

INVITED ARTICLE

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

AuthorMerte P. J. Peeters¹

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.

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 near-shore 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

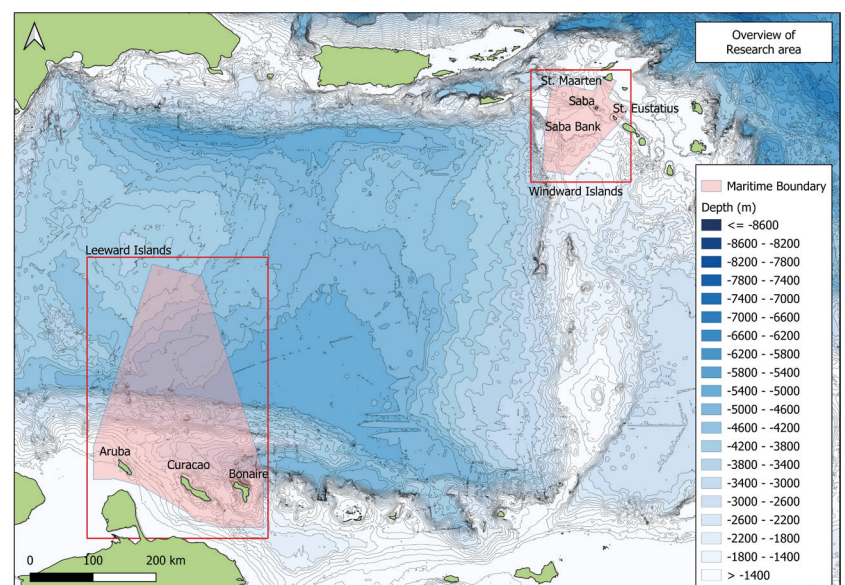


Fig. 1 Overview of the research sites in the Dutch Caribbean.

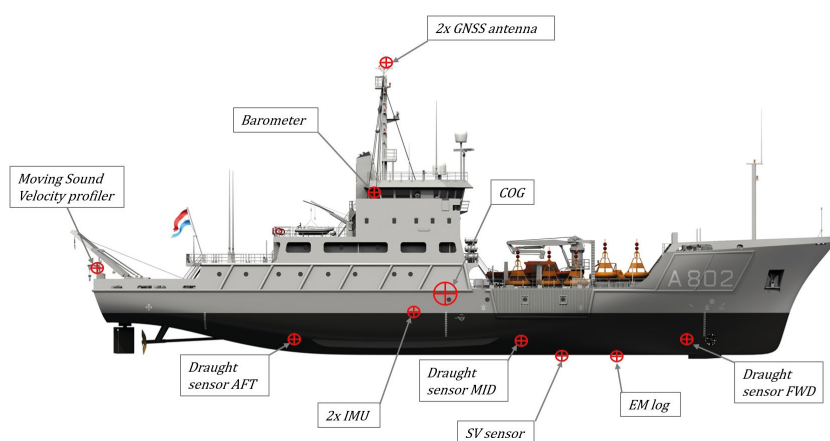


Fig. 2 Sensor geometry HNLMS Snellius.

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

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

where:

$SEP_{MSL-ITRF}$: 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

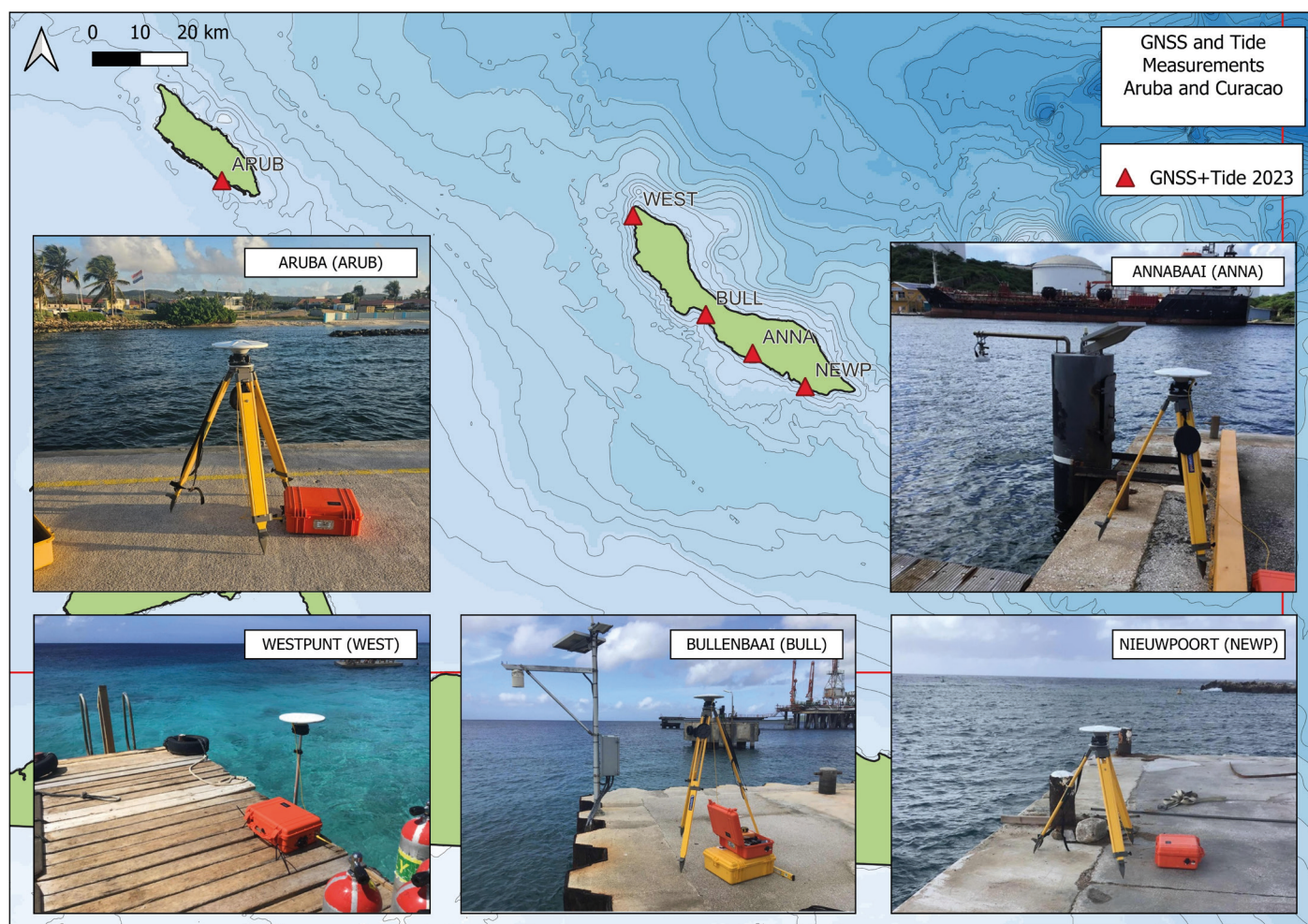


Fig. 3 Tide/GNSS measurements on Site 1.

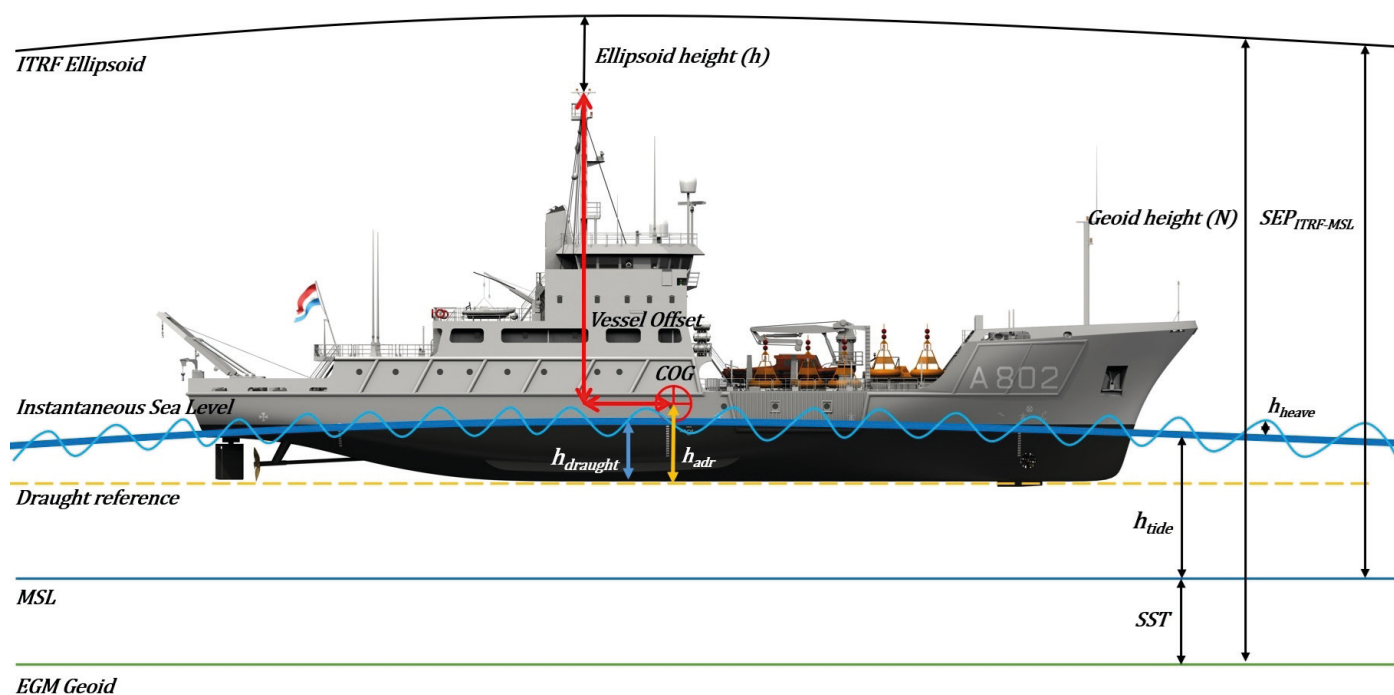


Fig. 4 Relation between vessel COG height and MSL.

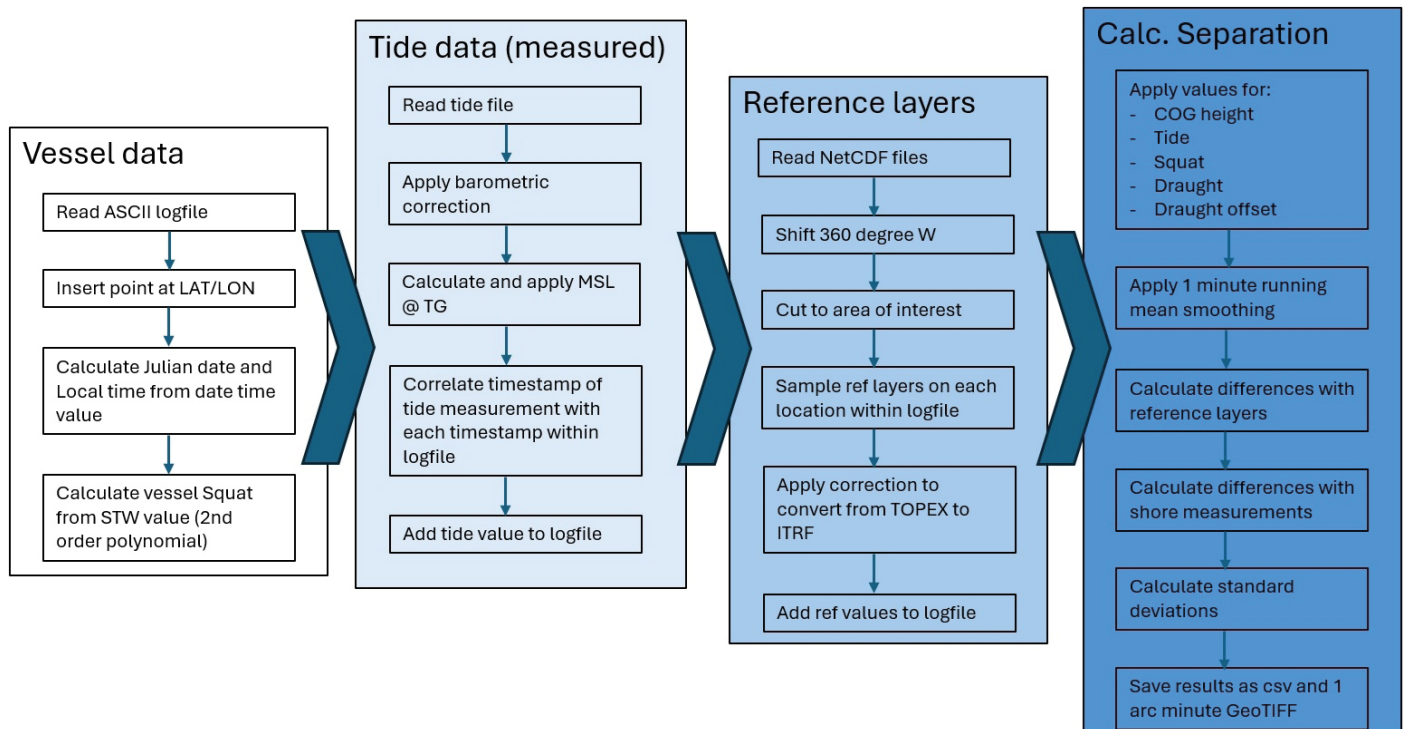


Fig. 5 Data processing workflow for Site 1.

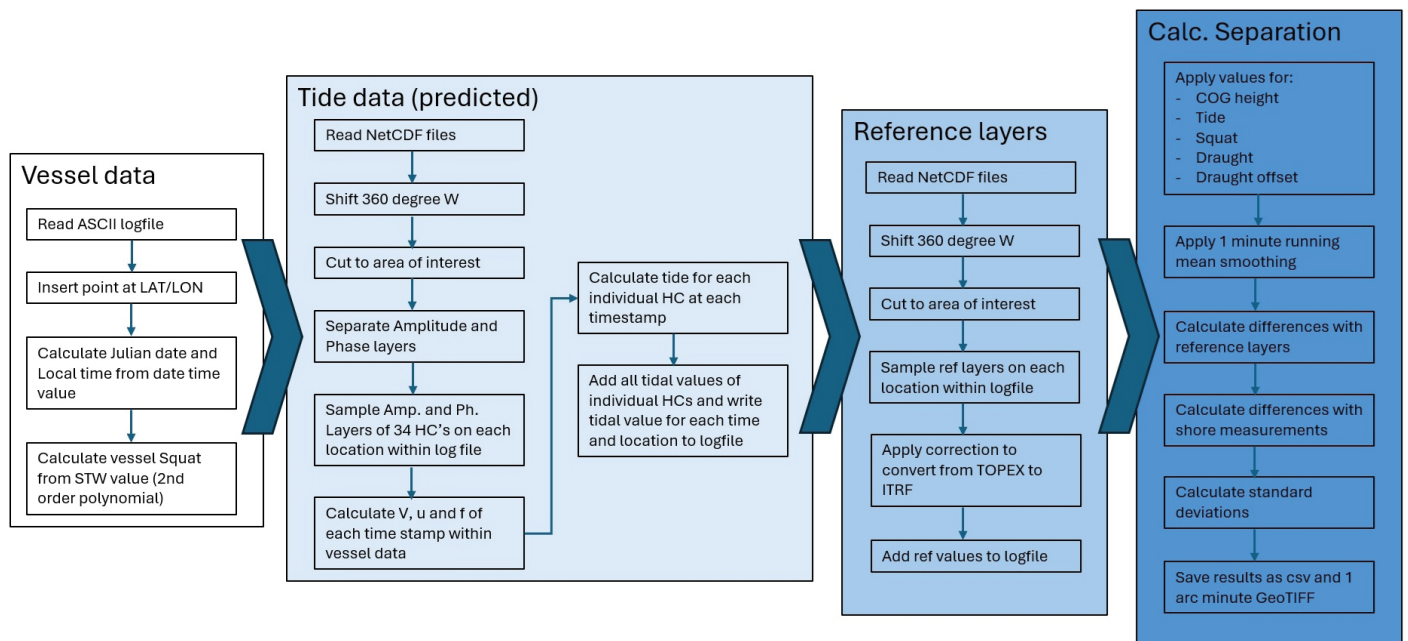


Fig. 6 Data processing workflow for Site 2.

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.

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 (Liibus 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

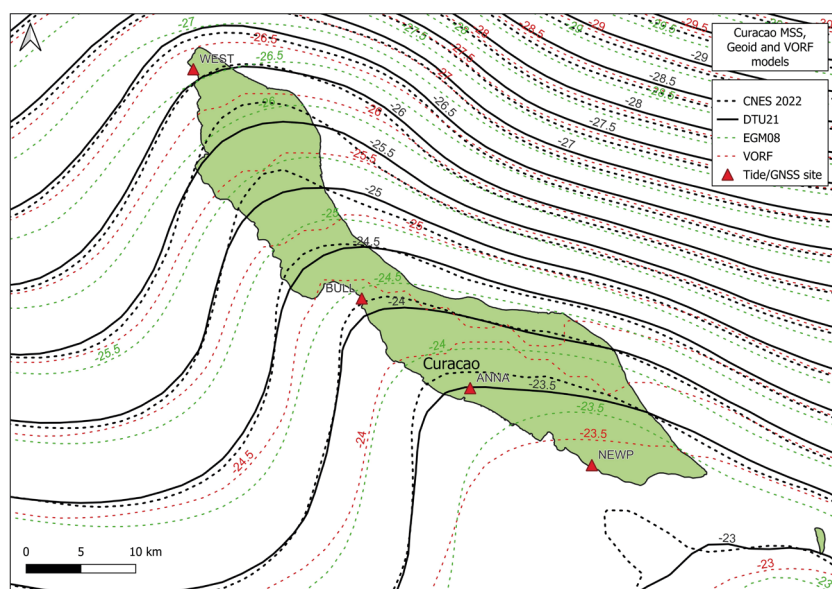


Fig. 7 Reference models Curaçao (Site 1).

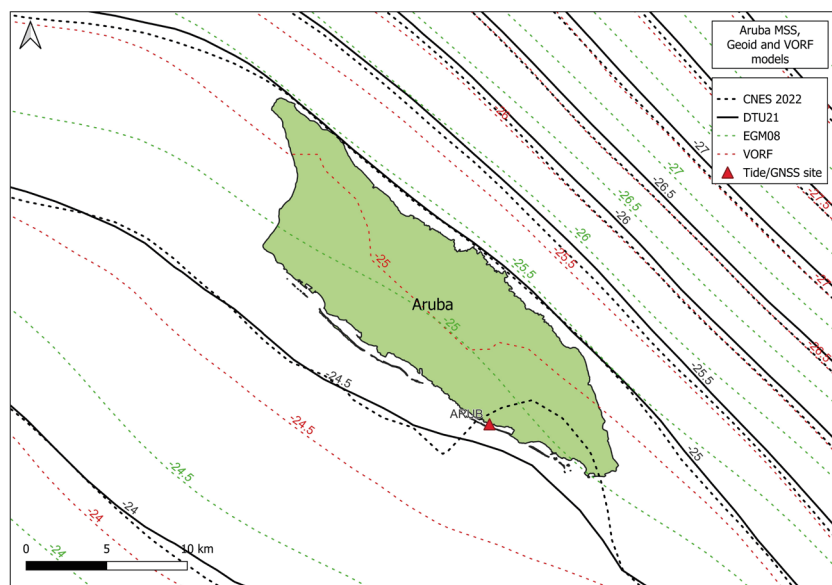
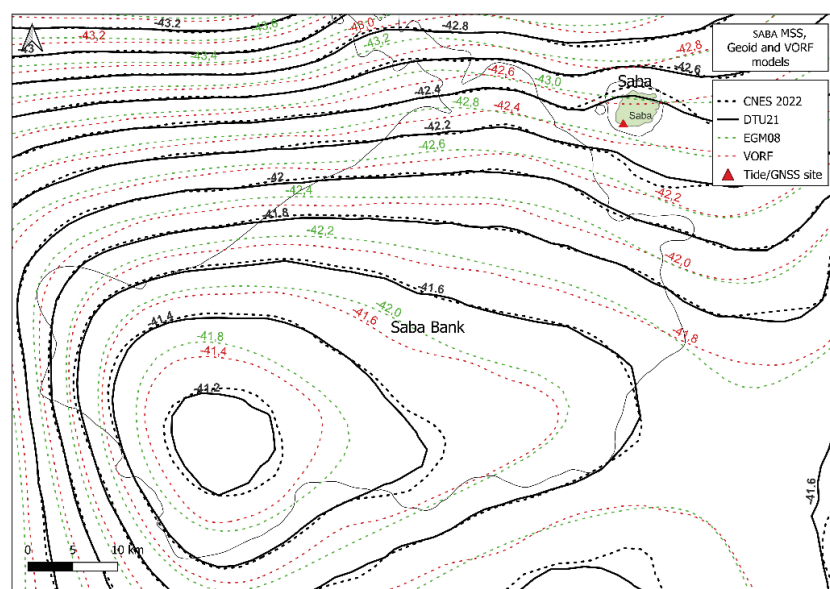


Fig. 8 Reference models Aruba (Site 1).

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

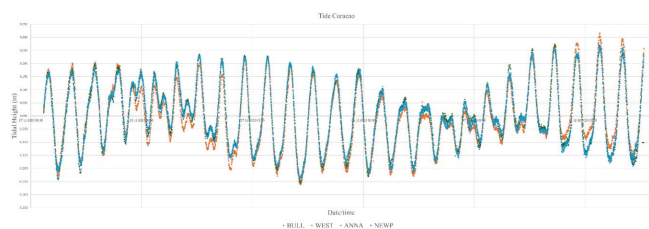


Fig. 10 Comparison of tidal measurements on Curaçao (Site 1)

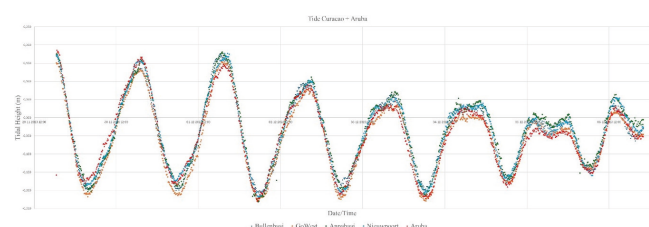


Fig. 11 Comparison of tidal measurements on Aruba and Curaçao (Site 1).

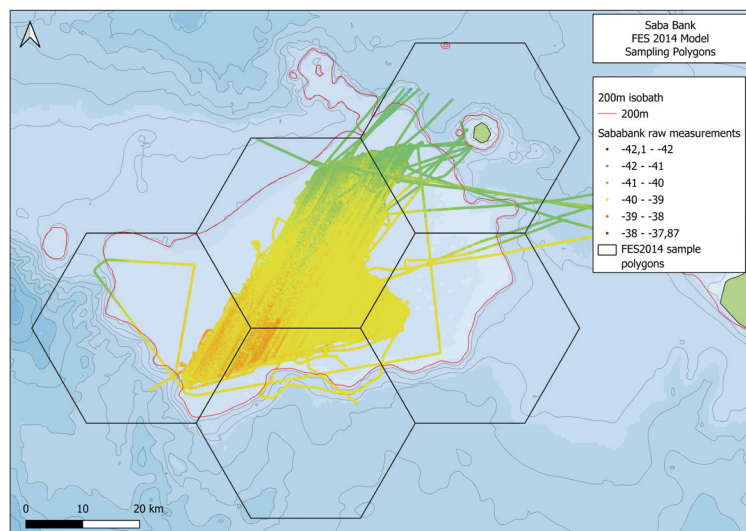


Fig. 12 FES2014 Sampling polygons Site 2.

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	-	-	-	-	-
Δ Curacao (vessel) (m)	-	0.139	0.026	0.061	-	0.120
Δ Sababank (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
Δ Time (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	Δ DTU21	Δ CNES22	Δ VORF	Δ EGM08
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

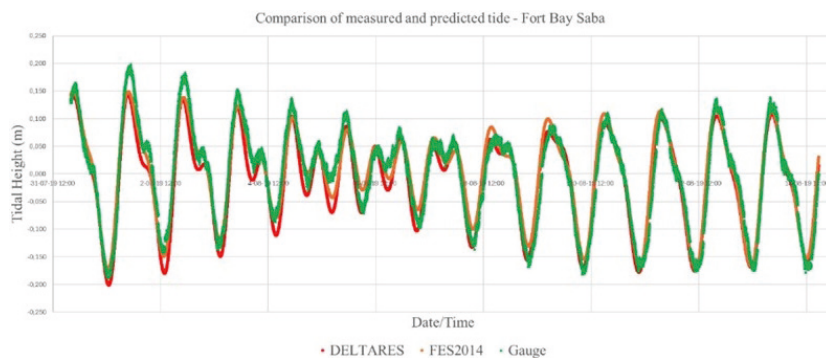


Fig. 13 Comparison of measured and predicted tide at SABA (Site 2).

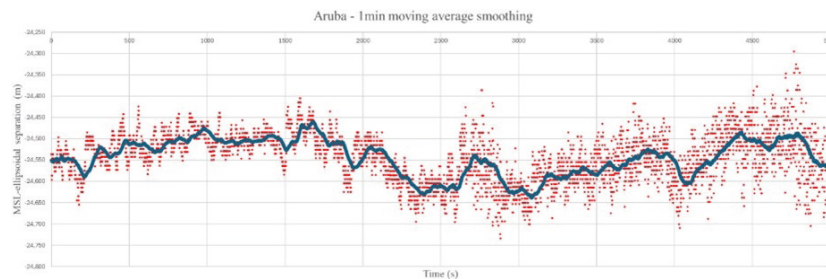


Fig. 14 Noise reduction by 1-minute moving averaging.

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.

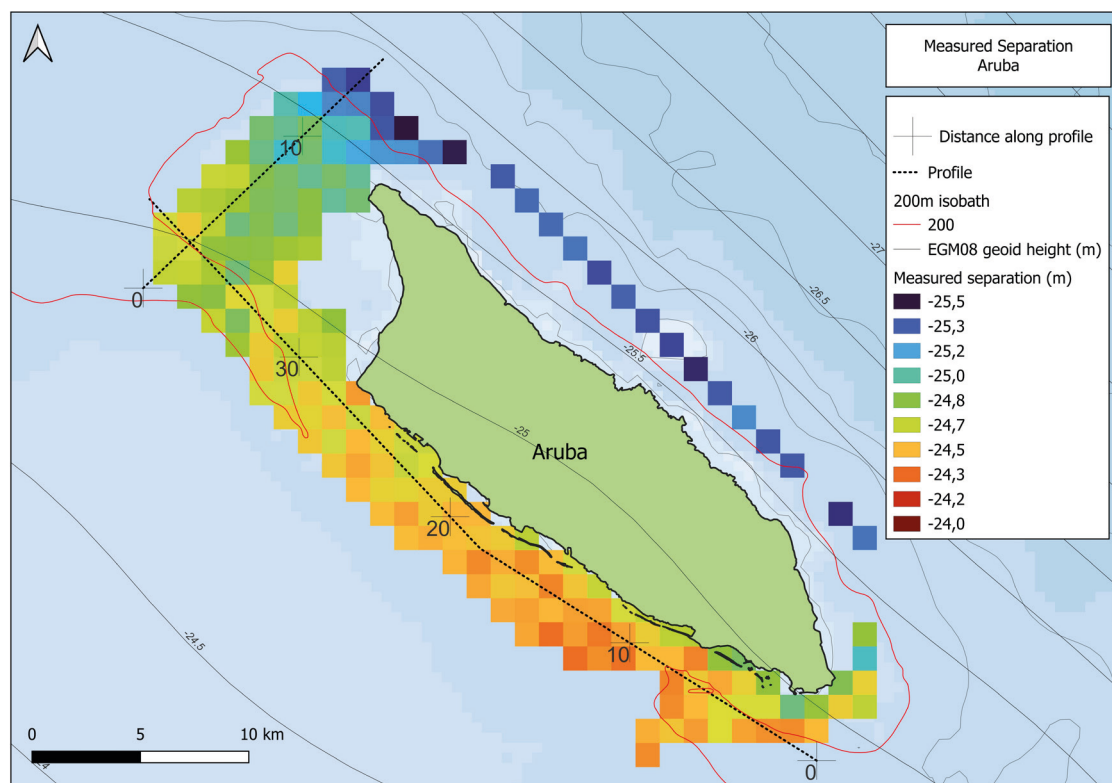


Fig. 15 Measured separation values near Aruba (Site 1).

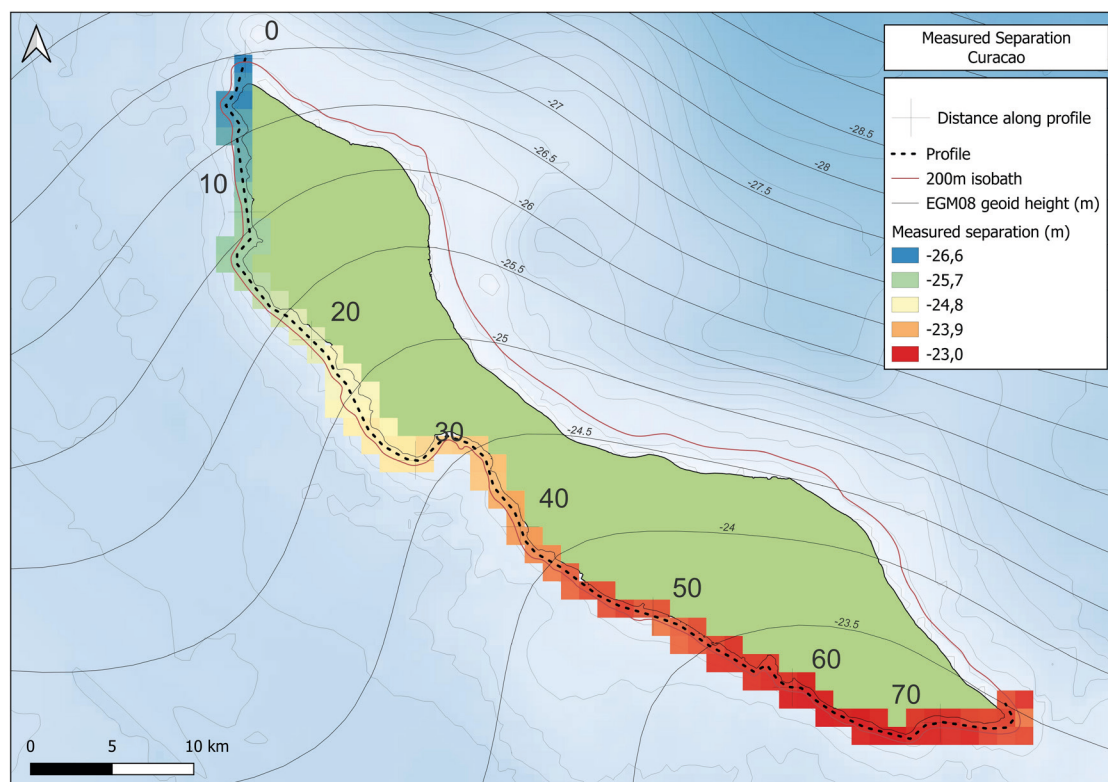


Fig. 16 Measured separation values near Curaçao (Site 1).

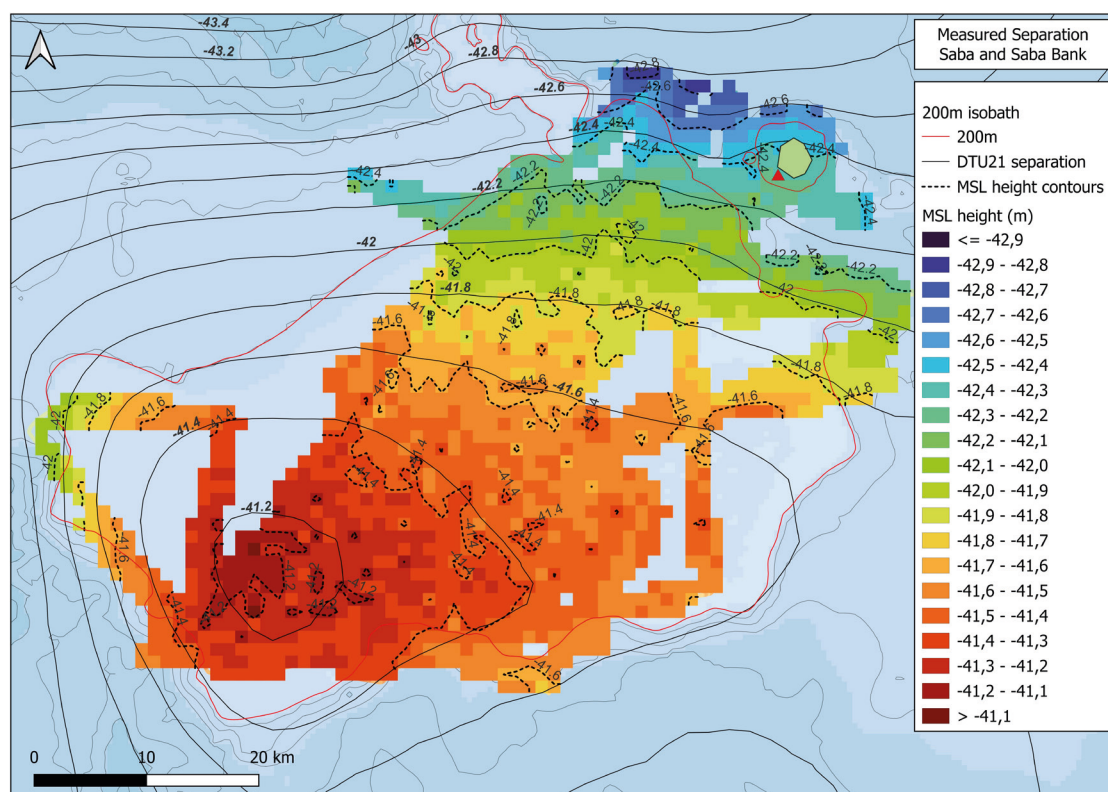


Fig. 17 Measured separation values near Saba and Saba Bank (Site 2).

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.

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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