOC UNESCO frameworks, the paper highlights emerging obligations and opportunities for data sharing. It argues that embedding clear data-sharing requirements into permits and contracts is essential to operationalise private ocean data sharing frameworks. Strengthening interoperability, incentives, and institutional coordination can unlock private sector data to support science-based decision-making, equity, and global ocean sustainability goals.

Keywords

ocean data sharing · private sector data · BBNJ agreement · Areas Beyond National Jurisdiction (ABNJ) · ocean governance; marine data policy · Ocean Decade

1 Introduction

A healthy and well understood ocean is and remains fundamental to global wellbeing. Despite substantial investment in ocean science, knowledge gaps persist across nearly all marine domains, including seabed mapping, marine ecosystems, and deep ocean systems. These gaps hinder effective sustainable ocean planning and management (SOPM), constrain marine spatial planning (MSP), and as such impede the ability to design and implement evidence-based conservation and management measures (Barzuna et al., 2025).

The United Nations Decade of Ocean Science for Sustainable Development (2021–2030) – the Ocean Decade – mobilises global efforts to advance "the science we need for the ocean we want". Achieving this vision depends on open, usable data, including important yet often inaccessible datasets collected and held by the private sector or collected under government licenses.

Important ocean data such as seabed mapping and ecological data underpin navigation, climate resilience, conservation, submarine infrastructure planning, and delivery of the 30 × 30 concept, established under the Kunming–Montreal Global Biodiversity Framework (CBD, 2023), which commits

✉ Laura Meyer · l.meyer@unesco.org

1 Ocean Decade Coordination Unit, Intergovernmental Oceanographic Commission of UNESCO

2 Decade Coordination Office for Ocean Data Sharing, Intergovernmental Oceanographic Commission of UNESCO

3 Seascape Belgium BVBA, Brussels, Belgium

countries to conserving and sustainably managing 30 percent of the world's land and marine areas by 2030. Seabed 2030 reports only 28.7 % global coverage as of April 2026, demonstrating the urgency of integrating data across sectors and jurisdictions (Seabed 2030, 2017).

In our previous IHR article (Burger & Meyer, 2025) we highlighted the crucial but underrecognised and under-utilised role of the private sector in unlocking such data. Industries including offshore energy, telecommunications, maritime infrastructure, and marine contractors routinely collect high quality environmental and bathymetric data in support of resource and infrastructure development projects around the globe. These data can significantly advance scientific understanding and hydrographic completeness (ODCDG, 2025). For the most part, however, this information is only used once and not made available for ocean science and ocean governance. Often, these data are considered proprietary by the company that conducted the survey and/or by the government that authorised the survey.

Recent policy developments, such as the Intergovernmental Oceanographic Commission (IOC) of UESCO Assembly Decision A33/3.4.2 and discussions at the Advisory Board for the Law of the Sea (ABLOS) Conference 2025, mark a shift toward operationalising data sharing commitments. This article broadens the perspective from areas under national jurisdiction to also encompass Areas Beyond National Jurisdiction (ABNJ), an expansion which is both timely and necessary by the entry into force of the Biodiversity Beyond National Jurisdiction (BBNJ) Agreement on the 17th of January 2026. This implementing agreement under the United Nations Convention on the Law of the Sea (UNCLOS) introduces new needs and obligations for transparency, data sharing, and international scientific cooperation in ABNJ (Fig. 1).

2 Data sharing imperatives

The ocean is monitored and sampled at a range of different scales, in both space and time. However, as the ocean is also an incredibly dynamic environment, each one of these observations is valuable. The value of an observation is increased if it is properly managed and curated, enriched with detailed information to aid the discoverability, accessibility, and reuse of the data associated with the observation. Holding observation data about the marine environment in inaccessible silos does not add value to those data and may mean that the return on investment for those data is lower. Cost-Benefit Analysis of the Marine Environmental Data and Information Network (MEDIN) in the UK and the Integrated Marine Observing System (IMOS) in Australia indicates that such data sharing initiatives are worth in the order of ten-times the investment on them to their local economy.

For an initiative such as the Kunming–Montreal 30 x 30 target, a complex set of inputs are required in the decision-making process as to which areas are the most sensitive or vulnerable, and therefore the most in need of protection. There are many different input datasets in a systematic conservation planning approach, from base data such as bathymetric charts and ecosystem type maps to the pressures on and types of human activities taking place at a location and to the location of other protected areas to ensure they act as a network (Harris et al, 2019). It can therefore be seen that the availability of appropriately formatted, easy to reuse data from across the wide variety of inputs required is vital in creating science-based, data-driven decisions in sustainable ocean planning and management.

However, IOC's and the Ocean Decade's work on advancing data sharing in national jurisdictions have shown that there is a variety of approaches to data sharing across the Member States of IOC. The current reality is that different countries have different policies and motivations around data sharing in their jurisdictions, and beyond national jurisdictions different actors (especially in the private sector) share in a range of motivations to engage (or not) in ocean data sharing.

Public and private sectors face several challenges relating to more and improved open data sharing. One particularly prominent issue at the time of writing is the at times real and at times perceived risks for national security, especially relating to bathymetry and the location of underwater infrastructure. Similarly, liability of data providers when data are put to downstream use in applications can be a concern for data holders although this can be mitigated using standard data licenses such as those from the Creative Commons suite which address liability.

Further issues, particularly faced by the private sector in terms of data sharing include who has data ownership and who has data responsibility, which will be defined hereafter. In ocean data sharing, data ownership refers to the legal or sovereign rights of states or organizations to control the terms under which data are shared, consistent with national

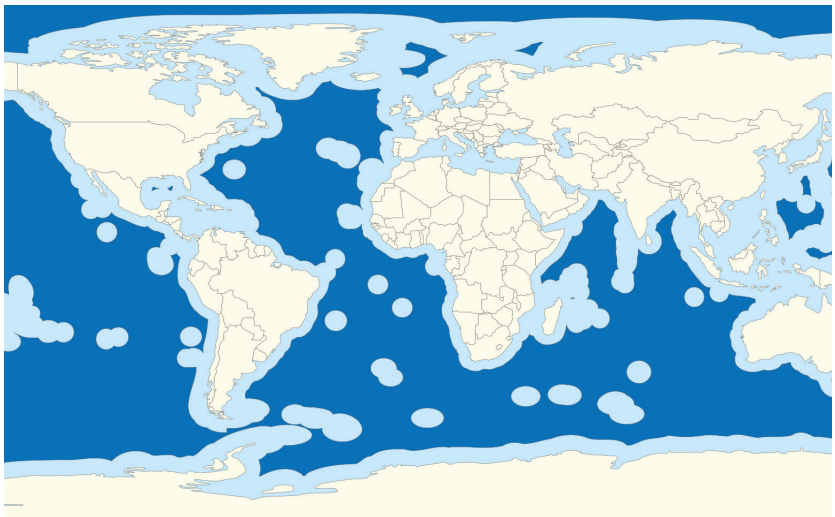


Fig. 1 Map from IUCN's Governing Areas Beyond National Jurisdiction Issues Brief (IUCN, 2022).

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jurisdiction and international law. Data responsibility, emphasised by the IOC Data Policy and Terms of Use (2023) and FAIR principles, focuses on the obligation to steward data so they are well-documented, ethically managed, preserved, and made openly usable for the global good, while still respecting the right of Member States and data owners to determine the terms of metadata, data and products sharing.

Ultimately, the data sharing objective and message should be to "default to openness; and to justify restrictions."

Maturing a global framework for data sharing requires addressing technical considerations as well as the organisational concerns outlined above. Through the International Oceanographic Data and Information Exchange (IODE) of IOC, the Ocean Data Information System (ODIS) has begun to provide a mechanism to exchange metadata (data about data) in a standardised way to enable the discovery of a wide range of ocean data sets. However, work needs to continue within ODIS to move to more actual data exchange which is the goal of the IOC Data Architecture approach adopted as a decision of the IOC Assembly in June 2025.

Conversations are ongoing across IOC and the Ocean Decade to facilitate the exchange of data, not least from the private sector. Strengthening the visibility and maturity of IOC's network of National Oceanographic Data Centres (NODCs) to create local, secure marine data archives across the globe is a key priority. Connecting these Data Centres through an improved ODIS with data exchange will facilitate the creation of new, high impact global data products to achieve the objectives of the Ocean Decade's and the outcomes of the 10 Decade Challenges. Providing clear, simple and actionable guidance for data providers to submit their data into this ecosystem is an ongoing process, as is evaluating the impact of such data submissions and providing appropriate credit and reward to data providers based on their sector and motivation for sharing data.

For example, for a research scientist the credit of citations for a dataset (analogous to citations for a paper) may be an appropriate form of reward. The ability to achieve this has been in place for almost 15 years (Leadbetter et al, 2013; the authors acknowledge that work is ongoing to increase adoption of this practice by journal publishers). However, such academic recognition provides little to no value to private sector companies. Similarly, private-sector incentives for data sharing, such as the potential for improved ESG rating scoring, is of little to no value for academic researchers. Discussions are ongoing with leading ESG ratings agencies proposing the inclusion of demonstrated and measurable ocean data sharing activities by private sector companies as a recognised contribution towards the UN Sustainable Development Goals in their scoring methodologies. Such recognition would provide new incentives and further motivation for private sector participation in ocean science and sustainable development.

3 Legal and policy foundations for ocean data sharing

International ocean governance increasingly treats data accessibility as essential to effective management and protection. These insights shape the evolving frameworks including UNCLOS (UN, 1982) and its new implementing agreement, the BBNJ Agreement (UN, 2023), concerning state responsibilities in Areas Beyond National Jurisdiction (ABNJ). Private sector datasets remain underused despite their relevance to SOPM, Environmental Impact Assessments (EIAs), and hydrography.

The 12th Conference of the Advisory Board on the Law of the Sea (ABLOS), held in October 2025 in Doha, Qatar, brought together legal experts, hydrographers, scientists, and policymakers to examine the interface between maritime law and operational practice. A key theme was the growing importance of ocean data – how it is governed, how it should be shared, and how legal frameworks such as UNCLOS, BBNJ, and IOC policies can be meaningfully implemented in real-world operations. Increasing expectations placed on governments and industry alike need to ensure that data collected under licences, permits, and commercial operations contributes to global scientific and sustainability objectives.

This moment is particularly relevant. Hydrographic offices, scientific institutions, and seabed mapping specialists are facing rapid shifts in the legal and policy landscape. MSP, SOPM, and the Kunming-Montreal Global Biodiversity Framework, all require reliable, accessible, and interoperable ocean data. The call to protect 30 % of the ocean by 2030 (the "30 × 30" target) depends heavily on high-quality bathymetric and environmental data to ensure that potential conservation measures are ecologically representative, well-designed, and evidence based.

A key development for improving ocean data accessibility is IOC Decision A33/3.4.2, which endorses the Corporate Data Group's recommendation for Advancing Ocean Data Sharing for Sustainable Development in Areas Within National Jurisdiction. The Decision calls on IOC Member States to integrate the IOC Data Policy and Terms of Use (2023) into offshore licensing and permitting so that data collected during licensed activities must be shared for national and global benefit. It addresses persistent barriers created by differing national approaches to private sector data sharing and promotes more consistent policies through close collaboration between governments, industry and research stakeholders. The Decision also establishes a dedicated working group to support implementation. Overall, it strengthens the foundations for open, interoperable ocean data systems and advances the goals of the Ocean Decade and Sustainable Development Goal 14 (SDG 14) – Life Below Water.

The new BBNJ Agreement's four pillars

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– Environmental Impact Assessments (EIA), Marine Genetic Resources (MGR), Area Based Management Tools (ABMT) including Marine Protected Areas (MPAs), and Capacity Building and Transfer of Marine Technology (CBTMT) – also all heavily rely on data sharing as a prerequisite for success.Therefore, the BBNJ Agreement introduces binding obligations for States Parties to share environmental baselines, monitoring results and scientific information, and to promote capacity building and technology transfer. It requires that scientific data used for management proposals, environmental assessments, and related decision-making, be made publicly accessible through a central international mechanism (known as the Clearing House Mechanism). Because much high-resolution bathymetric, biodiversity, and operational data in ABNJ is generated by private sector operators, States must establish national procedures to ensure these privately collected, datasets are submitted. This is essential not only for transparency but a matter of fairness, enabling developing countries and Small Island Developing States (SIDS) – whose capacity to collect such data is structurally limited – to participate on equal scientific footing in ABNJ governance building and technology transfer.

Under UNCLOS, a Flag State is the country in which a vessel is registered, and it holds legal authority and responsibility for ensuring that vessels flying their flag comply with all applicable international and national laws. This includes applicable environmental and reporting obligations, including Environmental Impact Assessment (EIA), monitoring and communicating the results of these assessments. Contractual arrangements between (private) parties do not transfer or reduce the Flag State's duties under the BBNJ Agreement; instead, they require the Flag State to ensure that operators acting on behalf of third parties comply fully with BBNJ procedures and any national conditions attached to the authorization. Effective Flag State oversight is therefore central to ensuring that privately generated ABNJ data is shared in accordance with international obligations.

International organizations such as the Intergovernmental Oceanographic Commission (IOC) of UNESCO are well positioned to support implementation by providing coordination, data standards and capacity development. Their involvement provides an important institutional link between treaty obligations, national implementation, and operational practices across sectors.

Effective implementation of ocean governance frameworks depends on clear operational tools, particularly well-designed contracts. These agreements must define data stewardship responsibilities, usage rights, delivery formats, and conditions for public release; without such clarity, privately collected ocean data may remain inaccessible. As most data from ABNJ are collected by technologically advanced States and well-resourced industries, there is a risk that these actors could dominate how such information is used. To prevent this, the BBNJ Agreement places strong emphasis on equity: requiring for data-governance systems that not only share information openly but also help build scientific and technical capacity in developing States, ensuring that the benefits of ocean data are distributed more fairly, rather than reinforcing existing global disparities. As countries prepare for the first BBNJ Conference of the Parties (COP) in January 2027, standardised guidance on data submission, repository use, interoperability, and the integration of privately collected information will be essential to implementing these equity commitments in practice.

With MSP, SOPM, global biodiversity commitments, and the 30 × 30 target all relying on high-quality, accessible data, the coming years offer a critical opportunity to embed data sharing requirements directly into contracts, permits, and operational frameworks, strengthening the scientific foundation of global ocean governance designed contracts. These agreements must define data stewardship responsibilities, usage rights, delivery formats, and conditions for public release; without such clarity, privately collected ocean data may remain inaccessible. Because technologically advanced States and industries generate most high-resolution ABNJ data, the BBNJ Agreement places strong emphasis on equity, requiring data governance systems that support global capacity development rather than reinforce existing disparities. As countries prepare for the first BBNJ quality, accessible data, the coming years offer a critical opportunity to embed datas haring requirements directly into contracts, permits, and operational frameworks.

4 Policy and contracting recommendations

Advancing ocean data sharing will only succeed if high level policy commitments are consistently translated into licensing conditions and contractual language. While the BBNJ Agreement and IOC policies provide a strong normative foundation, the practical reality is that most ocean data – particularly from the private sector – is governed by the terms set in offshore permits and commercial contracts. Clear and consistent contractual wording is therefore essential to ensure that valuable data does not remain locked in private archives.

A central development in this regard is the already mentioned IOC Assembly Decision A 33/3.4.2, which encourages Member States to integrate data sharing obligations into their offshore permitting regimes. As offshore energy, telecommunications, and marine infrastructure industries continue to collect data, embedding these expectations into offshore permits offers a scalable and efficient way to increase data availability.

The entry into force of the BBNJ Agreement extends similar expectations into Areas Beyond National Jurisdiction. States Parties must guarantee

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that environmental baselines, EIA results, and monitoring data are made accessible through international mechanisms. Because much of this information will be generated by privately operated vessels and platforms, States need to ensure that their national authorizations and contractual arrangements oblige operators to supply data and in formats that are interoperable and suitable for public release. This is equally a matter of equity: high resolution datasets generated by technologically advanced States and industries should serve the global community, including developing States and SIDS.

Contracts and permit conditions should clearly specify data stewardship responsibilities, define submission requirements, and set timelines for delivering both datasets and metadata. They should also indicate acceptable formats and standards, referencing IOC guidance, ODIS interoperability requirements, and National Oceanographic Data Centers' practices. Where necessary, limited embargo periods may be included, but these should be specifically targeted to avoid unnecessary restrictions. Clarity around liability and licensing terms, often addressed through standard open data licences, helps reduce real and perceived risks for companies and increases confidence in sharing. For companies, adopting a consistent internal approach to data stewardship and including data sharing provisions in all subcontracting and partnership agreements is equally important and helps avoid gaps in compliance.

To operationalise these recommendations, clear responsibilities must be assigned to each actor in the ocean data ecosystem. Governments and regulators should integrate mandatory data-submission clauses into all offshore permits and ABNJ authorisations, specifying timelines, required formats, and delivery to National Oceanographic Data Centres or the BBNJ Clearing-House Mechanism. Private-sector operators should ensure that all environmental, bathymetric, and monitoring data collected during operations are curated, quality-controlled, and delivered with complete metadata. International organisations – Intergovernmental Coordination Group for the Ocean Observing System (ICO), the International Hydrographic Organization (IHO), and the various Ocean Decade Programmes and Projects – should develop and maintain standardised contractual clauses, and interoperability guidance to support States and operators. National Oceanographic Data Centres, International Oceanographic Data and Information Exchange (IODE) and the Ocean Data and Information System (ODIS) nodes should act as the receiving and verification points, providing clear data-submission pathways and supporting industry in meeting compliance obligations while distributing data for global applications. By assigning concrete, actionable tasks to specific actors, these recommendations shift from high-level principles to operational practice. Together, they create a predictable, scalable, and internationally coherent system for ocean-data sharing across jurisdictions, including in ABNJ, thus advancing the Ocean Decade vision of a transparent, interoperable, and inclusive global ocean knowledge ecosystem.

Together, these measures help align legal obligations, operational practices, and global sustainability goals. Standardised but flexible clauses in offshore permits and contracts make data sharing a predictable and routine part of ocean activities rather than an exception. As States prepare for the first BBNJ COP towards the end of 2026 and as the Ocean Decade continues to advance, the widespread adoption of clear contractual language represents one of the most direct and practical ways to improve access to ocean data and strengthen the scientific foundations of marine governance.

References

Barzuna, C., Haugan, P., Barbière, J., Swift, A., Khan, M., Ansong, J. O., James, P. A. S., Scherer, M., Thiele, T., von Schuckmann, K., Abramic, A., Barrowclough, D., Cisneros Montemayor, A., Girón, A., Heaps, L., Koirala, S., Lyons, M., Paul, K., Priyanto, A. T., Randone, M., Rosado, S., Santos, C. F., Savoldelli, C., Spalding, A. K., Strand, M., Sumaila, U. R., Swaddling, A., Turner, J., Vestergaard, O. and Yulianto, I. (2025). *Handbook on sustainable ocean plans: A practitioners' guide*. World Resources Institute. https://doi.org/10.69902/8a3c346d

Burger, P. and Meyer, L. (2025). Harnessing private sector data for the Ocean Decade: Challenges and solutions. *The International Hydrographic Review, 31*(1), 166–170. https://doi.org/10.58440/ihr-31-1-n04

CBD (2023). *Kunming-Montreal global biodiversity framework*. Convention on Biological Diversity. https://www.cbd.int/gbf (last accessed 29 March 2026).

Harris, L. R., Holness, S., Finke, G., Kirkman, S. and Sink, K. (2019). Systematic conservation planning as a tool to advance ecologically or biologically significant area and marine spatial planning processes. In J. Zaucha and K. Gee (Eds.), *Maritime spatial planning* (pp. 71–96). Palgrave Macmillan. https://doi.org/10.1007/978-3-319-98696-8_4

IUCN (2022). *Governing areas beyond national jurisdiction*. International Union for Conservation of Nature. https://iucn.org/resources/issues-brief/governing-areas-beyond-national-jurisdiction (last accessed 29 March 2026).

Leadbetter, A. M., Raymond, L., Chandler, C., Pikula, L., Pissierssens, P. and Urban, E. (2013). *Ocean data publication cookbook* (UNESCO IOC Manuals and Guides No. 64). UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000373775 (last accessed 29 March 2026).

ODCDG (2025). *Advancing ocean data sharing for sustainable development in areas within national jurisdiction*. Ocean Decade Corporate Data Group, UNESCO IOC. https://oceandecade.org/publications/advancing-ocean-data-sharing-for-sustainable-development-in-areas-within-national-jurisdiction/ (last accessed 29 March 2026).

Seabed 2030 (2017). *Our mission*. The Nippon Foundation-GEBCO Seabed 2030 Project. https://seabed2030.org/our-mission/ (last accessed 29 March 2026).

UN (1982). *United Nations Convention on the Law of the Sea*

(adopted 10 December 1982, entered into force 16 November 1994). 1833 U.N.T.S. 397. United Nations, New York, USA. https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf (last accessed 16 April 2025).

UN (2023). *Agreement under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction* (adopted 19 June 2023, not yet in force). United Nations, New York, USA. https://www.un.org/bbnjagreement/en (last accessed 29 March 2026).

UNESCO-IOC (2024). *Ocean Decade Bathymetry Data Sharing Guideline* (The Ocean Decade Series, 58). UNESCO. https://oceandecade.org/publications/ocean-decade-bathymetry-data-sharing-guideline/ (last accessed 29 March 2026).

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CONFERENCE PAPER

From satellites to cetaceans: strengthening marine megafauna protection through integrated observation, data governance, and emerging ocean standards

Author
Emily Charry Tissier[1]

Preamble

The following work was presented at the 12th ABLOS Conference, 7–8 October 2025, Doha, Qatar in the oral session *Ocean observation and cooperation frameworks*.

Abstract

Rapid advances in satellite imagery, uncrewed aerial systems, and artificial intelligence now enable unprecedented detection of marine megafauna, yet protection remains uneven due to governance, economic, and data-access barriers. Drawing on projects in Canada's EEZ, Antarctica, and areas beyond national jurisdiction, this Note illustrates how technical readiness outpaces institutional frameworks. It proposes integrating biodiversity information into the International Hydrographic Organization's S-100 standard as a practical pathway to improve interoperability, adaptive management, and data equity. These steps provide practical near-term pathways to enhance monitoring, interoperability, and adaptive management for marine megafauna across diverse jurisdictions.

Keywords
marine megafauna · S-100 · remote sensing · artificial intelligence · data interoperability · ocean governance · biodiversity monitoring · uncrewed aerial systems

1 Introduction

Marine megafauna such as whales and penguins play critical ecological roles and hold cultural, economic, and conservation significance across the world's oceans. Yet despite decades of commitments under the United Nations Convention on the Law of the Sea (UNCLOS) to protect and preserve the marine environment, the effectiveness of protection measures remains uneven (UN, 1982). UNCLOS establishes a comprehensive legal framework for the oceans, but it does not prescribe how States should integrate rapidly evolving observation technologies into day-to-day management. As ocean uses intensify and biodiversity loss accelerates, the absence of interoperable ecological data standards presents a structural governance risk, not merely a technical challenge.

Today's observation landscape spans satellite platforms capable of wide-area monitoring, uncrewed aerial systems (UAS) that provide high-resolution local imagery, automated detection powered by artificial intelligence (AI), and acoustic platforms that complement visual datasets. These tools enable the detection of individual animals (Figs. 1 and 2), the mapping of colonies, and the characterization of habitats at spatial and

✉ Emily Charry Tissier · emily@whaleseeker.com
[1] Whale Seeker Inc., Montréal, Canada

temporal scales unimaginable when UNCLOS was adopted (Seymour et al., 2017; Fretwell & Trathan, 2021). The challenge is integrating these capabilities into institutional frameworks not designed for rapid, data-intensive ecological monitoring.

This Note draws on three applied case studies from work conducted by Whale Seeker and partners:

1. Dynamic vessel management in Canada's EEZ, where AI-assisted UAS detection increased the identification of endangered North Atlantic right whales compared with an AI that had no domain specific expertise.
2. Penguin and habitat monitoring in Antarctica, where drone imagery and AI revealed both new ecological insights and persistent gaps in Antarctic Treaty-era data-sharing practices.
3. Satellite-based whale migration analysis, undertaken with WWF, Fisheries and Oceans Canada, Princeton University, and others, illustrating the challenges of monitoring beyond jurisdictional borders.

Across these examples, a consistent pattern emerges: the technical capacity to observe marine megafauna exists, but the pathways to integrate, share, and govern these data are insufficiently developed. High-resolution imagery remains costly; open data sources are powerful for climate applications but too coarse for individual animals; and operational deployment is constrained by weather, permitting, and the lack of interoperable data pipelines.

To address this gap, the Note considers near-term, practical opportunities for strengthening marine megafauna protection by improving interoperability and data equity. In particular, it explores how biodiversity information could be integrated into the International Hydrographic Organization's S-100 framework, a global geospatial standard already used for navigation and ocean data products (IHO, 2022). An S-100-compatible biodiversity layer would provide a consistent foundation for science, planning, and adaptive management across jurisdictional boundaries.

2 The technological landscape

Modern ocean observation rests on a diverse set of complementary tools that operate across spatial and temporal scales. Satellites provide wide-area coverage suitable for identifying environmental conditions, surface features, and, in some cases, large marine animals. Very-high-resolution sensors can detect individual whales or penguin colonies in remote regions, extending monitoring to areas that are logistically difficult to access (Fretwell & Trathan, 2021). UAS supply high-resolution imagery capable of detecting individual whales, seals (Fig. 3), or seabird nests with exceptional precision, while minimizing disturbance and human risk (Seymour et al., 2017).

Automated AI models accelerate the analysis of these datasets, enabling near real-time detection, species identification, and habitat classification. These approaches are increasingly recognized as key components of "big data" frameworks for marine megafauna conservation, where large volumes of spatial information are used to understand movement, distribution, and threats at scale (Bax et al., 2019; Canonico et al., 2019). Acoustic platforms, though not the focus of this Note, contribute essential information in low-visibility conditions and complement visual data streams.

Individually, each modality offers unique strengths; together, they enable a multi-scale, multi-sensor approach suited to the detection and monitoring of marine megafauna. This integration is especially valuable for species that move across jurisdictional boundaries or inhabit remote regions where traditional surveys are challenging. For example, UAS can document fine-scale behaviours or distribution patterns, while satellites can simultaneously track environmental drivers influencing those movements on regional or basin scales.

Despite this technical maturity, operationalizing these tools within existing governance frameworks remains difficult. Weather, permitting requirements, data-processing logistics, and variable institutional capacity can limit the deployment of even the most sophisticated systems. In addition, cloud computing

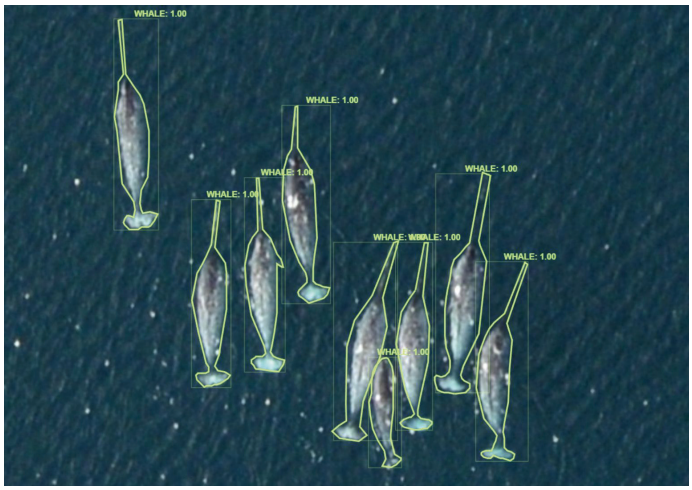


Fig. 1 Narwhal annotations.

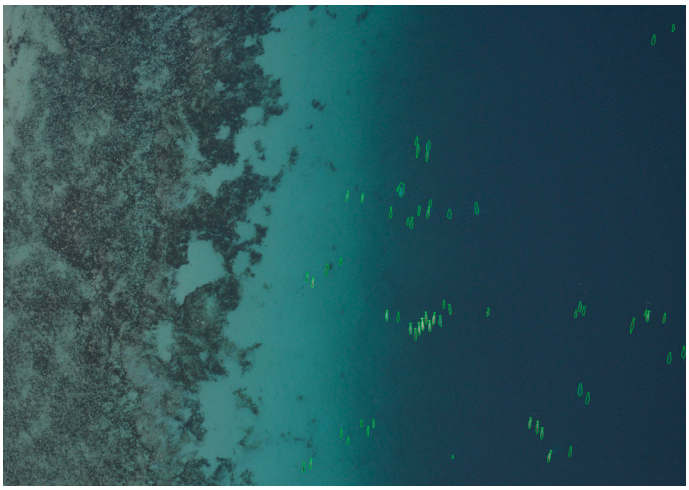


Fig. 2 Narwhal detections.

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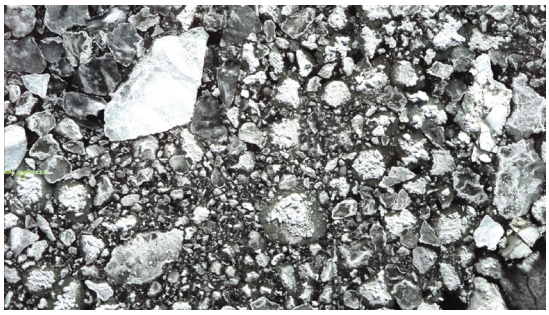


Fig. 3 Seal on ice, annotated in yellow on the left side of the image.

and AI validation require sustained investment, and high-resolution commercial imagery remains expensive, creating an uneven landscape in which well-resourced organizations can access advanced monitoring while smaller institutions, NGOs, and developing States may struggle (GOOS, 2025). The technological foundation for large-scale, consistent marine megafauna monitoring already exists; the remaining challenges lie in building the standards, data-sharing practices, and governance pathways needed to translate these capabilities into equitable and effective protection.

3 Case studies

3.1 Dynamic vessel management in Canada's EEZ

North Atlantic right whales are among the world's most endangered marine mammals, and vessel strikes remain one of the primary threats to their recovery. To support adaptive management in Canadian waters, Whale Seeker collaborated with Transport Canada and Innovation, Science and Economic Development Canada to deploy AI-powered detection tools within dynamic management zones.

Using UAS imagery processed through domain-informed datasets and standardized annotation protocols, the system improved whale detection performance, underscoring the importance of expert-curated training data in AI-enabled conservation applications (Seymour et al., 2017; Smit et al., 2022).

Improved detection can translate directly into more responsive vessel-speed restrictions and fishing-gear adjustments at finer spatial and temporal scales, aligning with the broader principles of dynamic ocean management, in which management measures respond in near real time to changing conditions (Maxwell et al., 2015). Expanding similar systems across Canada's EEZ would strengthen adaptive management and help fulfil national obligations under UNCLOS to protect and preserve the marine environment.

3.2 Antarctica: penguins, pathogens, and the open-data paradox

The Antarctic Treaty System promotes the free exchange of scientific data, positioning Antarctica as a global common for research. Yet, in practice, access to ecological datasets is often fragmented, restricted, or dependent on institutional gatekeeping. Working with Oceanites, the only charity organization providing open, long-term data on penguin colonies in Antarctica, Whale Seeker applied UAS imagery and AI models to monitor penguin colonies and habitat conditions.

These tools enabled high-accuracy detection of penguins, nests, and land-cover classes across hundreds of hectares of surveyed terrain, supporting improved assessments of colony health and potential vulnerability to emergent threats such as avian influenza. This experience is consistent with broader trends in polar wildlife research, where satellite and UAS datasets are increasingly used to discover new colonies and assess population responses to sea-ice change (Fretwell & Trathan, 2021).

However, the project also highlights persistent tension between the Treaty's open-data principles and the realities of scientific practice. While organizations such as Oceanites exemplify transparent and accessible data stewardship, many datasets remain siloed or available only to specific delegates or institutions. As climate change accelerates ecological pressures in Antarctica, broadening access to high-quality spatial data will be essential for informed management and global scientific collaboration (Bax et al., 2019).

3.3 Monitoring beyond borders: satellite-based whale migration analysis

Marine megafauna routinely traverse multiple EEZs and areas beyond national jurisdiction, making consistent monitoring a transboundary challenge. In collaboration with WWF, Fisheries and Oceans Canada, Princeton University, and other partners, Whale Seeker explored the use of high-resolution satellite imagery and AI to detect whales and infer migration timing and routes.

This work demonstrates both the promise and the constraints of satellite-based monitoring for wide-ranging species. While the imagery can reveal large-scale movement patterns, its utility is diminished by the fragmented nature of megafauna-related datasets. Information collected by governments, NGOs, private industry, and research institutions is often stored in

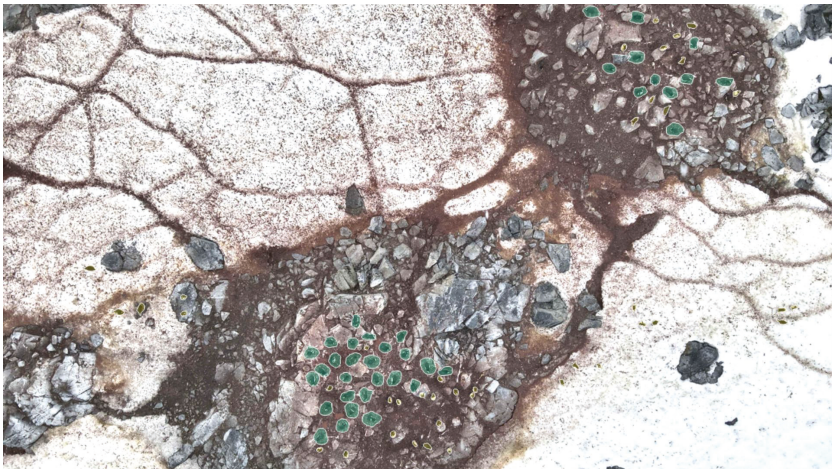


Fig. 4 AI-based detection of penguins (yellow) and nests (green) from UAS imagery collected with Oceanites.

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incompatible formats or unavailable beyond project boundaries.

The satellite pilot underscores the need for interoperability: without standardized formats and pathways for sharing spatial biodiversity information, the full value of emerging remote-sensing technologies cannot be realized. Migratory species will continue to move across jurisdictions, but monitoring systems, and the governance frameworks they support, must evolve to match that scale (Bax et al., 2019; Smit et al., 2022).

4 Challenges in implementation and data equity

Although modern remote-sensing tools are technically mature, several operational and structural barriers constrain their deployment at scale. Technology readiness does not automatically translate into effective protection; real-world outcomes depend on weather, permitting, data infrastructure, and unequal access to resources.

4.1 Operational constraints

Practical challenges can significantly delay or limit monitoring campaigns. Weather affects UAS flights and satellite visibility windows. Regulatory approvals for drone operations or wildlife surveys often take longer than the ecological windows during which information is most needed. Even when data are collected, integrating imagery, annotations, and detections into management workflows requires robust pipelines that many agencies do not yet have (UNESCO/IOC, 2023).

These obstacles reduce the responsiveness of marine mammal monitoring during critical periods such as migration, breeding, or heightened industrial activity.

4.2 Fragmented data and governance

Across all three case studies, a core limitation was not the ability to observe marine megafauna, but the difficulty of integrating and sharing the resulting data. Observations from satellites, drones, government surveys, NGOs, and private operators are typically stored in incompatible formats and seldom combined. Without interoperable standards, decision-makers lack the unified view needed for adaptive management.

This fragmentation is particularly problematic for migratory species whose ranges span multiple jurisdictions. When each entity collects data independently, with different methodologies, taxonomies, temporal scales, or access rules, the collective value of these observations is diminished (Bax et al., 2019).

4.3 The risk of a two-tier monitoring system

The economics of marine monitoring amplify inequities. High-resolution commercial imagery remains costly, particularly for small island States, Indigenous communities, and under-resourced NGOs. Open satellite data, such as from Sentinel, are transformative for climate and oceanography but too coarse to detect individual whales or small seabird colonies. AI and cloud computing require ongoing investment that many organizations cannot sustain.

Recent analyses of global ocean data systems emphasize that the ocean remains under-observed, especially in developing regions, and that data are often fragmented and hard to access (GOOS, 2025). These conditions risk producing a two-tier system: wealthy States, research institutions, and large industries gain access to advanced detection and analytics; others are left with outdated tools or no monitoring capacity at all. Such disparities undermine collective efforts to meet UNCLOS obligations and weaken regional and global conservation frameworks.

5 Pathways forward: integrating biodiversity into S-100

The International Hydrographic Organization's S-100 Universal Hydrographic Data Model already underpins a wide array of next-generation ocean data products, including bathymetry, surface currents, electronic navigational charts, and marine traffic management layers (IHO, 2022). Expanding this framework to include biodiversity information represents a practical, near-term opportunity to strengthen monitoring and management of marine megafauna.

5.1 Why S-100 is the logical foundation

S-100 is designed for interoperability. It provides a consistent structure for encoding, distributing, and visualizing diverse marine datasets used by coastal States, hydrographic offices, navigational systems, and industry. Because the standard is already integrated into operational workflows, adding biodiversity layers would not require the creation of an entirely new system; it would leverage and extend an existing global architecture (IHO, 2022).

A biodiversity-focused S-100 product could incorporate:

- Baseline species ranges and seasonal distributions
- Sensitive habitat areas
- Locations of colonies, calving grounds, or aggregation sites
- Metrics relevant to ecosystem services, including carbon cycling benefits
- Indicators of human pressure such as vessel density or noise proxies

By aligning biodiversity data with the same standards used for navigation and ocean management, such a layer would bridge science, conservation, and operational decision-making, an outcome strongly aligned with contemporary approaches to ecosystem-based ocean governance (Bax et al., 2019; Smit et al., 2022).

5.2 Supporting cross-jurisdictional consistency

Megafauna regularly cross boundaries between EEZs and areas beyond national jurisdiction, yet monitoring systems are rarely unified across these transitions. An S-100-compatible biodiversity layer would enable:

- Consistent encoding of observations collected by satellites, drones, vessels, and field teams
- Cross-border comparability, ensuring that different

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States and organizations work from compatible data structures
- Scalability, allowing fine-resolution local surveys to coexist with broad satellite-based products
- Integration with navigation tools already used by mariners, regulators, and hydrographic agencies

This standardization would reduce fragmentation and increase the collective value of existing and future monitoring efforts.

5.3 Advancing data equity

As highlighted in broader discussions on ocean data systems, equitable access to data is increasingly recognized as a prerequisite for just and effective ocean governance (UNESCO/IOC, 2023; GOOS, 2025). By offering a common format for biodiversity layers, S-100 could help mitigate inequities. When data are encoded consistently, sharing becomes easier, and interoperable datasets can be combined, even when collected by partners with varying levels of resources.

Standardization does not eliminate the economic barriers associated with imagery acquisition or AI processing, but it creates a more level playing field for the downstream use of information. States, NGOs, and local communities with limited monitoring capacity would be better positioned to interpret and apply biodiversity data for management, compliance, and conservation planning.

5.4 A practical first step

Developing an S-100 biodiversity layer is both technically feasible and strategically aligned with the direction of global ocean governance. It would create a foundational tool for integrating diverse observation modalities and improving the accessibility and utility of marine megafauna data. As technologies for remote sensing and AI continue to evolve, embedding biodiversity within widely adopted hydrographic standards can help ensure that these innovations translate into equitable and effective protection (Bax et al., 2019; Smit et al., 2022).

6 Conclusions and recommendations

Across national, polar, and transboundary contexts, the case studies presented in this Note illustrate a consistent conclusion: our capacity to observe marine megafauna has outpaced our capacity to govern, integrate, and apply the resulting data. Satellites, UAS, and AI-powered analytics can detect marine megafauna and seabirds with remarkable precision, yet implementation remains constrained by operational barriers, fragmented data practices, and unequal access to high-resolution imagery and analytical tools (Bax et al., 2019; UNESCO/IOC, 2025).

These challenges directly affect the ability of States and institutions to meet long-standing obligations under UNCLOS to protect and preserve the marine environment (UN, 1982). The rapid expansion of industrial activities in the ocean, including shipping, fisheries, energy, and coastal development, further raises the stakes. Without modernized data pathways, protection will continue to be uneven, and the gap between technological capability and ecological need will widen.

A practical and achievable response lies in standardization and interoperability. Integrating biodiversity information into the International Hydrographic Organization's S-100 framework offers a near-term opportunity to align emerging ecological datasets with the established geospatial infrastructure that already supports navigation, marine traffic management, and ocean monitoring (IHO, 2022). Such an approach would improve consistency across jurisdictions, enhance the utility of diverse observation methods, and help mitigate inequities in access to high-quality spatial data.

The following is recommended:

1. Develop an S-100 biodiversity layer: Initiate technical discussions within IHO and partner institutions to scope and prototype a biodiversity product specification that includes megafauna distributions, habitat sensitivity, and indicators of human pressure.
2. Support interoperable monitoring across jurisdictions: Encourage States, NGOs, industry, and research institutions to adopt compatible formats for megafauna observations, enabling shared analyses that reflect the full spatial extent of species movements.
3. Invest in data equity: Expand initiatives that facilitate access to high-resolution imagery, AI tools, and cloud-computing resources for under-resourced States and organizations, reducing the risk of a two-tier monitoring system.
4. Strengthen workflows linking observation to action: Integrate remote-sensing outputs into management systems for dynamic vessel regulation, protected area oversight, and environmental risk assessment, ensuring that detections translate into timely, evidence-based decisions (Maxwell et al., 2015).
5. Foster collaboration among data holders: Promote partnerships that combine government, NGO, academic, and private-sector datasets using standardized methods and annotation frameworks, increasing the collective value of existing monitoring efforts (Bax et al., 2019; Smit et al., 2022).

The tools needed to observe marine megafauna at meaningful scales already exist. The critical work now lies in ensuring that these innovations are accessible, interoperable, and embedded within governance frameworks capable of translating observations into protection. Standardizing biodiversity information within S-100 is an actionable step toward that future, one that strengthens science, supports decision-makers, and advances our shared responsibility to safeguard ocean ecosystems.

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References

Bax, N. J., Miloslavich, P., Muller-Karger, F. E., Allain, V., Appeltans, W., Batten, S. D., Benedetti-Cecchi L., Buttigieg P. L., Chiba S., Costa D. P., Duffy J. E., Dunn D. C., Johnson C. R., Kudela R. M., Obura D., Rebelo L.-M., Shin Y.-J., Simmons S. E. and Tyack P. L. (2019). A response to scientific and societal needs for marine biological observations. *Frontiers in Marine Science, 6*, 395. https://doi.org/10.3389/fmars.2019.00395

Canonico, G., Buttigieg, P. L., Montes, E., Muller-Karger, F. E., Stepien, C., Wright, D., Benson, A., Helmuth, B., Costello, M., Sousa-Pinto, I., Saeedi, H., Newton, J., Appeltans, W., Bednaršek, N., Bodrossy, L., Best, B. D., Brandt, A., Goodwin, K. D., Iken, K., Marques, A. C., Miloslavich, P., Ostrowski, M., Turner, W., Achterberg, E. P., Barry, T., Defeo, O., Bigatti, G., Henry, L.-A., Ramiro-Sánchez, B., Durán, P., Morato, T., Roberts, J. M., García-Alegre, A., Cuadrado, M. S. and Murton, B. (2019). Global Observational Needs and Resources for Marine Biodiversity. *Frontiers in Marine Science, 6*:367. https://doi.org/10.3389/fmars.2019.00367

Fretwell, P. T. and Trathan, P. N. (2021). Discovery of new colonies by Sentinel-2 reveals good and bad news for emperor penguins. *Remote Sensing in Ecology and Conservation, 6*(4), 337–344. https://doi.org/10.1002/rse2.176

GOOS (2025). *Global Ocean Observing System: Status Report 2025* (Report No. GOOS-310). The Intergovernmental Oceanographic Commission (IOC) of UNESCO, Paris, France; Joint Centre for Oceanography and Marine Meteorology in situ Observations Programmes Support (OceanOPS), World Meteorological Organization (WMO) Geneva, Switzerland. https://www.ocean-ops.org/goosreport/goosreport2025.pdf (last accessed 8 May 2026).

IHO (2022). *Universal hydrographic data model* (ed. 5.0.0). IHO S-100, International Hydrographic Organization, Monaco. https://iho.int/uploads/user/pubs/standards/s-100/S-100_5.0.0_Final_Clean_Web.pdf (last accessed 29 March 2026).

Maxwell, S. M., Hazen, E. L., Lewison, R. L., Dunn, D. C., Bailey, H., Bograd, S. J., et al. (2015). Dynamic ocean management: Defining and conceptualizing real time management of the ocean. *Marine Policy, 58*, 42–50. https://doi.org/10.1016/j.marpol.2015.03.014

Seymour, A. C., Dale, J., Hammill, M., Halpin, P. N. and Johnston, D. W. (2017). Automated detection and enumeration of marine wildlife using unmanned aircraft systems and thermal imagery. *Scientific Reports, 7*, 45127. https://doi.org/10.1038/srep45127

Smit, K. P., Van Niekerk, L., Harris, L. R., McQuatters-Gollop, A., Shannon, L. J. and Sink, K. J. (2022). A roadmap to advance marine and coastal monitoring, biodiversity assessment, and international reporting: A developing nation perspective. *Frontiers in Marine Science, 9*, 886373.

UN (1982). *United Nations Convention on the Law of the Sea* (adopted 10 December 1982, entered into force 16 November 1994). 1833 U.N.T.S. 397. United Nations, New York, USA. https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf (last accessed 29 March 2026).

UNESCO/IOC (2023). *IOC Strategic Plan for Ocean Data and Information Management (2023–2029)*. The Intergovernmental Oceanographic Commission (IOC) of UNESCO, Paris, France.

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NOTE / TECHNICAL REPORT

SidescanTools: an open source software for sidescan data processing

Authors
Mia Schumacher[1], Finn Spitz[2] and Christian Lüke[2]

Abstract
Sidescan sonars are a key tool for maritime mapping, object detection, and wreck inspection. This paper presents SidescanTools, an open-source software to process common sidescan data formats (XTF, JSF). The Python-based application provides core functionalities such as bottom detection, geometric and radiometric corrections, and gain normalisation, thereby enhancing data resolution and range. Processed results can be exported to georeferenced raster images. SidescanTools was developed within the frame of Ghostnetbusters, a project for the detection of small objects on sonar data in collaboration with sonoware GmbH/Kiel and Geomar Helmholtz Institute for Ocean Research, Kiel, funded by WTSH Schleswig Holstein.

Keywords
side scan · open-source software · python · side scan data processing

1 Introduction
Sidescan sonar is a widely used technology to create high resolution images of the seafloor. It has become an important tool in numerous marine applications, including underwater construction and archaeology, environmental monitoring and offshore energy exploration (Blondel, 2009). Sidescan sonars are also employed by non-profit organisations to help identify human traces, such like the search for litter, anquoring marks etc. (e.g. Díaz-Mendoza et al., 2024; Bruns et al., 2020). The process of converting raw sonar data into informative and interpretable images is necessary in order to make the data usable and requires a full processing chain (BSH, 2016). Coverage and spatial resolution depend on the emitted frequency where higher frequencies (usually hundreds of kHz) allow for higher resolution (orders of centimetres) at the cost of swath width (few hundreds of meters) whereas lower frequencies (order of few to tens of kHz) can cover wider swath areas (several kilometres) with less resolution (order of meters) (Grządziel, 2023; Lurton, 2010).

While sidescan sonar systems have become more affordable and easier to operate compared to other surveying technologies like multibeam echo sounders, the processing of raw sonar data usually still relies on expensive commercial software packages. This reliance on proprietary software has limited accessibility for small organisations like NGOs or hobbyists interested in underwater exploration and marine science.

To address this, we present SidescanTools, a new open-source software package designed to read and process sidescan sonar data. This article provides an overview of SidescanTools, with details about its features, functionalities, and potential applications in marine science and underwater acoustic imaging. SidescanTools has been developed within the framework of Ghostnetbusters, a joint project by sonoware GmbH and GEOMAR Helmholtz Centre for Ocean Research. Visit the project on https://www.sidescantools.de/.

2 Principles of sidescan sonar
A sidescan sonar can either be towed behind, hull- or pole-mounted on a ship or on an autonomous underwater vehicle (AUV). It operates by emitting sound pulses from an electroacoustic transducer, which is usually oriented perpendicular to the track of the ship. The directivity of the acoustic transducer is very sharp in the horizontal (or azimutal) range, usually well below one degree. The image is created from the received backscatter signal, which is recorded and sampled (digitised) by the sidescan sonar system. As

✉ Mia Schumacher · mschumacher@geomar.de
[1] GEOMAR Helmholtz Centre for Ocean Research, 24148 Kiel, Germany
[2] sonoware GmbH, 24118 Kiel, Germany

the acoustic signal travels through the water column, its energy gets attenuated and absorbed, partially reflected and scattered by the seafloor and any object present. The intensity and travel time of the returned echoes are used to create a two-dimensional image of the sea floor on a ping-by-ping (time-by-time) basis as the sensor moves forward (Lurton, 2010; Blondel, 2009). The resulting image represents the received acoustic backscatter intensity, where stronger returns typically indicate harder surfaces, while weaker returns are due to softer, more absorbent materials and smaller grain sizes. The reflected signal strength depends strongly on the seafloor roughness. This allows for the differentiation of sea floor types and the identification of objects on the seabed, like stones, wrecks etc. Two of the most important parameters that influence data quality are the frequency at which acoustic pulses are emitted and the altitude of the sensor above the sea floor. Higher frequencies travel less far than lower frequencies, but they provide higher resolution data enabling users to detect smaller objects. For the detection of (human-made) objects, high-frequency sensors are the right choice whereas for large mapping activities, lower frequency transducers with wide ranges would be more suitable (Marx et al., 2023; Grządziel, 2023; Díaz-Mendoza et al., 2023).

2.1 Main steps for sidescan sonar data processing

The following processing steps are necessary to obtain reasonable and interpretable results (Grządziel, 2023; Lurton, 2010; Blondel, 2009).

2.1.1 Navigation pre-processing

Depending on the available navigation and attitude systems and how the sensor is mounted, the geo-locations of the pings can be inaccurate and need adjusting. The use of poor quality GNSS (Global Navigation Satellite System) can lead to gaps and/or jumps in the coordinates or other unwanted behaviour and hence result in large positioning errors. In most cases, these can be corrected using filtering techniques to smooth the navigational data. In case the sensor is towed, output cable length may be the only measure to derive to the true position of the sensor if no USBL (Ultra Short Base Line) is used. This introduces additional uncertainty if the cable is not exactly in line with the vessel track (Blondel, 2009). Navigation processing is the first step prior to any further processing.

2.1.2 Geometric corrections

Slant range is the direct line-of-sight between the transducer and the seafloor. It is derived from the two-way travel time of an acoustic pulse from the transducer to the sea floor and back. Hence, slant ranges of neighbouring samples are very similar close to nadir where travel times are per se short, whereas at far distance from the transducer, they become significantly different. This change in range across the swath leads to perspective distortions by the slanted view: Two objects with mutual distance seem closer to each other at far range than two object with the same mutual distance that are at close range. Assuming a flat sea floor, the true ground distance can be derived using trigonometry as shown in Section 3.3.2 and Fig. 1 (Lurton, 2010) and (Blondel, 2009) . This requires the concept of bottom detection which will be explain further in Section 3.3.1.

2.1.3 Radiometric corrections

Radiometric correction addresses signal variation, attenuation and reverberation effects that occur when acoustic waves travel through water. Signal variation depends on various factors like distance, wave motion, beam pattern and instrument motion. More distant objects have weaker backscatter returns than objects closer to the transducer due to lower incidence angles and larger travel distances.

The typical antenna directivity pattern for a two-sided sonar device has a main lobe at around 45° with the main energy being emitted at around 35–65° (Chang et al., 2010). Side lobes with weaker signal strength usually also exist and need to be considered. Beam incidence angles can be calculated from phase shifts of the return signal that occur due to the speed of an object relative to the sensor. The effect of distance-related signal loss is compensated by applying Time Varying Gain (TVG) (Lurton, 2010). This mostly already happens during data acquisition inside the sonar hardware as a function of travel time and frequency. Motion of the sonar instrument (e.g. due to waves, differences in platform speed etc.) but also insufficient TVG can be the source of changes of ping energy that result in intensity patterns (e.g. stripes) along the track line. All of the above are systematic errors which can be corrected using statistics on beam pattern, distance from sonar and ping energy level normalisation. These corrections and other optional data processing steps are described in Section 3.4.

2.1.4 Georeferencing

Georeferencing is the process of adding geospatial information to a dataset, which in this case means transferring relative image coordinates to real-world coordinates (e.g. longitude/latitudes or coordinates in a projected reference system like Universal Transverse Mercator (UTM)). At this stage layback, the offset between the transducer and the GPS antenna, has to be taken into account and compensated. On a ping-by-ping basis, the centre (nadir) coordinates along with the outer swath edge coordinates and the sample size are used to form an evenly spaced grid with coordinates for each data sample. Sample in this case refers to slant range corrected backscatter value. The backscatter values are then mapped onto this grid using interpolation techniques. Coordinates of the inner swath and at the outer edges are calculated based on the ground range as described in Sections 3.3.1 and 3.3.2 (Lurton, 2010; Blondel, 2009). This approach becomes less accurate if

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bathymetry is varying laterally. If additional information about bathymetry is available, the sidescan mosaics can be fit to a more precise location by co-registering objects in the sidescan data with sea floor features on the bathymetry. However, this functionality is not implemented in SidescanTools. Conclusively, the georeferenced data from single files may be merged into one mosaic.

3 SidescanTools

SidescanTools is open-source, written in Python and uses some external libraries. The GitHub project includes a *requirements.yml* file to make installation via Anaconda easy (Anaconda, 2025).

The tool has been developed for full processing of data from commercial sidescan sonars. The aim is to apply geometric and radiometric corrections, to overall enhance image quality and to generate georeferenced images with user defined parameters on an easy-to-use graphical interface. As an alternative for advanced users who need to run SidescanTools on a system without UI (e.g. for deployment on AUVs or to save memory) the tool can also be used via a command line interface (CLI). In both cases, settings and parameters are stored and read from a configuration file *project_info.yml*. The implemented processing steps are explained in the following.

3.1 Design principles

The development of SidescanTools follows several key principles:

a. Open-source: SidescanTools is freely available and open-source under GPLv3 license, mainly targeted at NGOs or private people who use sidescan sonars and need to process and plot data.
b. Modularity: The software is designed with a modular architecture that allows for easy extension and customisation of functionalities, e.g. headless operation for near real time use e.g. on AUVs.
c. User-friendliness: SidescanTools aims to maintain an intuitive interface with focus on functionality and performance.
d. Compatibility: Support for open and cross-platform data formats aims for a broad applicability across different sonar systems and manufacturers.

3.2 Supported data formats

SidescanTools supports two primary open data formats:

a. JSF: An open file format developed by Edgetech, widely used in the marine industry. This file format has been decoded according to the official Edgetech documentation (Edgetech, 2025). Note that the format may be subject to future changes and unexpected errors may occur if the input file doesn't meet the decoded format.
b. XTF: A cross-platform readable file format that serves as a common standard for sonar data. It consists of several packets each delivered with an own header, which makes it a highly versatile file format (Kermarrec et al., 2020; Blondel, 2009). The XTF format is particularly useful because almost any raw sonar data format can be converted to XTF.

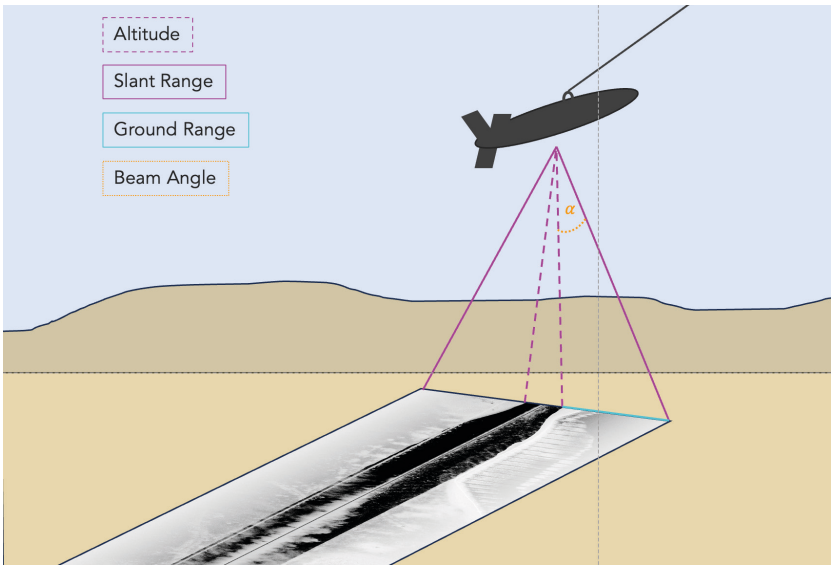


Fig. 1 Basic geometry of side scan sonar.

3.3 Key features and functionalities

The following sections describe how the previously mentioned processing steps for geometric and radiometric corrections, removal of noise and artifacts, image quality enhancement and the generation of georeferenced images are implemented in SidescanTools.

3.3.1 Bottom detection

Accurately identifying the sea floor in sonar data is crucial for subsequent processing steps and has to be done manually if no altitude/depth information is available. Usually, the bottom line is associated with the first bottom return, which is the first echo that the sonar receives from the bottom. In some cases, for example if sea grass or high obstacles (boulders, wrecks) that do not represent the true sea floor, are present, these would falsely be declared as first returns by most automatic edge detection algorithms. Here, the bottom line must be manually adjusted to the true bottom by the user. In SidescanTools, this is implemented as follows:

a. Chunk-based data presentation: The data are divided into chunks and visualised on the graphical user interface. Several common image adjustments like different colour palettes, hue, saturation, contrast and zoom levels are available to the user.
b. Threshold based detection: An algorithm with user-defined threshold is applied to convert the sidescan image into a binary mask which discriminates water column and ground pixels. On this masked image, an edge detection algorithm is deployed to find the most probable edge in the resulting binary image. This is done by finding all edges in the image and evaluating which edge is the most probable bottom line, which must preferably go through the whole image from top to bottom and have only ground pixels below itself. The threshold can

be adjusted for each data chunk individually. This can be helpful for surveys with changing altitudes where different thresholds are required to correctly differentiate between water column and ground. Usually, starboard and portside lines are merged to find a common bottom line for both sides. In most cases, this is the best strategy because the nadir angle is small and thus neglectable, hence the bottom line is assumed to represent the sonar altitude. If this assumption does not hold for some specific cases, different strategies e.g. to separate the starboard and portside edge detection results can be selected.

c. Manual mode: To adjust falsely detected bottom lines, users can adjust the bottom line by drag-clicking on the chunk at the correct position. In the background, the bottom line is an array that masks the data array and is updated by the user's input and saved for later processing steps.

3.3.2 Geometric correction: slant range correction

Commonly, slant range correction is applied at this stage, using information of the detected bottom line from the previous step to remove the water column and to relocate the measured backscatter values across track. This correction is essential for accurate representation of ground distances and object sizes in the final image. The data are thereby projected onto a flat-assumed, horizontal sea floor. The assumption of a flat sea floor is required, because sidescan sonar measurements do not provide any additional information about across track water depths. Slant range correction is essential for accurate representation of ground distances and object sizes in the final image. The slant correction works by calculating the true ground distance for each sample with index *i* across the track as the hypotenuse of the triangle that is formed by nadir depth and the horizontal distance on ground *d* (Fig. 2; Blondel, 2009).

$$d_i = \sqrt{\left(\frac{c \cdot t_i}{2}\right)^2 - h^2} \quad (1)$$

where $\frac{c \cdot t_i}{2}$ is the slant range at sample index *i* at time



Fig. 2 Original (upper) and slant corrected (lower) data chunk. The 'seam' in the corrected data is typical for processed sidescan data and is due to the small blind area directly below the sonar transducer.

t, *c* is local speed of sound in water and *h* the local height above ground.

The result is a non-uniform vector of intensities for each ping that needs to be placed into a uniformly sampled vector of maximum original resolution. This introduces across track gaps which are then filled by linear interpolation of the entire vector. Often, the nadir angle of a sonar is not known and therefore assumed to be 0°. This is not problematic in most cases but leads to a small number of samples at close range which causes single intensities being stretched over multiple indices – a phenomenon that is often observed in processed sidescan data. The sonar is "blind" in these areas at close range.

3.4 Radiometric corrections

Radiometric corrections encompass downsampling of the data, removal of noise and artifacts and the correction of intensity gains to make objects appear with constant brightness across track, independent of their distance to the sonar.

3.4.1 Downsampling of data

If the raw sidescan data have significantly higher resolution – that is, they contain more samples per ping than required by the user, the resolution can be reduced by downsampling the data. Although this process results in some loss of information, the discarded data is often redundant and can be safely omitted to enable faster processing and reduce memory usage (Crochiere & Rabiner, 1983). In SidescanTools, this is implemented using SciPy's decimate function, which downsamples each ping signal individually by an integer factor (SciPy community, 2025).

3.4.2 Removal of artifacts: Pie-Slice filter

A Pie Slice filter can be used to remove stripy noise and artifacts (Wilken et al., 2012). The following implementation of this filtering approach is completely based on their work. These artifacts are usually visible in the sonar image as horizontal parallel stripes that are potentially tilted (Fig. 3). Often, the source is not known and noise artifacts may be caused by incorrect internal beam pattern correction, roll movements of the sensor, impact of waves, interference with other systems or electronic noise. To apply the pie slice filter, the data are separated into chunks of equal dimensions and transformed to the spectral domain by a two-dimensional fast Fourier transform (2D-FFT). In the spectrum, noise stripes become visible as spots of high energy that lie on a tilted line.

To remove these artifacts, the position of the bright spots is analysed in a first step. A straight line is then fitted through the centres of these spots to find the tilted axis on which the source of these artifacts is located. This line serves as the centre line for suppressing the spectral amplitudes, on which an attenuation of up to 80 dB is applied. To prevent an introduction of new artifacts by this filter, the suppression is applied in x-direction as a fading function to prevent

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sharp edges in the spectrum. Because the spots usually become more spread in their y-positions towards the outer edges of the image, the suppression itself is widened in y-direction. This is what gives the algorithm its name, because it looks like pie slices in a spectrum (Fig. 3). The slices are then rotated to fit between the points which shall be suppressed. As a last step, the spectrum is transformed back into the time domain. In SidescanTools, the width of the filter and the maximum attenuation are chosen to be 0.05 and 80 dB. These default values perform well in all situations that the authors encountered and should therefore also work for unknown sonar devices.

3.4.3 Gain normalisation: BAC and EGN

Gain normalisation equalises the return signal such that that the image appears with consistent brightness regardless of its distance or angle from the sonar. This also compensates for signal dispersion and attenuation over longer ranges, making distant objects more visible. Although most sonars apply a time-varying gain during data acquisition to amplify signals at greater distances, this built-in correction is not always optimal. Therefore, applying gain normalisation as an additional step helps to improve the overall image quality. SidescanTools offers two algorithms for this task which can be selected by the user depending on the amount of available data. Both are black-box approaches, meaning they only work on observed values and have no information about the sonar system and its parameters. It is however important to note that the type of seafloor plays a crucial role for the relationship between incidence angle and backscatter amplitude. The below described methods for gain normalisation cannot entirely account for changes in geomorphology during a survey. It is recommended to start a new survey file every time a geomorphological boundary crossed. Empirical gain normalisation (EGN) tables can then be calculated for the different geomorphological realms.

Beam angle correction

To compensate for angle-dependant signal attenuation, the beam angle correction (BAC) algorithm estimates the beam pattern of the sonar device from the recorded data. This algorithm only takes data of the currently processed file into account and returns good results if little data are provided. If more data are available, the more sophisticated EGN (see next section) method would yield better results. When applying BAC, the incidence angle to the sonar is calculated for each sample of each ping for the current recording. All samples of the same angle are then averaged to get an estimated beam pattern. This is used to adjust the intensities of each sample across all pings. This approach is independent of the distance to the ground and therefore needs only little data to work (Chang et al., 2010):

$$s'(\omega,r) = s(\omega,r) \cdot B(\omega) \quad (2)$$

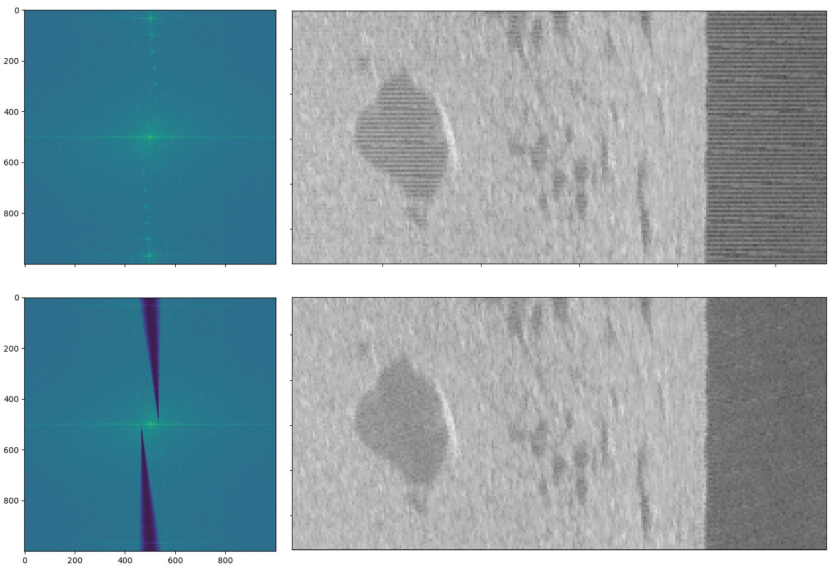


Fig. 3 Left: 2D-FFT of an 1000 × 1000 pixel image chunk before and after filtering. Right: Snippet of the data before and after filtering.

The correction table for BAC is defined with the above Eq. 2, where $B(\omega) = \frac{1}{N\omega} \sum_{i=1}^{N\omega} s(\omega)$, ω, r: beam angle/range and $N\omega$: number of samples with the same beam angle.

Empirical gain normalisation (EGN)

EGN is an empirical method to estimate the sonar beam pattern and depends, contrary to BAC, on both range and angle:

$$s'(\omega,r) = s(\omega,r) \cdot B(\omega,r) \quad (3)$$

The correction table for EGN is defined with the above Eq. 3, where $B(\omega) = \frac{1}{N\omega,r} \sum_{i=1}^{N\omega,r} s(\omega,r)$, ω beam angle, r: range and $N\omega$: number of samples with the same beam angle and range.

Note the additional range dependency of $B(\omega,r)$ and $N\omega$,r for EGN which is different to BAC.

Based on statistical analysis, an EGN table is created which can be used to normalise the intensity of the backscatter values. This correction table can be applied to all sidescan data that have been recorded with the same device (Blondel, 2009).

At first the EGN table is calculated by binning all backscatter values depending on their incident angle and ground range. At this stage, all recordings from all files imported into the current project are included. The project should therefore contain only data from a survey of one specific sonar system. The result is a matrix of binned values with the average calculated for each bin. The resulting table is a matrix of bins in which each bin contains the average of its assigned values.

Provided that sufficient data are present, the mean value of each bin now represents the transmitted energy from the sonar and has thus become independent from any reflecting objects or other ground returns. The inversion of this matrix yields the so called EGN Table and is used to normalise all backscatter intensities depending on their angle and range

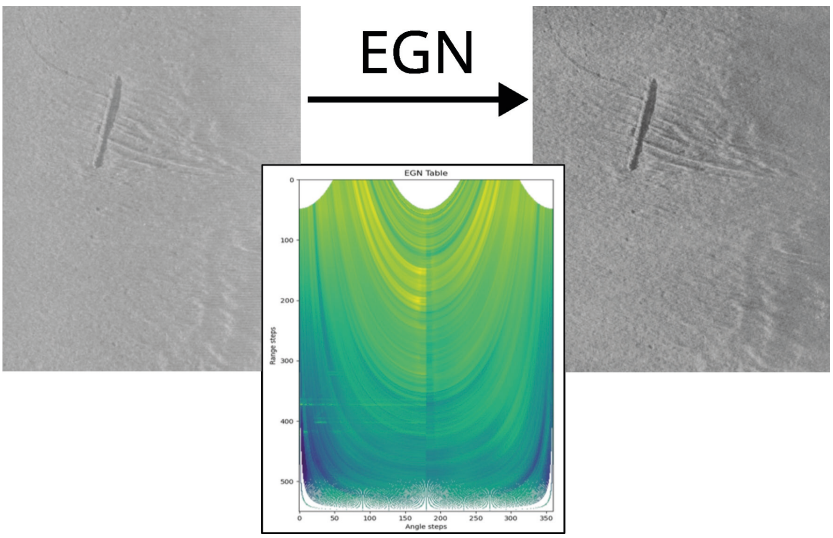


Fig. 4 Applying EGN to an image chunk.

of the current dataset (Fig. 4). It also may be used for later recordings of the same sonar system.

The user should keep in mind that this method only works for an individual instrument and only if sufficient data are available. If unsure, it is safer to use BAC.

3.5 Post-processing

To further improve the quality of the resulting images, additional filters can be applied like sharpening or Contrast Limited Adaptive Histogram Equalization (CLAHE). This is useful to make objects stand out more from the background and to improve the performance of object detection methods.

3.5.1 Sharpening filter

Image sharpening can be implemented by enhancing the contrast with a homomorphic filter. The concept is to design a filtering function that can operate on the illumination and reflectance components of the image separately (Gonzalez & Woods, 2001). The illumination component of the image is influenced by slow spatial changes and is therefore displayed by the low frequency components in both dimensions of the 2D-spectrum. In contrast, the reflectance component tends to vary more abruptly, especially at the edges of objects, and is therefore more present in the high frequency components of the 2D-spectrum. These associations are only rough approximations, but they can be used to achieve an overall sharper image.

To control the ratio of illumination and reflectance, a two-dimensional symmetric filter is designed to attenuate low frequencies and enhance high frequency components of the image.

3.5.2 Contrast limited adaptive histogram equalization

Adaptive Histogram Equalization (AHE) is a commonly used image processing technique to enhance contrast. It is called adaptive, because it calculates several histograms, each for a specific region of the image, and redistributes the lightness values of each region. This achieves an improved local contrast and sharper definitions of edges of objects in each region. Because of the nature of sidescan images, there are often regions of nearly constant intensities. Since the histogram of such regions is highly concentrated, AHE tends to overamplify the contrast in these regions. This also causes overamplification of noise and makes the resulting image look grainy. To avoid this, CLAHE is used here. This works by clipping the region histograms at a user defined threshold to reduce the problem of noise amplification. For more information about the working principle of CLAHE, please refer to (Zuiderveld, 1994).

4 Georeferenced image export

Georeferencing is the process of mapping image coordinates to global coordinates. The following section describes how these steps are implemented in SidescanTools.

4.1 Navigation pre-processing

To create a coherent georeferenced image, the raw navigation data are pre-processed in several steps:

a. Remove duplicates: If duplicate coordinates are present e.g. due to poor GNSS quality, these are removed. The remaining unique coordinates are stored in a separate array, referred to as 'unique arrays' (one per channel).
b. Interpolate and fit to original length: As the unique arrays are usually shorter than their originals (because duplicates have been removed), they are interpolated using the cubic b-spline method from scipy interpolate package (Virtanen et al., 2020). To re-gain full array length and maintain the true number of pings, the interpolated coordinates are evaluated on the ping sequence of original length. The resulting array is referred to as 'uniformed ping array'.
c. Smooth track: The interpolated coordinates are smoothed using a Savitzky-Golay filter as implemented in scipy (Savitzky, 1964). This filter preserves trends and reduces sharp peaks by fitting low-order polynomials to the data with a moving window. A window size of 100 pings and a polynomial order of two has proven to be a good choice between preserving local tendencies and at the same time avoiding large jumps in the data.
d. Course over Ground (CoG): To derive correct outer swath coordinates later on, course over ground or bearing angle is needed. This is calculated using the arctan of the distances between the current i^{th} and the following $(i+1)^{th}$ ping position of the smoothed and interpolated track:

$$\theta(i)=\tan^{-1}(dx_i,dy_i) \quad (4)$$

where θ is the course angle, (dx_i,dy_i) represent the distances between the i^{th} and the $(i+1)^{th}$ coordinate
e. Offsets: If not already implemented via the acquisition software, SidescanTools offers the user to add offsets between the GNSS antenna and the sonar transducer as well as a cable out length, if

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the sonar has been towed. The vessel coordinate system is shown in (Fig. 5). *X* is positive in forward direction of the ship from the GNSS antenna position, *Y* is positive to the right side of the ship from the GNSS antenna position. Negative *X/Y* values indicate that the sonar is located behind/left of the GNSS antenna. If the sonar is towed and the layback has not been implemented prior to the survey, the user can enter a cable length, which is converted to layback assuming a rope angle of 45° at the towpoint. This method cannot account for layback changes due to currents or drift. It is assumed to be static, which in reality is true only if there is no current.

Note that in early development raw heading values were used to calculate outer swath coordinates. This led to inaccuracies due to drift and water current which is why it has been replaced by the calculated course over ground.

4.2 Determination of outer edge coordinates

Sonar data are provided as a time-series of consecutive pings and only the centre (nadir) coordinates are known from the raw data. Inner-swath and outer edge coordinates can be determined using ground range and course angle information:

a. Outer edge coordinates: Longitudes and latitudes must first be converted into a metric coordinate system (here Universal Transfer Mercator, UTM). The outer swath coordinates can then be calculated like so:

Backbord

$$N^{out} = N_{nad} - g \cdot \cos\theta \quad (5)$$
$$E^{out} = E_{nad} + g \cdot \sin\theta$$

Starbord

$$N^{out} = N_{nad} - g \cdot \cos\theta \quad (6)$$
$$E^{out} = E_{nad} + g \cdot \sin\theta$$

where $N_{out/nad}$ / $E_{out/nad}$ represent the outer/nadir Northing/Easting coordinates, respectively, g is the ground range, θ is the course angle.

b. For later use, the computed UTM coordinates are converted back to longitudes and latitudes.

c. To obtain coordinates for each individual sample, an evenly spaced raster of coordinates is now formed between the nadir and outer edge. The resolution of the raster is determined by dividing the ground range by the number of samples, which at the same time represents the finest possible pixel resolution of the data (Fig. 6).

4.3 Mapping data to raster

4.3.1 Creating XY array

The arrays of interpolated, regularly spaced sample coordinates are written to a table which can optionally be exported to disk to investigate navigation. This table will be used in the next step to map the backscatter values on.

4.3.2 Generate output raster

The output raster generation is mainly accomplished

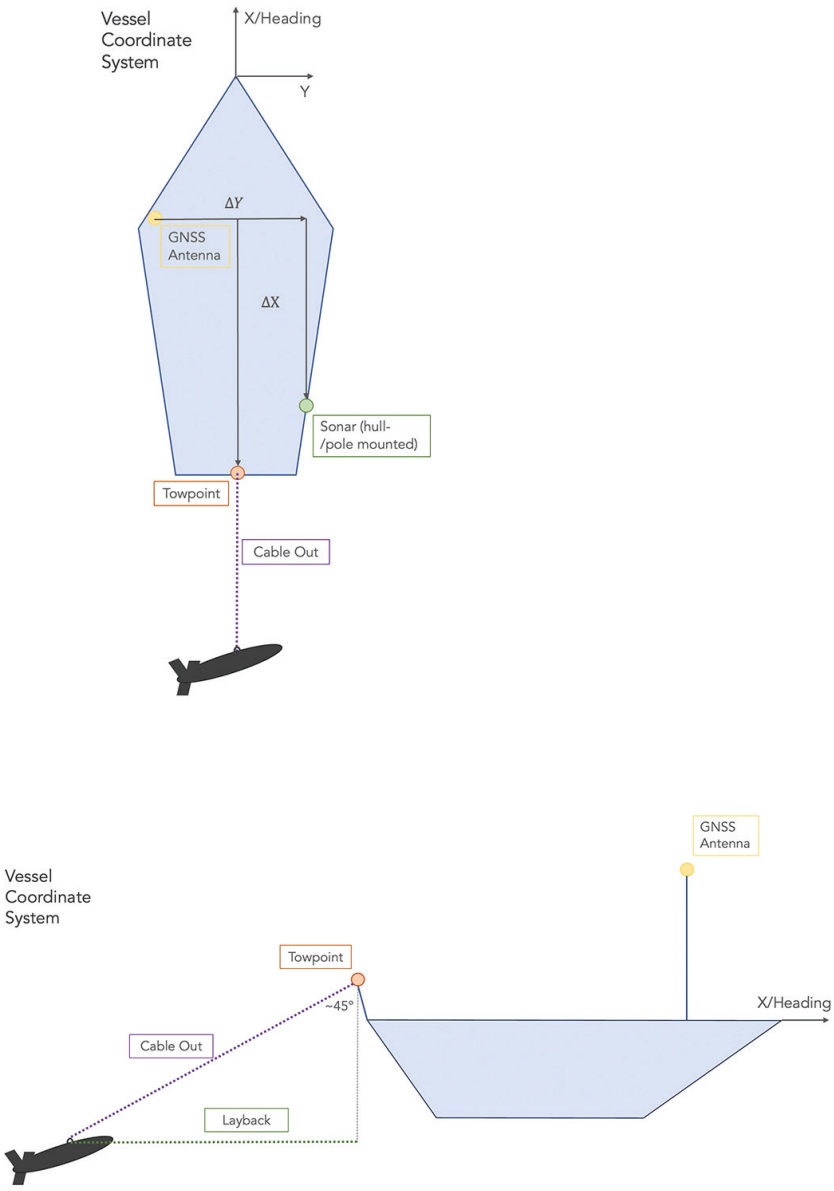


Fig. 5 Vessel coordinate system from top (upper) and side (lower) view.

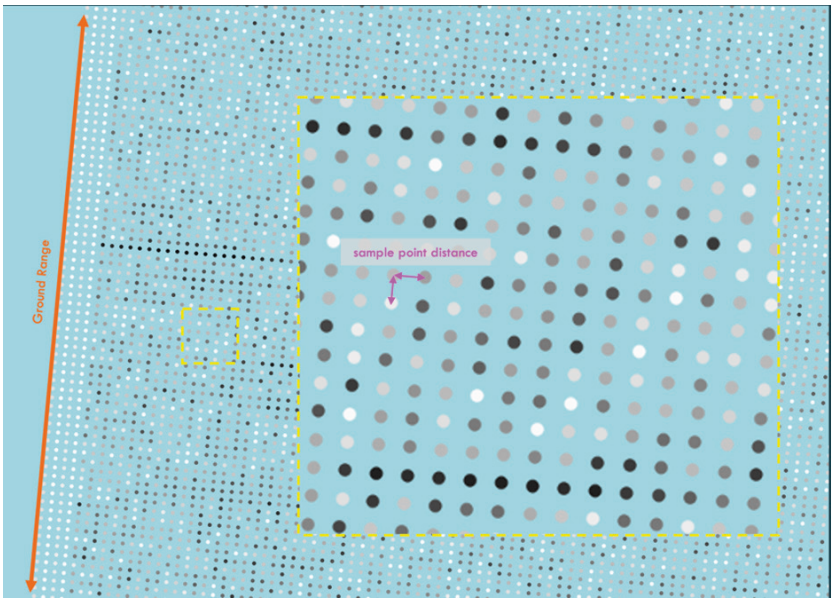


Fig. 6 Creating a regularly spaced array of coordinates for each sample point.

with Generic Mapping Tools (GMT) (Wessel et al., 2019). Firstly, the previously created coordinate raster is concatenated with the backscatter data to obtain an *xyBs* (longitude, latitude, backscatter) data array. This serves as input to a GMT nearneighbor algorithm which maps the backscatter values on the coordinate raster. Optionally, to reduce noise and data size, a GMT block-median can be applied prior to the nearneighbor gridding. The following parameters are necessary:

a. Region: Describes the bounding box of the data to be processed and is automatically derived with the *gmtinfo* command. The coordinate precision, which defines the accuracy of the size of the region bounding box, is based on the number of decimal places of the coordinates. This is to select an optimal bounding box size, to reduce computing time.
b. Resolution: The resolution is typically user-defined and specifies the cell size of each pixel in the output grid. It can be adjusted in the UI.
c. Search radius: The nearneighbour algorithm additionally needs a search radius parameter, which specifies the number of neighbours around a grid cell that the algorithm includes to calculate the cell's interpolated value. This is also user defined, but if unsure, double the resolution value usually yields good results.
d. Clip backscatter values to range: As the output image data can only have values between 0-255, the output raster is clipped to this range using *xarray* package (Hoyer, 2017). Minimum/maximum values will be replaced by '0'/'255', respectively. This ensures to avoid empty cells with unreasonably low/high numbers.
e. Assign CRS: So far, there is no information about a coordinate system and/or geodetic projection yet. This is assigned using *rioxarray* package and set to EPSG:4326/WGS 84 with *rioxarray.set_crs.* Optionally, if the UTM export option is selected by the user, the dataset is reprojected to the respective UTM Zone with *rioxarray.reproject.*
f. Export: The final raster is exported as a compressed Geotiff with *rioxarray.to_raster.*

5 Discussion and outlook

SidescanTools is designed for an easy workflow to process sidescan data and export geo-referenced images. It is less extensive in functionality compared to other popular commercial software packages, which is mainly due to restricted data formats.

It is further known that some loss of metadata happens when converting proprietary raw data formats to the cross-platform XTF format. Due to these limitations, we can only work with the available metadata which might result in inaccuracies. Furthermore, SidescanTools was originally developed to process data from a pole-mounted Starfish device used with poor quality GPS and without attitude information. Although we tried to take common error sources into account, the (navigation) pre-processing has been tailored to the need of reducing errors of this specific setup. Data from other devices may contain other error sources that potentially have not been taken care of yet.

SidescanTools is also available as a CLI version for head-less use e.g. on AUVs during dives. This enables the data to be processed online without requiring the AUV to be retrieved and may be useful for diving operations where the AUV must be able to alter its course spontaneously and based on 'what it sees' to target specific objects. This procedure has been successfully run in a first field test.

SidescanTools is still in active development, but has reached a feature range that makes it well usable for sidescan data processing. As it is an open-source alternative it has potential to grow with increasing user numbers. We rely on a community for feedback about lacks, additional or missing features and general suggestions for improvement. Issue reporting or feature requests can be submitted directly in the git repository (https://github.com/sonoware/sidescantools/issues).

References

Anaconda (2025). *Anaconda*. Anaconda Inc., Austin, USA. https://anaconda.org/ (last accessed 10 November 2025).

Blondel, P. (2009). *The Handbook of Sidescan Sonar*. Chichester: Praxis Publishing Ltd.

Bruns, I., Holler, P., Capperucci, R. M., Papenmeier, S. and Bartholomä, A. (2020). Identifying Trawl Marks in North Sea Sediments. *Geosciences, 10*(11), 422. https://doi.org/10.3390/geosciences10110422

BSH (2016). *Guideline for Seafloor Mapping in German Marine Waters Using High-Resolution Sonars* (1st ed.). Federal Maritime and Hydrographic Agency, Hamburg/Rostock, Germany. https://www.bsh.de/download/Guideline-for-Seafloor-Mapping.pdf (last accessed 25 March 2026).

Chang, Y.-C., Hsu, S.-K. and Tsai, C.-H. (2010). Sidescan sonar image processing: Correcting brightness variation and patching gaps. *Journal of Marine Science and Technology, 18*. https://doi.org/10.51400/2709-6998.1935

Crochiere, R. and Rabiner, L. (1983). *Multirate Digital Signal Processing* (2nd ed.). Englewood Cliffs: NJ: Prentice-Hall.

Díaz-Mendoza, G. A., Krämer, K., von Rönn, G. A., Schwarzer, K., Heinrich, C., Reimers, H.-C. and Winter, C. (2023). Circular structures on the seabed: differentiating between natural and anthropogenic origins—Examples from the Southwestern Baltic Sea. *Front. Earth Sci., 11*:1170787. https://doi.org/10.3389/feart.2023.1170787

Díaz-Mendoza, G. A., Krämer, K., von Rönn, G., Heinrich, C., Schwarzer, K., Reimers, H. C. and Winter, C. (2024). Hotspots of human impact on the seafloor in the Southwestern Baltic Sea. *Continental Shelf Research*.

Edgetech (2025). *JSF File and Message descriptions* (Rev P, 11.09.2025). https://www.edgetech.com/wp-content/uploads/2023/04/0023492_Rev_P.pdf (last accessed 7 November 2025).

Gonzalez, R. C. and Woods, R. E. (2001). *Digital Image Processing* (2nd ed.). Upper Saddle River, New Jersey : Prentice-Hall, Inc.

https://doi.org/10.58440/ihr-32-1-n01

Grządziel, A. (2023). The Impact of Side-Scan Sonar Resolution and Acoustic Shadow Phenomenon on the Quality of Sonar Imagery and Data Interpretation Capabilities. *Remote Sensing, 15*(23), 5599. https://doi.org/10.3390/rs15235599

Hoyer, S. H. (2017). xarray: N-D labeled Arrays and Datasets in Python. *Journal of Open Research Software, 5*(1), 10.

Kermarrec, E., Saman, L. and Tauvry, S. (2020). *eXtended Triton Format (XTF): File format* specification (Rev. 42). https://www.ecagroup.com/en/xtf-file-format (last accessed 25 March 2026).

Lurton, X. (2010). *An Introduction to Underwater Acoustics* (2nd ed.). Heidelberg: Springer Berlin.

Marx, D., Feldens, A., Papenmeier, S., Feldens, P., Darr, A., Zettler, M. L., Heinicke, K. (2023). Habitats and Biotopes in the German Baltic Sea. *Biology, 13*(1), 6. https://doi.org/10.3390/biology13010006

Savitzky, A. M. (1964). Smoothing and Differentiation of Data by Simplified Least Squares Procedures. *Analytical Chemistry, 36*(8), 1627–1639.

SciPy community (2025). *scipy.signal.decimate*. https://docs.scipy.org/doc/scipy/reference/generated/scipy.signal.decimate.html (last accessed 7 November 2025).

Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S. J., Brett, M., Wilson, J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., et al. (2020). SciPy 1.0: fundamental algorithms for scientific computing in Python. *Nature Methods, 17,* Article 3. https://doi.org/10.1038/s41592-019-0686-2

Wessel, P., Luis, J. F., Uieda, L., Scharroo, R., Wobbe, F., Smith, W. H. F. and Tian, D. (2019). The Generic Mapping Tools version 6. *Geochemistry, Geophysics, Geosystems, 20*, 5556–5564. https://doi.org/10.1029/2019GC008515

Wilken, D., Feldens, P. and Wunderlich, T. (2012). Application of 2D Fourier filtering for elimination of stripe noise in side-scan sonar mosaics. *Geo-Marine Letters, 32*, 337–347. https://doi.org/https://doi.org/10.1007/s00367-012-0293-z

Zuiderveld, K. (1994). *Contrast limited adaptive histogram equalization*. In P. S. Heckbert (Ed.), *Graphics gems IV* (pp. 474–485). San Diego: Academic Press Professional, Inc.

GENERAL INFORMATION

A new era for Malaysia's hydrography: Rear Admiral Dr Najhan bin Md Said takes the helm

Contributing Member State
National Hydrographic Centre · Royal Malaysian Navy · Malaysia



Malaysia has entered a new era in hydrography with the appointment of Rear Admiral Dr Najhan bin Md Said as the nation's new Chief Hydrographer. His leadership marks a decisive step in advancing Malaysia's capabilities in seabed mapping, marine geospatial data, and maritime domain awareness.

Rear Admiral Dr Najhan officially assumed office on 27 October 2025, succeeding Rear Admiral Dato' Hanafiah bin Hassan. The handover ceremony, held at the National Hydrographic Centre (NHC) in Port Klang, was officiated by Admiral Tan Sri Dr Zulhelmy Ithnain, Chief of Navy, who expressed confidence that the new Chief Hydrographer would continue steering the Centre towards innovation and operational excellence.

Born in Tanjung Kling, Melaka, on 27 July 1973, Rear Admiral Dr Najhan began his naval career in 1991 and was commissioned two years later as an officer in the Executive Branch. His early posting to the Royal Australian Navy Hydrographic School at HMAS Penguin in 1996 sparked a lifelong commitment to hydrography, a discipline in which he has since earned national and international recognition.

Throughout more than three decades of service, Rear Admiral Dr Najhan has held a range of key appointments including Deputy Director General of Hydrography, Senior Director of the Planning and Development Division at Navy Headquarters, Deputy Commander of the Eastern Fleet Command Headquarters and Commanding Officer of KD PERANTAU. Beyond the Navy, he has contributed his expertise to the National Security Council and the National Task Force Headquarters, playing an instrumental role in policy formulation and operational planning related to maritime security.

Rear Admiral Dr Najhan is widely recognised as a Subject Matter Expert in the technical aspects of maritime boundaries determination. He is actively engaged in a series of negotiations concerning maritime boundaries. Additionally, he led Malaysia's Special Team responsible for the submission to the United Nations regarding the continental shelf beyond 200

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nautical miles, representing a significant milestone in the nation's maritime sovereignty.

Internationally, he has been an active participant within the International Hydrographic Organization (IHO), serving as a member of the Sub-Committee on Undersea Feature Names (SCUFN) since 2018. In 2024, he was elected Vice-Chair of SCUFN for the 2024 to 2028 term, further underscoring his standing and credibility within the global hydrographic community.

Academically, Rear Admiral Dr Najhan holds a Doctor of Philosophy and a Master of Science in Hydrography from Universiti Teknologi Malaysia, as well as a Master of Maritime Studies from the University of Wollongong, Australia. His academic research in coastal erosion, marine habitat mapping, and seafloor ecosystems continues to contribute to Malaysia's expanding body of maritime knowledge.

Assuming leadership of the NHC at a time when hydrography intersects with digital innovation and climate resilience, Rear Admiral Dr Najhan envisions the Centre as a regional leader in ocean data management, marine geospatial infrastructure, and navigational safety. His focus on modernisation, data integration, and international collaboration is expected to further strengthen Malaysia's role within the East Asia Hydrographic Commission (EAHC), the North Indian Ocean Hydrographic Commission (NIOHC), and the IHO.

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GENERAL INFORMATION

The Third Portuguese-Spanish Hydrography Conference (3JLEH)

Authors

Luis Javier Gomez Saavedra[1] and António José Henriques de Albuquerque e Silva[1]

1 Introduction

From 9 to 11 October 2024, the city of Cádiz hosted the Third Portuguese-Spanish Hydrography Conference (3JLEH; Fig. 1). For the first time since its creation, the conference was held on Spanish soil, marking a significant milestone in the history of Iberian cooperation in hydrography and marine sciences.

The event was jointly organised by the Instituto Hidrográfico de la Marina (IHM) of the Spanish Navy and the Portuguese Hydrographic Institute (PT-IH), with the collaboration of the University of Cádiz (UCA) and the International Campus of Excellence of the Sea (CEI·Mar). Together, these institutions provided a strong scientific, operational, and academic framework for the conference.

The 3JLEH brought together experts, researchers, naval professionals, and students to explore contemporary challenges and opportunities in hydrography and related maritime disciplines. The choice of Cádiz – one of Europe's oldest cities and a historic maritime hub – was highly symbolic, linking centuries of nautical tradition with modern scientific and technological debate.

2 Hydrography in the 21st century: more than nautical charts

Traditionally associated with safe navigation through accurate seabed mapping and nautical chart production, hydrography has evolved significantly in recent decades. The Cádiz conference clearly illustrated how the discipline now extends far beyond its classical role, intersecting with coastal management, marine geology, environmental monitoring, underwater archaeology, and the development of blue-economy initiatives.

Reflecting this evolution, the scientific programme was structured around twelve thematic



Fig. 1 Conference opening ceremony.

✉ Luis Javier Gomez Saavedra · lgomsaa@fn.mde.es

[1] Instituto Hidrografico de la Marina, Spain

areas: hydrography, cartography, navigation safety, maritime services, oceanography, marine geology, marine environmental chemistry, marine pollution, marine technologies, marine geospatial data infrastructures, underwater archaeology, and blue economy. This multidisciplinary approach positioned the 3JLEH as a platform not only for technical exchange, but also for broader reflection on the future of marine science, sustainability, and coastal resilience.

3 Organization, context and the significance of Cádiz

Four key institutions convened the conference (Fig. 2). The IHM and PT-IH, as the national hydrographic authorities of Spain and Portugal, respectively, represent long-standing partners with a shared responsibility for navigation safety and marine knowledge. Their collaboration with UCA and CEI·Mar – both internationally recognized academic actors – ensured a balanced integration of scientific research, operational hydrography, and education.

Hosting the conference in Cádiz carried particular significance. Home to the Spanish Hydrographic Institute and shaped by centuries of naval activity, trade, and scientific exploration, the city embodies a deep and enduring connection to the sea. During the opening session, institutional representatives highlighted Cádiz's maritime identity and its suitability as a meeting point for the Iberian hydrographic community. The event also marked a symbolic turning point, as it was the first Portuguese-Spanish edition held outside Portugal.



Fig. 2 Main organizer's authorities.

4 Attendance, expectations and community engagement

Interest in the conference was strong from an early stage. By July 2024, approximately 150 participants had registered, with attendance rising to nearly 200 over the course of the event. Participants included hydrographers, oceanographers, marine geologists, environmental scientists, technology developers, military personnel, and students from both countries.

This high level of participation reflected growing awareness of hydrography's expanding role. Many of today's most pressing marine challenges – coastal erosion, habitat degradation, pollution, and climate-driven sea-level rise – cannot be addressed without reliable bathymetric, sedimentological, and oceanographic data. The Cádiz conference underscored that hydrography is no longer a niche technical field, but a foundational component of marine science, public policy, and economic development.

5 Programme highlights: bridging science and society

Although the full proceedings have not yet been published, the programme featured a wide range of scientific presentations, technical workshops, and thematic sessions. Topics included advances in multibeam sonar systems, LiDAR coastal mapping, marine geospatial data infrastructures, and applications of hydrography in underwater archaeology.

A distinctive feature of the Cádiz edition was its strong public outreach component. Alongside the scientific sessions, the organisers arranged activities aimed at bringing marine science closer to society. Visitors were able to tour two research vessels: the Malaspina-class hydrographic vessel of the Spanish Navy and the UCADIZ research vessel of the University of Cádiz. These visits showcased modern hydrographic instrumentation, from echo-sounders to autonomous

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systems, and offered a tangible introduction to marine data acquisition.

Additional activities included static demonstrations of hydrographic equipment, exhibitions of historical nautical cartography, and educational sessions for students and families. This outreach programme reinforced a central message of the conference: understanding and protecting the sea is a shared societal responsibility.

6 Institutional significance and Iberian cooperation

The opening session featured high-level Spanish and Portuguese representatives from naval and scientific institutions, highlighting the strategic importance of the event. Their interventions stressed that hydrography is inherently international: coastal processes, pollution, marine ecosystems, and navigation safety transcend national borders.

As neighbouring maritime nations with shared Atlantic and Mediterranean responsibilities, Spain and Portugal have a long tradition of cooperation. The Cádiz conference further strengthened this partnership, particularly through the involvement of academic institutions such as UCA and CEI·Mar, opening new opportunities for joint research projects, staff exchanges, and training programmes. A recurring theme was the need to attract and train new generations of hydrographers, at a time when technological complexity and societal demand are rapidly increasing.

7 Opportunities and challenges ahead

The conference highlighted the growing need to integrate hydrography more closely with other marine sciences and with policy-making processes. In a context of accelerating climate change and increasing coastal pressure, hydrographic data is essential for coastal defence planning, marine spatial planning, port development, marine protected areas, and blue-economy strategies.

By fostering dialogue and cooperation among Iberian institutions, the 3JLEH laid the groundwork for coordinated surveys, harmonised cartographic standards, and shared geospatial data infrastructures, contributing to a more coherent and effective approach to marine governance.

8 Conclusion: a milestone for Iberian marine science

The Third Portuguese-Spanish Hydrography Conference stands as a milestone for the scientific and maritime communities of Spain and Portugal. It reflects a modern vision of hydrography—technologically advanced, multidisciplinary, and socially relevant. By choosing Cádiz as its host city, the conference bridged historical maritime heritage with contemporary scientific exploration. By engaging both specialists and the public, it narrowed the gap between expert knowledge and societal awareness.

The legacy of the 3JLEH is clear: hydrography is no longer limited to nautical charts. It is a cornerstone of marine sustainability, coastal resilience, and the scientific, economic, and cultural relationship that Iberian societies maintain with the sea.

9 Historical evolutions of the conference

Created as the Hydrographic Engineering Conference in 2010 by the Portuguese Hydrographic Institute, the event emerged as a national forum dedicated to scientific and technical reflection on hydrography and marine sciences. Its first edition, held in the context of World Hydrography Day and the 50th anniversary of PT-IH, established a biennial platform for knowledge exchange and professional interaction (Fig. 3).

Between 2012 and 2018, the conference expanded steadily in scope, participation, and international visibility. Initially national in focus, it progressively incorporated a broader range of disciplines –oceanography, marine geology, chemistry, and geospatial technologies – consolidating its role within the Portuguese scientific community.

A major turning point occurred in 2020 with the creation of the Portuguese–Spanish Hydrography Conference, reflecting formal cooperation between the Portuguese and Spanish Hydrographic Institutes. Despite the constraints of the COVID-19 pandemic, the hybrid format adopted that year demonstrated the resilience of the event. Subsequent editions in 2022 and 2024 strengthened Iberian cooperation and internationalization, with Cádiz hosting the first edition on Spanish territory.

10 Way ahead – 4th Portuguese-Spanish Hydrography Conference (2026)

The 4th Portuguese–Spanish Hydrography Conference will take place from 24 to 26 June 2026 in Lisbon, at the facilities of the Portuguese Hydrographic Institute (IH-PT), within the framework

of the World Hydrography Day celebrations.

Jointly promoted by IH-PT and the Instituto Hidrográfico de la Marina, the conference will continue to serve as an open and interdisciplinary forum for scientific and technical exchange. The 2026 edition particularly encourages contributions that explore emerging and strategic interfaces between hydrography and other marine disciplines, with special emphasis on Marine Biology and Critical Submarine Infrastructures. These themes reflect the increasing relevance of ecosystem-based approaches, environmental monitoring, and the protection, resilience, and management of underwater assets essential to modern societies.

Researchers and practitioners from academia, public institutions, industry, and operational services are warmly invited to contribute to this forum dedicated to advancing marine knowledge and fostering sustainable and innovative solutions for the oceans.



Fig. 3 Open session of the 1st conference (2010).



Fig. 4 4th Portuguese-Spanish Hydrography Conference, 24–26 June 2026, Lisbon, Portugal.

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IHO
International
Hydrographic
Organization