Revista Brasileira de Cartografia
ISSN 1808-0936 | https://doi.org/10.14393/revbrascartogr
Sociedade Brasileira de Cartografia, Geodésia, Fotogrametria e Sensoriamento Remoto

Unification of Vertical References in the Coastal Zone: A Comprehensive Review for Blue Amazon Management

Unificação das Referências Verticais na Zona Costeira: Uma Revisão Abrangente para a Gestão da Amazônia Azul

Salomão Soares [1] e Regiane Dalazoana [2]

1 Federal University of Paraná, Curitiba, Brazil. E-mail. salomao.soares@ufpr.br.
ORCID: https://orcid.org/0000-0003-4826-776X
2 Federal University of Paraná, Curitiba, Brazil. E-mail. regiane@ufpr.br.
ORCID: https://orcid.org/0000-0001-5468-0679

Received: 11.2025 | Accepted: 04.2026

Abstract: This review article discusses the strategic challenge of unifying topographic and bathymetric data into a continuous model, an essential condition for managing the 5.7 million km² of the Blue Amazon and for the development of the Brazilian coastal zone. The complexity of this integration lies in the dynamic nature of multiple vertical datums that vary over time and space. It is demonstrated that the traditional connection via tide gauges or the determination of Separation Models (SEP) presents limitations at the national scale. Furthermore, conventional satellite altimetry technologies and geoid modeling reveal a significant coastal observational gap at the ocean-continent interface. Therefore, the Sea Surface Topography is fundamental for the unification of vertical references in the coastal zone; however, its rigorous determination still faces inseparable barriers in both technical-scientific and operational spheres. International experiences highlight the need for a transition to interdisciplinary approaches. It is concluded that overcoming the coastal observational gap in Brazil requires abandoning deterministic interpolations in favor of stochastic techniques, coupled with high-resolution hydrodynamic and geoidal models, aligning the country with the guidelines of the International Height Reference System (IHRS) to ensure efficient and sovereign management of its coastal and maritime territory.
Keywords: Vertical *Data*. Sea Surface Topography. Blue Amazon.

Resumo: Neste artigo de revisão, discute-se o desafio estratégico de unificar dados topográficos e batimétricos em um modelo contínuo, condição essencial para a gestão dos 5,7 milhões de km² da Amazônia Azul e para o desenvolvimento da zona costeira brasileira. A complexidade desta integração reside na natureza dinâmica de múltiplas referências verticais que variam no tempo e no espaço. Demonstra-se que a tradicional conexão via marégrafos ou a determinação de Modelos de Separação (SEP) apresenta limitações em escala nacional. Além disso, as tecnologias convencionais de altimetria por satélite e a modelagem do geoide apresentam uma severa lacuna observacional na interface oceano-continente. Sendo assim, a Topografia do Nível Médio do Mar é fundamental para a unificação das referências verticais na zona costeira; porém, a sua determinação rigorosa ainda enfrenta barreiras indissociáveis nas esferas técnico-científicas e operacionais. Experiências internacionais evidenciam a necessidade de uma transição para abordagens interdisciplinares. Conclui-se que a superação da lacuna observacional costeira no Brasil exige o abandono de interpolações determinísticas em prol de técnicas estocásticas, acopladas a modelos hidrodinâmicos e geoidais de alta resolução, alinhando o país às diretrizes do Sistema de Referência Internacional de Altitudes (IHRS) para garantir a gestão eficiente e soberana do seu território costeiro e marítimo.
Palavras-chave: *Data* Verticais. Topografia do Nível Médio do Mar. Amazônia Azul.

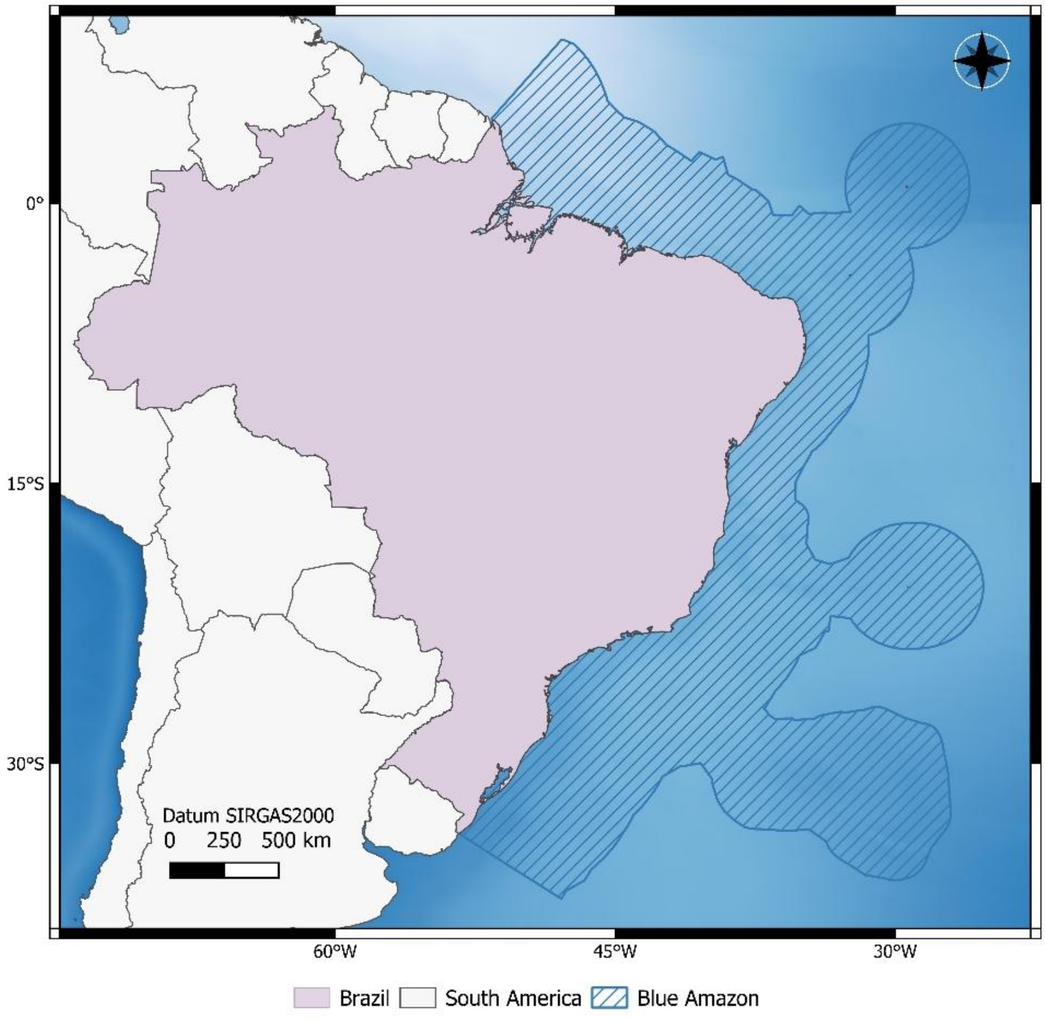
1 INTRODUCTION

The land and sea cartographies developed independently, resulting in a heterogeneous set of data referring to different vertical datums (i.e., reference surfaces used to measure heights and depths) (FIG, 2006; 2014). According to the United Nations (2019), an integrated, continuous model of land and marine areas is essential for promoting the sustainable development of coastal regions. The systemic understanding of elevations and depths (altitudes and bathymetry) facilitates the identification of suitable sites for human activities, deepens understanding of physical phenomena and ecosystems, and supports the management of ocean and marine resources (Filmer et al., 2024). Increasingly accurate technologies are driving demand for fast, reliable solutions. Thus, the connection between different datasets referenced at distinct points along the coastal boundary (i.e., reference points used for positioning and calculations) becomes essential to meet industrial and scientific requirements (Slobbe et al., 2013).

In 2019, the United Nations Expert Committee on Global Geospatial Information Management (UN-GGIM) elected 'Elevation and Depth' as one of its 14 fundamental geospatial data (United Nations, 2019), highlighting the urgency of developing integrated models that describe, in a unified manner, the terrestrial and submerged surfaces. Ocean-continent integration, in addition to a cartographic need, is a pillar for achieving the 2030 Agenda's Sustainable Development Goals (SDGs), playing a critical role in planning resilient coastal cities (SDG 11), mitigating global climate change (SDG 13), and in the conservation and sustainable use of marine resources (SDG 14).

According to the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística – IBGE, 2022), more than 50% of the brazilian population lives within 150 km of the coastal zone, which extends for over 8,500 km along 17 states and 463 municipalities. This coastal strip hosts a high concentration of economic and social activities, including cities and urban areas, ports, industries, tourism, fishing, aquaculture, and energy generation (MMA, 2018). Through the Brazilian Continental Shelf Survey Plan (Levantamento da Plataforma Continental Brasileira – LEPLAC), Brazil expanded its maritime jurisdiction to approximately 5.7 million km², consolidating the so-called Blue Amazon. Figure 1 shows the current limit of the Blue Amazon (IBGE, 2024), and the maritime part is represented by model DTU25MSS (Andersen & Nilsson, 2025).

Figure 1 – Limit of the Blue Amazon.



Elaboration: The authors (2026).

Management of the Blue Amazon requires scientific, political, and technological coordination. From an environmental perspective, problems such as marine pollution, overfishing, and the impacts of climate change are highlighted. Rising sea levels and ocean acidification threaten reefs and mangroves (MMA, 2018; IOC-UNESCO, 2024). Energy security and natural resource exploitation pose dilemmas, mainly due to the expansion of offshore activities and the need to balance development and conservation. The recent research authorization for maritime drilling in the Foz do Amazonas basin illustrates this scenario (IBAMA, 2025). It is a strategic region through which more than 95% of Brazilian foreign trade circulates and which accounts for about 95% of national oil production. This indicates the need for investments in monitoring, patrolling, and scientific infrastructure to ensure sovereignty and sustainable use (Marinha do Brasil, 2023).

At the institutional level, the fragmentation of public policies and the interruption of strategic initiatives have hindered data integration, especially since, in 2019, the collegiums were defunct, which paralyzed the National Cartography Commission (Comissão Nacional de Cartografia – CONCAR) and its committees, including the Integration Committee of Vertical Land and Sea Components (Comitê de Integração das Componentes Verticais Terrestres e Marítimas – CICVTM). These actions disrupted the integration of geodesic data and references between the continent and the ocean (MMA, 2018; Decreto n° 9,759, 2019). The absence of continuous oceanographic and geodetic data, as well as a national coastal altimeter network, compromises modeling and forecasting capacity (Silva et al., 2024; Santana, 2024). However, the creation of the National Geoinformation Commission (Comissão Nacional de Geoinformação – CONGEO) in 2025 marks the restructuring and strengthening of geoinformation governance (Portaria GM/MPO n° 32, 2025).

In this context of institutional resumption and search for technical solutions, it becomes evident that there is a need to improve integration between land and sea references. Traditional binding, based on tidal seasons, does not provide the necessary spatial resolution or integration, as its interpolation alone, without accounting for hydrodynamic effects, is limited (Luz, 2016). The definition and connection between vertical datums, integrating ocean and continent, present complexities, given the variations in vertical reference depending on the context of definition (Wöppelmann et al., 2006). Enhancing integration strategies is crucial to overcoming these challenges.

Sea Surface Topography (SSTop), known as Mean Dynamic Topography (MDT) in oceanography, plays a key role in integrating vertical frameworks into coastal areas (Heck & Rummel, 1990). The SSTop is determined using satellite altimetry and geoidal models and is defined as the difference between the mean sea surface (MSS) and the geoid, incorporating hydrodynamic effects such as currents (movements of large water masses), temperature, and salinity. Because it presents a continuous and high-resolution surface, SSTop allows the extrapolation of mean sea level to areas without tidal seasons, becoming a robust alternative for vertical ocean-continent linkage (Santana & Dalazoana, 2022; Souza, Dalazoana & Santana, 2025).

In addition, the SSTop is useful in studies of ocean circulation and climate modeling, deepening knowledge of phenomena such as *El Niño* and *La Niña* (Dong et al., 2025). For operational oceanography, aimed at the management of the Blue Amazon, SSTop can be used in ocean forecasting systems to monitor and predict currents, tides, and variability of ocean circulation (Mulet et al., 2021; AVISO, 2025). SSTop estimates derived from satellite observations and coastal measurements are already used to validate and improve the accuracy of high-resolution ocean circulation models (Tang et al., 2025).

However, determining SSTop in the coastal zone poses considerable challenges for conventional satellite altimetry. The contamination of the signal in the vicinity of the earth, within the "footprint" (area covered by the sensor), and the applied corrections, such as tidal and atmospheric, introduce greater uncertainties in this area (Bosch, 2002; Andersen & Scharroo, 2011; Filmer et al., 2018). This compromises the quality of the MSS models and the gravity anomalies obtained from altimetry, which are used as input for the generation of geoidal models (Guo et al., 2025). Geoidal models also present problems near the coast due to the often inadequate coverage of land, sea, and air gravimetric data, and to omission and errors resulting from their limited spatial resolution from orbital sensors (Mazloff et al., 2014; Ribeiro et al., 2022).

The recent advancement of SAR altimeter missions, driven by the arrival of the SWOT satellite, raises expectations for improvement in products derived from satellite altimetry (Nilsson et al., 2025). Despite this, an observational gap still persists due to the absence or degradation of observations, especially in shallow areas and with complex bathymetry, where accuracy can be significantly reduced (Slobbe et al., 2013; Birol et al., 2025).

In view of recent technological and methodological advances in Coastal Geodesy, this article aims to update and expand discussions already initiated. We revisit the bases established by Santana et al. (2020) on Separation Models (SEP) and by Santana and Dalazoana (2020), regarding the integration of vertical land and ocean references. By updating the state of the art, we identified methodological complexities and barriers in the correlation between reference levels in the Brazilian coastal zone. We present the usual vertical references and deepen the relationships between geometric, physical, and maritime components. We analyzed new strategies to determine the SSTop and highlighted international updates. We highlight the transition from coastal modeling to interdisciplinary approaches that integrate gravity, hydrodynamics, and advanced stochastic techniques. Finally, we have outlined ways for Brazil to establish a continuous and aligned Unified Vertical Reference System with the IHRF to properly manage the Blue Amazon.

2 VERTICAL REFERENCES FOR HEIGHTS AND DEPTHS

Vertical references are surfaces adopted as sources or bases for height and depth measurements. They can vary in the coastal zone, depending on the purpose. They are fundamental to ensure consistency in the representation of the height of points over the continent and the depths in the ocean. The following is an overview of the main vertical references used in the coastal zone.

2.1 Brazilian vertical datums and the leveling network

The development of height systems in Brazil, as well as in the height networks of other nations with oceanic edges, was based on mean sea level (MSL). Brazil has two vertical datums that serve as origins of the Brazilian Geodetic System (BGS). They are represented by the MSL, determined from the annual averages of the Port of Imbituba, in Santa Catarina, between 1949 and 1957, and the Port of Santana, in Amapá, between 1957 and 1958 (IBGE, 2019).

This classical conception considered the MSL, free of disturbances, as the theoretical reference that best fit the geoid and thus was adopted as a vertical terrestrial reference. However, given that sea level is in constant motion, engineering works in coastal regions need to be connected to the country's official height network and, moreover, they need to know the relationship between the current local MSL and the land vertical datum (IBGE, 2009).

Before the adjustment of the height network using geopotential numbers in 2018, the distribution of gravimetric observations was insufficient, making it impossible to calculate the necessary differences in geopotential to obtain altitudes with physical significance (IBGE, 2019). Thus, historically, the choice was made to provide normal-orthometric altitudes, to which the gross deviations measured in the field were corrected for non-parallelism of the equipotentials (LUZ, 2008). Currently, the BGS uses the Molodensky normal height, applying real gravity to calculate potential differences and average normal gravity to obtain the height (IBGE, 2019). It is pointed out that, due to the obtaining of the geopotential number based on geometric leveling, which depends on a reference, there remains a systematic effect associated with the datum used (the so-called offset of the datum). This means that any time variation not modeled in the MSL, if defined as the origin, systematically affects the entire leveling network, propagating inwards.

Other issues to be considered are temporal evolution and the existence of this leveling network, which began in 1945. Until 1990, the value of $4mm\sqrt{km}$ was used for quality control of section closure; after this period, it was changed to $3mm\sqrt{km}$, becoming the shaking verification technique and the minimum criterion for densification (IBGE, 2017). However, in a recent study on the geodetic control of the tidal station of Imbituba ($1mm\sqrt{km}$), Santos, Soares & Klein (2022) pointed out an average rate of vertical variation of benchmarks (BMs) in the region of $-0{,}17\ mm/a$. That is, over the years, verifying shaking becomes an increasingly complex activity. As for the network's existence, it is not uncommon to have difficulty finding these BMs in good condition. Soares, Dalazoana & Araki (2025) reported that 49.6% of the BMs that make up the height network were destroyed or not found in the Geodetic database. In addition, among the BMs classified as in good condition, with high priority for physical reality verification, 86% had not been visited for more than 20 years.

2.2 Physical heights (H) and the International Height Reference System - IHRS

Physical height concepts are commonly based on the near-stationary gravity field of the Earth, using the geopotential number (C) of a P point, defined as the difference between the potential of gravity at the reference surface (W_0) and at the point in question (W_P). Several metric height systems used as national systems can be derived from this relationship; the most common are the orthometric height, the normal height, and the normal orthometric height. For more details on these types of physical heights, see Heiskanen and Moritz (1967); Freitas and Blitzkow (1999); Sánchez (2002); Luz (2008); IBGE (2019).

For their practical realization, these physical height systems require the materialization of a vertical datum that serves as the reference surface. Historically, this materialization was achieved through the classical determination of the vertical datum, which established MSL as the surface that best represents a global equipotential. This served as a basis for implementing vertical control networks in countries.

However, it is now known that factors such as ocean currents, temperature, salinity, and winds cause MSL to vary from one location to another. As a result, one country's "zero" does not correspond to another's "zero" (Sánchez & Sideris, 2017). Thus, these local reference areas only approach the geoid due to the SSTop effect and local sea level anomalies, with deviations that can reach 2 m (Torge & Müller, 2012; Sánchez & Sideris, 2017). Add to this the limitations of the classical method of spirit leveling, which, despite its very high local accuracy, is subject to systematic errors on a large scale. This is a time-consuming and expensive procedure, restricted to connected continental areas and unable to connect oceans (Heck, 2004).

Contemporary geodesy seeks to establish global reference systems that integrate, with high precision, geometric and physical parameters of the Earth (Sánchez et al., 2021). Despite the advances already made in celestial and terrestrial geodetic systems, the absence of a unified global vertical framework persisted until the International Association of Geodesy (IAG) adopted IHRS in 2015 (Drewes et al., 2016).

The practical implementation of this system, called the International Height Reference Frame (IHRF), aims to provide consistent physical coordinates worldwide. The IAG has standardized W_0 at 62,636,853.4 m^2s^{-2}, with a formal error of ± 0.02 m^2s^{-2}, as the reference potential for the IHRS/IHRF, i.e., the global geoid. The current goal is to determine static values with an accuracy of ± 0.1 m^2s^{-2} (equivalent to ± 1 cm) (Sánchez & Sideris, 2017; Sánchez et al., 2021).

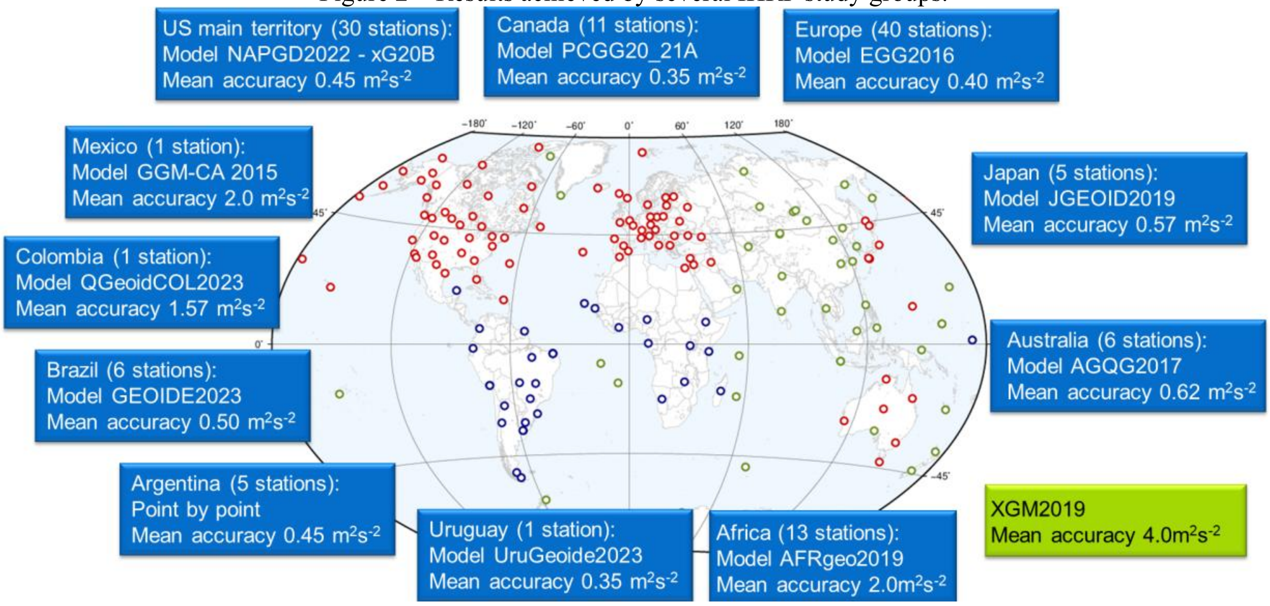
IHRS/IHRF promotes the unification of local vertical datums and ensures consistency in geodetic and oceanographic applications. However, the materialization of this global system faces a significant hurdle: the wide disparity in the density and quality of essential data among countries. Global geopotential models (GGMs), such as EGM2008 and XGM2019e, provide the long-wavelength component but lack adequate spatial resolution. Thus, to achieve centimetric accuracy, potential determination must be based on integrating GGMs with land-, sea-, and air-gravimetric data to generate high-precision regional models (Ribeiro et al., 2022). An example of this national effort to overcome these shortcomings is the US project GRAV-D (NOAA, 2023).

Currently, the global strategy is based on flexible standardization (Huang & Ågren, 2024), focusing on regions with sparse data (such as parts of Brazil), aiming to improve data collection to solve the Geodesy Boundary Value Problem (GBVP) (Vergos et al., 2024). Figure 2 presents the results obtained by several study groups involved in determining IHRF.

According to Sánchez et al. (2024), the first solution for IHRF was completed, achieving 3-40 cm accuracy in geopotential numbers. Geometric and potential metadata and coordinates will be published on the website of the IHRF Coordination Center (https://ihrfcc.topo.auth.gr/), which is responsible for ensuring the long-term sustainability of the IHRS/IHRF. Also, according to the authors, the next solution for IHRF will be determined, considering new stations, new gravity data, improved patterns and models (topography and GGM), improved calculation algorithms, etc.

At the national level, IHRF's determination drives the formation of research consortia and inter-institutional task forces. These are governed by the guidelines of the Geodetic Reference System for the Americas (Sistema de Referência Geodésica para as Américas – SIRGAS), which acts on the integration of IHRF stations in the Americas (Guimarães et al., 2024a).

Figure 2 – Results achieved by several IHRF study groups.

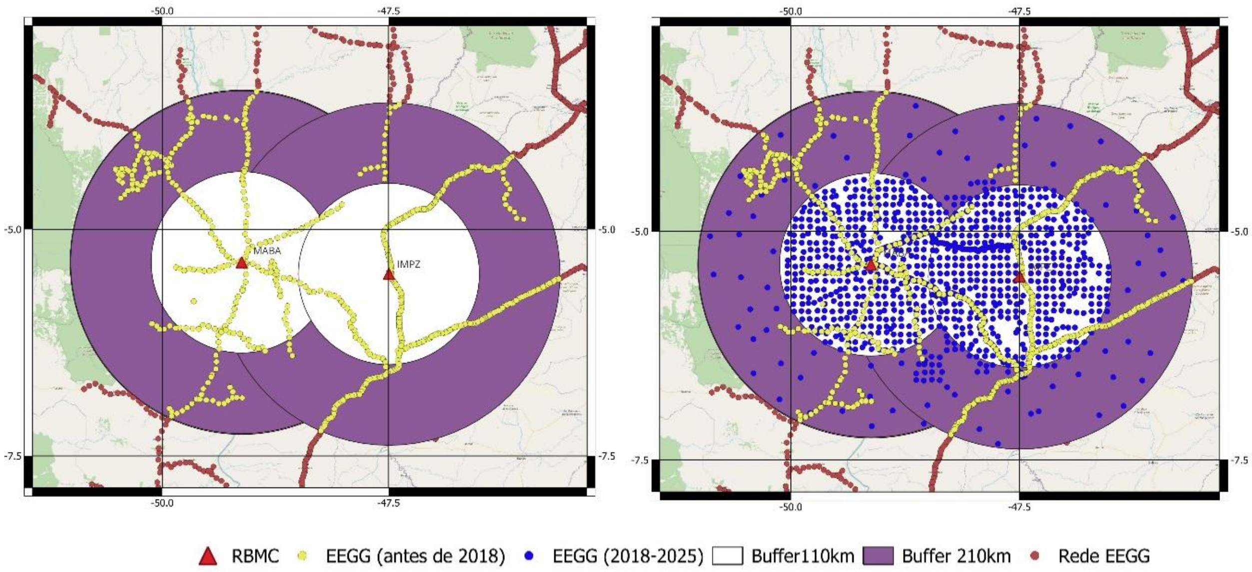


Source: Sánchez et al. (2024).

IBGE acts as the main official driver of the process, being responsible for selecting six stations from the Brazilian Network for Continuous Monitoring of GNSS Systems (RBMC) to compose the first IHRF solution, located in Imbituba (SC), Presidente Prudente (SP), Cuiabá (MT), Brasília (DF), Marabá (PA), and Fortaleza (CE). The institute's operational actions include densifying gravimetric surveys around these stations and the complex task of linking them to the leveling network (Guimarães et al., 2022a; Guimarães et al., 2022b; Padilha, 2025). It should be noted that the first major step of IBGE occurred in 2018, with the readjustment of the leveling network based on geopotential numbers and the adoption of normal as official altitudes (IBGE, 2019). Accessing the IBGE geodetic database, of the 6 stations selected to become IHRF stations, only the Imbituba station is not connected to the leveling network (IBGE, 2026).

The IBGE's commitment to ensuring the minimum infrastructure necessary for the densification of IHRF in Brazil is evident in Figure 3 below, which shows that the Marabá station, representing the country's Northern Region, presented, until 2018, a critical scenario for a reference station. After 2018, there was a significant commitment to densifying the leveling network and gravity stations in the region. According to data from the geodetic database, the effort sought to include the neighboring station at Imperatriz (MA), which is a positive indication that the IBGE aims to expand the number of IHRF stations in Brazil.

Figure 3 – Temporal evolution of gravity stations in the vicinity of RBMC stations in Marabá and Imperatriz.



Elaboration: The authors (2026).

In parallel with the BGS infrastructure, institutions such as the Polytechnic School of USP (Escola Politécnica da USP – EPUSP), the Center for Geodetic Studies (Centro de Estudos de Geodesia – CENEGEO), and the Geographic and Cartographic Institute (Instituto Geográfico e Cartográfico – IGC) have made coordinated efforts to advance absolute gravity in the country. About 15 absolute gravity stations were deployed, strategically close to the RBMC stations. This initiative is important not only for the physical consolidation of IHRF but also for the materialization of the International Terrestrial Gravity Reference Frame (ITGRF) in the national territory (Guimarães et al., 2020; Guimarães et al., 2022b).

The improvement of the national system of altitudes has focused on modeling geopotential using mathematical formulations for GBVP resolution, such as the Brovar Series and the Fast Fourier Transform (Ferreira, 2011; Silva, 2020). In addition, given the country's continental dimensions, the Residual Terrain Model (RTM) has been used to fill gaps in gravity data, enabling the modeling of high-frequency components of the gravity field (Padilha, 2025). In the IHRF stations located in the coastal zone, the strategy has required methods that integrate data from marine gravimetry campaigns conducted by the Bureau Gravimétrique International (BGI), the Brazilian Navy, and the National Petroleum Agency (Agência Nacional do Petróleo – ANP), in addition to the contribution of satellite altimetry, aiming for a more accurate representation of local heterogeneity (Ribeiro et al., 2022, 2023). The state of the art in this unification is represented by modern regional geoid and quasi-geoid models, such as SAM_GEOID2023 and SAM_QGEOID2023, developed to connect the vertical datums of South America to the global reference system (Guimarães et al., 2024b; Guimarães et al., 2025).

2.3 Ellipsoid height (h) and conversion models

Ellipsoidal height (h) is the vertical distance from a point to a specific reference ellipsoid, measured along the normal at its surface (Heiskanen & Moritz, 1967; Seeber, 2003). There are several ellipsoids adopted globally, such as WGS84 for the GPS system, Topex for certain products derived from satellite altimetry, and PZ-90 for the GLONASS system. The value depends intrinsically on the adopted ellipsoid, which requires geodetic transformations to ensure data compatibility. Renganathan (2010), for example, found, through Eq. (1), that the ellipsoidal altitudes associated with the Topex ellipsoid are approximately 70 cm lower than those associated with the WGS84 ellipsoid:

$$\delta h = h_1 - h_2 = -\big((a_2 - a_1)\cos^2\Psi + (b_2 - b_1)\sin^2\Psi\big) \tag{1}$$

where δh corresponds to the difference of the altitudes h_1 and h_2 referred to the two ellipsoids, a_1 and a_2 are the larger semieixes and b_1 and b_2 are the smaller semieixes of the ellipsoids, and Ψ is the geocentric latitude of the point of interest for which the conversion is desired.

The ellipsoidal model is a highly stable reference surface for interoperability between disparate vertical datums (Robin et al., 2016). In addition, the determination of ellipsoidal height is extremely useful for monitoring deformations, showing that the Earth's crust is not a static reference. The use of GNSS time series allows quantification of Vertical Land Motion (VLM), as GNSS stations fixed to the Earth's crust record the vertical movement of the terrain itself (Calado, 2023).

Despite its geometric utility, the ellipsoid is a mathematical surface that, because it is not equipotential, does not allow heights to describe the flow of fluids (such as water) under the action of gravity. Water does not flow from "greater h" to "lesser h" (Luz, 2008). Therefore, conversion models are necessary to assign physical significance to ellipsoidal height, such as geoidal models. Dos Santos (2019) presented an analysis of the flow of the Saint Lawrence River in Canada using GNSS surveying and geometric leveling. The use of ellipsoidal height without a conversion model indicated an inverse flow direction relative to the river's natural flow, demonstrating the complete detachment of the gravity field from the Earth. To solve this limitation, the ellipsoidal height is related to a physical reference. The main physical reference is the geoid, the equipotential surface of the gravity field that best fits the MSL. The height of a point above the geoid is called the orthometric height (*H*). The vertical separation between the geoid and a specific reference ellipsoid is called the geoid height (*N*). The geometrical relationship between them is obtained from the following relation according to

Eq. (2):

$$h = H + N \tag{2}$$

However, the precise determination of the orthometric height (*H*) presents a significant practical difficulty, as it depends on knowledge of the density and distribution of topographic masses between the surface and the geoid, and details in this regard can be found in Freitas and Blitzkow (1999) and at IBGE (2019). In order to avoid any hypothesis about these densities, the concept of normal height (HN) was developed, whose reference surface is the quasi-geoid, away from the ellipsoid by the height anomaly (ζ), according to Eq. (3):

$$h = H_N + \zeta \tag{3}$$

In countries such as Brazil, which have adopted the normal heights, the official transformation between the ellipsoidal height and the vertical reference of BGS is carried out through conversion models, with hgeoHNOR2020 being the current model (IBGE, 2023). This is not a pure geoidal or quasi-geoidal model, but rather a conversion surface adjusted from GNSS observations on leveling network benchmarks, based on an adaptation of the gravimetric geoidal model in the MAPGEO2015 grid (IBGE, 2023). The hgeoHNOR2020 is restricted to the country's continental area, where model uncertainties are well known and documented. Therefore, its use in the oceanic area is inadequate.

2.4 Nautical Charter Datum and the Maritime vertical references

At the maritime interface, the primary vertical reference for navigation safety and engineering works is the Nautical Charter Datum (CD), adopted in Brazil as the Reduction Level. The International Hydrographic Organization (IHO, 2010) recommends using the Lowest Astronomical Tide (LAT) as a DCN and the Highest Astronomical Tide (HAT) as a reference for vertical authorizations, being both levels predicted under average astronomical and meteorological conditions, preferably calculated with a 19-year time series (Pugh, 1987). However, the Brazilian Navy adopts the Reduction Level as the CD, calculated from a mathematical combination of specific harmonic components (Brazilian Navy, 2024; DHN, 2017).

The fundamental reference level in the coastal zone is Mean Sea Level (MSL), defined as the average height of the sea surface relative to a terrestrial reference (IHO, 2010). The MSL serves as a primary reference for the other hydrographic levels. However, since MSL is not an equipotential surface, it moves away from the geoid, creating a separation called SSTop. As the IBGE (2009) points out, this difference represents a significant practical complication. A terrestrial vertical datum is usually defined by the determination of MSL at a single point of origin at a given time; however, due to SSTop, the physical MSL measured at other points and times does not coincide with this reference. This offset (Δ) directly impacts the accuracy of the connection between altitudes and depths in engineering projects.

Estimates of MSL and SSTop can be obtained by integrating data from satellite altimetry and tide gauge; however, the reconciliation requires distinct corrections. The effect of the inverse barometer, for example, can generate discrepancies of up to 7 cm and is commonly applied in satellite altimeter products but neglected in tidal series (Ponte, 2006). Critical factors, such as the nature of tide gauge relative measurement, also require attention, as the equipment records sea level relative to the crust, which may suffer subsidence or submergence (VLM), which requires GNSS monitoring to avoid contamination of long-term time series (Wöppelmann & Marcos, 2016; Calado, 2023). In addition, comparing global MSS models with tidal series requires epoch-based kinematic translation and correction of effects such as land tides and ocean loading, without which high-precision ocean-continent integration becomes unfeasible (Pugh, 2004; IBGE, 2010; Santamaría-Gómez et al., 2017).

2.5 The Separation Model (SEP) and ocean-continent integration

The Separation Model (SEP) is a mathematical model that describes the geometric separation between the CD and a global reference ellipsoid (Santana et al., 2020). With an implemented SEP model, it is possible to use high-precision GNSS positioning (tide-GPS) for real-time depths. It should be noted that the SEP and geoidal models are complementary in determining a Unified Vertical Reference System, which requires the integration of information from ellipsoidal, geoidal, and oceanic references. However, the construction of SEP imposes significant scientific and operational obstacles (Santana et al., 2020).

The first obstacle is a lack of data infrastructure and high implementation costs. The need for a solid base of tidal, geodetic, and gravimetric data constitutes a bottleneck, as the low spatial density of tide gauges makes precise extrapolation difficult (Santana & Dalazoana, 2020). In addition, obtaining highly accurate geoidal models in the marine environment often requires airborne gravimetry campaigns, which entail high costs (Slobbe et al., 2018b). Add to this the kinematics of the crust, in which continuous VLM processes require uninterrupted monitoring (Feng, Jin & Zhang, 2012; Santana et al., 2020; Calado, 2023).

Moreover, temporal and morphological rigor is difficult to achieve. The definition of a tide level requires a long series, but the coastline has constantly changing topography (canals and sandbanks), which alters wave propagation over the years, while weather disturbances introduce chaotic noise into hydrodynamic models (Pugh, 2004; Santana & Dalazoana, 2020; Slobbe et al., 2018b). Hydrodynamic modeling also has operational shortcomings in complex zones: barotropic (2D) models are often unable to represent baroclinic processes, and 3D models are computationally costly. In intertidal zones, the definition of LAT breaks down, forcing the adoption of artificial mathematical approximations that sacrifice physical rigor (Slobbe et al., 2018a). Finally, vertical referencing errors cause anomalies that compromise the subdecimetric accuracy required for modern nautical charts (Slobbe et al., 2018a; Santana et al., 2020).

In the face of these obstacles, the isolated SEP model is geometrically fragile for continental integration. Robustness is only achieved when the geoid provides the absolute equipotential base of the gravity field in conjunction with the SEP. However, geoid modeling at the ocean-continent interface is still hindered by the low quality of near-shore orbital data and the scarcity of gravimetric data.

2.6 Vertical references derived from satellite altimetry

The information derived from satellite altimetry has high spatial resolution and high accuracy in deep regions referred to a global reference ellipsoid (Plag & Pearlman, 2009). The combination of data derived from satellite altimetry and tide gauges mitigates the problems associated with the low spatial resolution of tidal observations (Dalazoana et al., 2009). Moreover, satellite altimetry provides essential information for refining the geoid based on deviations from the vertical (Guo et al., 2025).

Seeber (2003) presents the measurement principle of satellite altimetry, based on the emission of energy pulses in the microwave range. In general, radar altimeter technology operates in the Ku band at approximately 13.5 GHz, corresponding to a wavelength (λ) of 2.2 cm.

The fundamental measure of the altimeter is sea surface height (SSH), defined as the vertical distance between the sea surface and a reference ellipsoid (e.g., GRS80, Topex, WGS84). It is calculated according to Eq. (4) (Chelton et al., 2001):

$$SSH = h_{sat} - (R + \sum \Delta R_{corr}) \tag{4}$$

where,

h_{sat}: Satellite height above the ellipsoid (determined by GNSS, SLR, DORIS);

R: The range measured by altimetry radar, which corresponds to the distance between the satellite and the sea surface, is determined by multiplying the speed of light in a vacuum by the time of the electromagnetic signal's round trip, divided by 2 $\left(R = \frac{1}{2} c. \Delta t\right)$;

$\sum \Delta R_{corr}$: Combined fixes that involve

ΔR_{iono}= Ionospheric delay;

$\Delta R_{tropo} = \Delta R_{dry} + \Delta R_{wet}$ (Tropospheric delay);

ΔR_{tide}= Ocean tidal corrections;

ΔR_{IB}= Inverted barometer correction;

ΔR_{SSB}= Sea State Bias.

Details on the errors that influence radar altimeter measurements, including their magnitudes and estimation methods, can be found in Chelton et al. (2001) and Birol et al. (2025). Another important reference for the connection of vertical datums is MSS, which is derived from the time-average of SSH, and the spatial (continuous) materialization of the ellipsoidal height of mean sea level is an essential component for SSTop determination (Chelton et al., 2001).

2.7 Permanent tidal concepts

An important technical aspect of the global definition of reference surfaces is the treatment of permanent tidal deformation, which results from the continuous deformation of the Earth due to the gravitational attraction of the Sun and Moon. According to Mäkinen (2021), to address the permanent deformation of the Earth and the field of gravity, two concepts (tide-free and mean-tide) are applied to the Earth's geometric shape, and three concepts (tide-free, zero-tide, and mean-tide) are applied to the field of gravity.

In the tide-free concept, also known as non-tidal, tidal effects are completely eliminated from uplifts, position, and potential; it is as if the Sun and Moon do not exist, or are artificially moved to infinity. In the concept of mean-tide, the average effect of the tide, along with its direct and indirect effects on the potential, is considered in the positions. The zero-tide concept indirectly considers only the effects of the permanent tide on potential.

According to Sánchez et al. (2021), traditional conversion formulas between different tide systems were developed by Ekman (1989). Such formulations assess the potential on the surface of a sphere, generically treating the tide-free model. Due to the flattening of the Earth, the accuracy of 1 millimeter is the methodological limit achievable with this spherical approximation. To overcome this limitation, Mäkinen (2021) reviewed the full theory, redefining formal terminology from "systems" to "concepts" of tide and outlining rigorous conversion formulas with 0.1 mm accuracy.

The compatibility of these concepts is critical for ocean-continent integration. Ellipsoidal heights referenced to global systems (such as ITRS/ITRF and SIRGAS2000) are conventionally treated in the tide-free concept, whereas sea surface altitudes obtained from satellite altimetry commonly adopt the mean-tide concept (Filmer et al., 2024). Consequently, in the relationship between tidal observations and MSS models, as well as in the determination of SSTop, it is necessary to reconcile the references. To ensure geodetic rigor and avoid systematic biases, both the geoidal models and the altimetric surfaces (MSS) need to be strictly linked to the same permanent tidal concept before any mathematical operation.

According to Mäkinen (2021), the purely geometric component of ellipsoidal height is strictly identical to the zero-tide and mean-tide concepts. The transition from tide-free coordinates, such as those originating from GNSS positioning linked to ITRF/SIRGAS2000 and represented in the mathematical formulations by the NT index, is carried out directly by the sum of the projection of the displacement vector over the normal to the ellipsoid (h_T), as presented in Eq. (5):

$$h_{MT} = h_{ZT} = h_{NT} + h_T(\varphi). \tag{5}$$

Therefore, to ensure correct integration with MSS models, the geometric sea-surface altitude determined in the tidal stations must be converted into the mean-tide concept using Eq. (6), whose numerical expression for correction, given in millimeters, depends exclusively on the geodesic latitude:

$$h_T(\varphi) = 60{,}34 - 179{,}01\,\mathrm{sen}^2\,\varphi - 1{,}82\,\mathrm{sen}^4\,\varphi \tag{6}$$

where,

h_{NT}: Ellipsoidal height in the concept tide-free (non-tidal);

h_{MT} e h_{ZT}: Ellipsoidal height in the mean-tide and zero-tide concepts respectively;

$h_T(\varphi)$: Radial correction of the permanent tide to the geometric coordinate (mm);

φ: Geodesic latitude of the station.

3 SSTOP'S DETERMINATION STRATEGIES TO CONNECT VERTICAL REFERENCES

SSTop's determination strategies have two strands: the oceanographic approach and the geodetic approach, which can be combined (Rio & Hernandez, 2004; Filmer et al., 2018; Tang et al., 2025). According to Heck (2004), oceanographic approaches such as steric leveling and dynamic leveling (geostrophic) aim to determine potential differences between coastal points or over oceanic regions. These are approximate assessments of the general hydrodynamic equations of motion. Local temperature and salinity data are needed to calculate the seawater density and thus the hydrostatic pressure field. From these data, it is possible to infer the geostrophic currents and, by vertical integration, SSTop (Rio & Hernandez, 2004). The main problems of this approach are the complexity in acquiring these data and the lack of spatial resolution in coastal regions, where tide gauges are usually installed (Freitas et al., 2002). Global ocean models are designed for use in the deep ocean, and their use on the coast and in shallow continental shelves should be evaluated with caution (Woodworth et al., 2012).

In geodesic approaches, the most direct way to think about vertical datums connection in continental regions is through geometric leveling combined with gravity measurements. This method determines the potential difference of gravity (geopotential number, C) between a fundamental point (P_0, usually a tidal station) and any other point (P) using the integral (or discrete sum) of gravity (g) along the leveled height difference (dn) (Heck, 2004).

Vertical datums connection strategies through SSTop determination have been evolving gradually. This approach is based on the fundamental geometric principle of separation between the mean sea surface and the geoid, expressed by Eq. (7):

$$SSTop = h_{MSL} - N \tag{7}$$

where $SSTop$ is the Sea Surface Topography; h_{MSL} is the ellipsoidal height of the mean sea level. This variable can be spatially and continuously materialized through a Mean Sea Surface (MSS) model derived from satellite altimetry or on a spot and local basis through GNSS positioning on the benchmarks of the tide gauge stations; N is the geoidal height at the same point or region, provided by a global geopotential model or regional geoidal model.

The practical application of this connection strategy, however, requires strict time compatibility. Because reference surfaces are dynamic, connecting the MSL derived from tidal observations to MSS models requires harmonizing observation times, accounting for atmospheric effects such as the inverse barometer effect, and applying the concept of the permanent tide (Giehl, Dalazoana & Santana, 2022; Filmer et al., 2024). In addition, propagating MSL to a common reference time requires removing the VLM effect from tidal series using continuous GNSS time series to ensure correct spatial linkage. Neglecting this temporal and physical harmonization introduces systematic biases that make precise integration at the ocean-continent interface impossible.

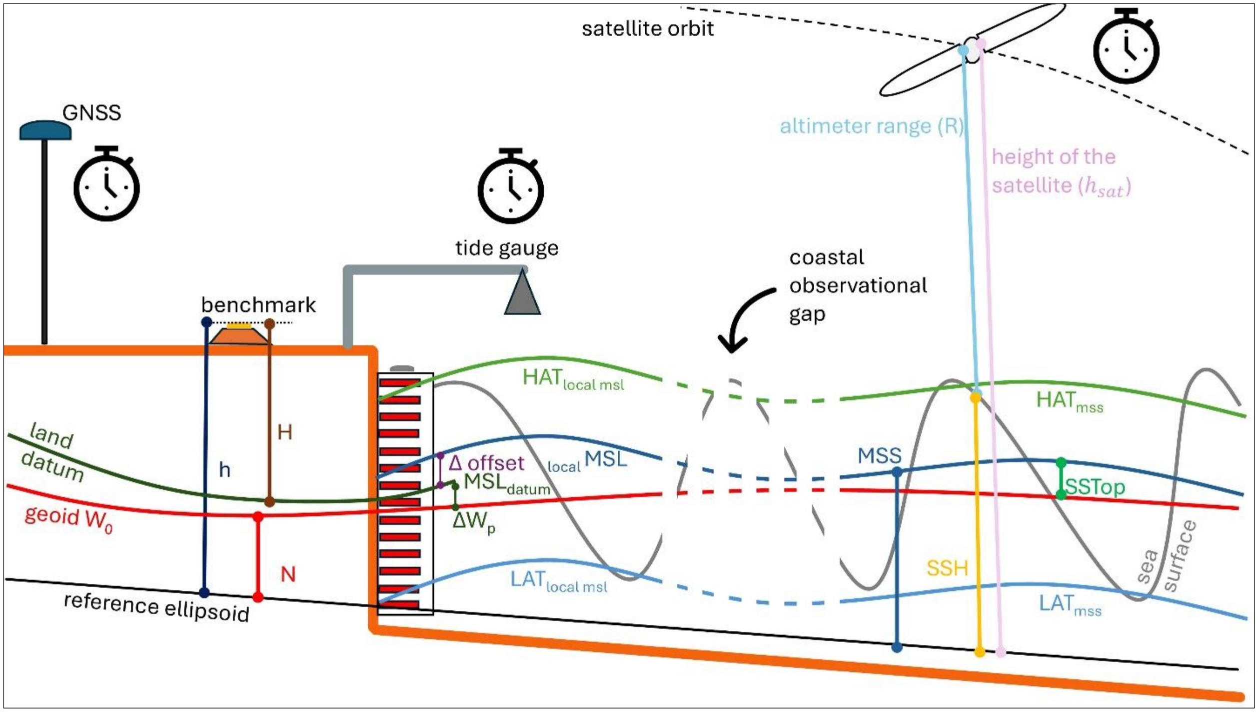
The limitations of the gravity and satellite positioning approach include the low accuracy of these geoid models along the coast (Huang, 2017) and the low spatial resolution of GNSS. The integration strategy of satellite altimetry products represents an invaluable advance for oceanography and geodesy, providing an accurate mapping of global ocean dynamics, enhancing our understanding of the oceans, and promoting the unification of vertical datums.

It should be noted that satellite altimetry does not perform point measurements, but rather calculates an average value corresponding to the sea surface that reflects the signal emitted by the sensor. In coastal regions, this signal, contaminated by noise from the roughness of the ocean surface and the specular reflection of the land, compromises measurement accuracy. That is, near the coastal zone, satellite altimeter products lose quality, which creates an observational gap, making it difficult to connect directly with data from tidal observations (Vignudelli et al., 2005; Andersen & Scharroo, 2011).

With the advancement of synthetic aperture radar (SAR) altimetric missions, there is an expectation of improvement in spatial resolution and data accuracy compared to conventional altimetric missions (Idžanović et al., 2017; Nilsson et al., 2025). SAR technology mitigates some signal contamination through Doppler processing and improves resolution along the trail; however, such processing requires complex (retracking) algorithms specifically designed to discriminate between shallow-water echoes and terrestrial reflections (Passaro et al., 2014; Birol et al., 2025). Thus, the coastal observational gap tends to shrink. Giehl, Dalazoana & Santana (2022) obtained positive results in the absolute comparison between the satellite Sentinel-3A and the tide gauge stations of the Geodetic Permanent Tide Gauge Network (Rede Maregráfica Permanente para Geodésia – RMPG), at an average distance of 5 km from the coastal zone; however, Filmer et al. (2024) recommend caution in interpreting the results at distances below 10 km.

Satellite altimeter products have significantly improved our knowledge of the open ocean and are now an essential component of many operational marine systems and climate studies. But its near-shore use remains a challenge, both technically and scientifically (Birol et al., 2025). Figure 4 illustrates these relationships between the areas and the occurrence of the coastal observation gap. The clocks in the figure illustrate the importance of reconciling reference periods in due analyses.

Figure 4 – Conceptual scheme of the relationship between the vertical references in the coastal zone and the coastal observational gap for integration with the products derived from satellite altimetry.



Elaboration: The authors (2026).

To bridge this gap, advances in the geometric, physical, and maritime components are needed. Regarding the geometric component, the connection between valid satellite altimetry data at sea and land-based tide gauge stations poses a complex spatial extrapolation challenge for evaluating MSS models. The literature shows that classical deterministic interpolation methods (such as the inverse of the square of distance, linear or cubic) often collapse in the coastal zone because they fail to filter residual terrestrial noise and, especially, because they do not provide an adequate quantification of uncertainty (Cressie, 1993; Le Traon, Nadal & Ducet, 1998). In this context of probabilistic rigor requirement, advanced geostatistical approaches and machine learning techniques such as Kriging and Bayesian inference via Gaussian processes (Souza, Dalazoana & Santana, 2025; Rasmussen & Williams, 2006), emerge as the frontier of knowledge to model the ocean's spatial covariance and fill the coastal void stochastically and physically coherent (Lary et al., 2016). With this, it is possible to determine the optimal reliability distance for MSS models in the coastal zone.

In addition to purely spatial/statistical interpolation, the limitations of satellite altimeter products in the coastal zone also open the door to the use of hydrodynamic modeling as a necessary element for SSTop. It uses physical equations to simulate water movement in the ocean, accounting for factors such as winds, tides, pressure gradients, and bathymetry (Iliffe et al., 2013; Slobbe et al., 2018; Tang et al., 2025). Long-term hydrodynamic simulations can also be used to estimate the average ocean circulation and thus assist in SSTop determination when integrated with geoidal models and tidal observations (Jahanmard et al., 2021).

Despite this, the care of the method permeates resolution and parameterization, as well as the quality of the forces and contour conditions. Rigorous validation of hydrodynamic models with independent observational data and quantification of model results uncertainties are necessary to increase confidence in estimates (Turner et al., 2010; Shi & Myers, 2016; Tang et al., 2025).

In this scenario, the evolution of connection techniques needs to occur in all directions. It is not sufficient to have a high-resolution hydrodynamic model if the coastal geoidal model is of low quality. Since the sea level values of hydrodynamic models are, as a rule, linked to maritime-level references connected to land in tide gauges, their rigorous conversion to ellipsoidal altitude is intrinsically dependent on an optimal geoidal model. It is only through this precise conversion that a continuous linkage between local coastal observations and MSS models becomes possible. Thus, the evolution of SSTop is irrevocably linked to the evolution of geopotential modeling in the coastal zone, which will enable the determination of a high-precision geoid, essential for serving as a physical-geometric bridge and isolating the dynamic signal from the ocean.

Thus, thinking about a global altimetric connection necessarily involves the evolution of IHRF and GBVP, a fundamental concept in physical geodesy that seeks to determine the Earth’s gravitational field and the shape of the geoid from measurements on the Earth’s surface (Freitas & Blitzkow, 1999; Guimarães & Blitzkow, 2011). SSTop can be viewed as a component of GBVP, which represents the difference between the ocean's physical surface and the geoid. The solution of the GBVP, in its various formulations, such as the Stokes problem or the Molodensky problem, allows for determining the geoid and, consequently, deriving SSTop (Mather, 1974). On the other hand, the solution depends on the quality and density of gravity data available at Earth’s surface; obtaining high-quality data in oceanic areas is complex, which affects the accuracy of the GBVP solution and, consequently, SSTop in these regions. Regional and local geoid models linked to the IHRF's purpose contribute to advancing the unification of vertical datums in the coastal zone (Guimarães et al., 2025). However, for this modeling to enable a continuous and rigorous transition in the ocean-continent interaction, it is essential to conduct systematic campaigns to collect gravimetric and oceanographic data, overcoming the observational vacuum that still restricts coastal geodetic integration.

4 INTERNATIONAL EXPERIENCES

In the face of increasing demands for coastal management, analyzing international approaches enables us to assess their applicability to the Brazilian context. The following is an overview of VDatum solutions in the United States, VORF in the United Kingdom, BATHYELLI in France, and AUSHYDROID in Australia. The evaluation of these initiatives highlights distinct strategies and recurring challenges in the search for a continuous and precise vertical reference at the ocean-continent interface.

4.1 VDatum

VDatum is a free computing tool, developed jointly by NOAA’s Office of Coast Survey (OCS), National Geodetic Survey (NGS), and the Center for Operational Oceanographic Products and Services (CO-OPS), with the functionality to transform heights/depths between maritime, physical, and geometric datums. Periodic updates are made to include new areas and improvements of methods and models, currently in version 4.7.1, released in June 2025 (NOAA, 2025).

Since the pilot project carried out in Tampa Bay in the Florida region in 2000, where the Princeton Ocean Model hydrodynamic model was used reaching a standard deviation of 2.7 cm between the data predicted by the model and those observed in the region (Parker et al., 2001; Parker et al., 2003), to the present day, VDatum has progressed consistently, now having national scope, and with the aim of expanding its coverage to at least 220 nautical miles of the coast (Tang et al., 2025).

The methodology is based on the creation of transformation grids that contain the separation values between vertical datums at specific points in a geographical area (NOAA, 2012). According to Myers et al. (2005; 2007), the process begins with the collection of bathymetry and shoreline data, followed by the generation of a finite element grid. Then they apply the boundary conditions in the Advanced Circulation

Model for Oceanic, Coastal and Estuarine Waters (ADCIRC), currently version 55.

Applications developed before 2016 used the Tidal Constituent and Residual Interpolation (TCARI) tool, developed by Hess et al. (1999), which applied a first-order deterministic solution of Laplace's equation for spatial interpolation. Later applications used a new statistical interpolation method, the Spatially Varying Uncertainty (SVU) method (Shi & Myers, 2016). The new interpolation approach not only reduced bias and errors but also produced spatially variable uncertainty (Tang et al., 2025). Finally, the data is sent to NGS for inclusion in the software VDatum (Myers et al., 2005).

VDatum has the tidal network structure of the National Water Level Observation Network (NWLON), comprising 306 tide gauges, as well as a significant number of temporary stations (Michalski, 2023). As an example of a stretch of 8,200 km resembling the Brazilian coast, 1,987 tide gauges were used, according to Myers apud Keysers et al. (2015). In addition, recent updates for West Coast and Chesapeake/Delaware Bay have incorporated satellite altimetry data, ellipsoidal reference IGS14, and the experimental geoidal model xGEOID20B (Tolkova et al., 2023; Tang et al., 2025).

xGEOID is a series of experimental geoidal models developed by NGS, which combine gravity data obtained from satellites, ground surveys, and airborne gravimetry (NGS, 2025). This is a preliminary product, conceived as an intermediate step for the launch of the new US geoidal model. The suffix 20B indicates that the model uses data available until approximately 2020 and, specifically in version "B", incorporates airborne measurements from the GRAV-D project (NOAA, 2023). Thus, in the coastal zone, the observation gap between terrestrial gravimetry and marine and satellite gravimetry is eliminated, thereby considerably improving the determination of the geoidal model at the ocean-continent transition.

In determining SSTop, defined as the elevation of xGEOID20B relative to local MSL, all MSL data were based on the most recent reference time (1983-2001). The differences between the model and observations from tide gauges are presented in Table 1 (Tang et al., 2025).

Table 1 – Statistics of the SSTop interpolated by minimum curvature and SVU methods.

Region	Method	Minimum (m)	Maximum (m)	Mean (m)	SD (m)
All sub regions	Min. Curvature	-2.29	0.067	-0.219	0.058
All sub regions	SVU	0.019	0.06	0.029	0.002

Source: Tang et al. (2025).

4.2 Vertical Offshore Reference Frame (VORF)

The VORF project was initiated in 2005 by the UK Hydrographic Office (UKHO) to establish a set of continuous vertical surfaces connecting the main reference systems used in land and maritime regions. The model's area of coverage included the territorial waters of the United Kingdom and Ireland up to the limit of the continental shelf. According to Iliffe et al. (2013), one of the main purposes was to allow precise transformation of GNSS-derived depths directly onto tidal surfaces, such as the CD, thereby optimizing hydrographic surveys and reducing dependence on tidal observations or local tide models.

The methodology was structured in three main steps. The first consisted of determining the MSS model in relation to the GRS80 ellipsoid. In oceanic regions, more than 30 km from the coast, the altimetric model DNSC06MSS was used, derived from TOPEX/Poseidon, Jason-1, ERS-1, ERS-2, Geosat, and GFO missions. In coastal areas, where the altimetry is degraded, historical series of 75 tide gauges from the Permanent Service for Mean Sea Level (PSMSL) network and more than 385 temporary tide gauges operated by the British Royal Navy were integrated, with 253 stations with a 3-month average, 25 between 3 months and 1 year, and 107 with more than 1 year of data. These data were adjusted to the reference period 2000.0 using a space-time model (Iliffe et al., 2007).

The second stage involved transforming mean sea levels to the ETRF89 system using leveling connections, GNSS observations, and datum-correction models. The third and final step consisted of modeling the tidal surfaces (CD, LAT, HAT, MSL, among others) from high-resolution hydrodynamic models with a 3.5 km mesh and empirical observations. The surfaces were interpolated using the thin-plate spline (TPS) technique, with a maritime distance function that weights connectivity between points (Turner et al., 2010). All interpolations used the geoidal model OSGM05 as a basis, thus achieving SSTop by placement by least squares and a covariance function derived from the characteristics of the tide gauge and altimetry data (Iliffe et al., 2013).

The model was validated through 245 tests at coastal points, 63 comparisons between tide gauges and GNSS, and 6 offshore campaigns. The results showed that the model achieves, in most areas, an accuracy of 0.10 m in coastal zones and 0.15 m in the open sea, with a 68% confidence interval (1σ). However, significant discrepancies were identified at some points, such as in Portland, where 0.69 m differences between observed and modeled values were observed, highlighting VORF's limitations in zones with highly complex hydrodynamics (UKHO, 2015).

4.3 BATHYmetry referred to the ELLIpsoid (BATHYELLI)

The project, led by Service Hydrographique et Océanographique de la Marine (SHOM), was launched in 2005 with the aim of establishing vertical hydrographic datums throughout the French metropolitan coastal area in a consistent, accurate, and accessible way (Tanguy et al., 2014).

It generates surface models for maritime vertical references, such as MSL, LAT, HAT, and Hydrographic Zero (HZ), referenced to the GRS80 ellipsoid and the RGF93 legal geodetic system. The project's principle is to unify the MSL obtained from tide stations with the MSS observations from satellite altimetry, using satellite altimetry data at a distance of 10 miles from the coast (~16 km). To fill gaps between these measurements and ensure spatial continuity, kinematic GPS surveys were embarked and post-processed up to 15 nautical miles (~28 km) to construct continuous vertical surfaces. For data unification, the method of least squares with covariance functions was used on a finite element grid (Pineau-Guillou & Dorst, 2013).

Currently, the project is in version 2.1, released in March 2023. According to SHOM, the BATHYELLI is not certified for navigation; it is a scientific and technical reference, useful especially for integration with GNSS systems, hydrographic survey planning, and interoperability between vertical surfaces (SHOM, 2023). Table 2 presents the comparison between the Maritime Vertical References 2014 (RAM 2014) and the BATHYELLI v1.1 model.

Table 2 – Statistics of the difference in mean sea ellipsoidal heights between RAM 2014 and BATHYELLI v1.1 products.

Sea coastline	N° of ports	µ(ΔNM/GRS80)	RMS(ΔNM/GRS80)
Atlantic	40	0.7 cm	16.8 cm
Continental Mediterranean	13	12.2 cm	36.3 cm
Mediterranean Corsica	7	1.9 cm	11.6 cm

Source: Tanguy et al. (2014).

4.4 AUSHYDROID

AUSHYDROID evolved as an Australian solution to connect vertical land and sea references, with the aim of allowing precise transformations between the Chart Datum (LAT) and the reference ellipsoid (Todd et al., 2004). The central motivation was to address the growing need for continuous, high-resolution coastal data for applications such as flood modeling, maritime safety, and coastal planning, especially in the face of rising sea levels (Keysers et al., 2015). Currently, the AUSHYDROID working group is led by the Intergovernmental Committee for Survey and Mapping (ICSM), under the Australian Hydrographic Office (AHO), tasked with developing a model to facilitate vertical connection along the entire Australian coastline (Filmer et al., 2024).

The current analysis was based on determining the ellipsoidal height of Lowest Astronomic Tide by connecting tidal observations from GNSS, ocean tide models, MSS, and geopotential models with SSTop. To overcome the observational gap of satellite altimetry models, they adopted the bicubic interpolation between models and tide gauges using the General Bathymetric Chart of the Ocean (GEBCO) model in approximation (Filmer et al., 2018). Recent assessments indicate that, in coastal regions, accuracy was ± 20 cm but degraded in complex areas such as estuaries and bays, where, in some cases, errors exceeded 50 cm compared to tide gauges. This limitation points to the need for a higher density of tide gauges connected to the reference ellipsoid and better modeling in critical areas. Of the 142 tide gauges available in the study area, only 25 were used; the rest were excluded due to restrictions such as a lack of GNSS connectivity, missing metadata, or short-lived records (< 41 days). The best results were only achieved with 19 tide gauges with observations over 5 years (Filmer et al., 2024).

Filmer et al. (2024) highlight that although models can accurately perform MSS, there are uncertainties in the calculations of global geopotential models and in the quality of the oceanographic information used in these models. In addition, there is scarcity and heterogeneity in the observational data along the coast, especially the absence of GNSS connections in historical tide gauges.

5 BRAZILIAN CONTEXT

The absence of a Unified Vertical Reference System in Brazil prevents direct interoperability among different geospatial datasets. Hydrographic data produced by the Brazilian Navy are usually referred to the CD; civil topographic surveys generally use the local mean sea level or references associated with the BGS; GNSS observations are referred to the ellipsoid; while geoidal models provide equipotential surfaces intended for conversion between geometric and physical references.

This diversity of vertical references highlights a conceptual and operational fragmentation between civil, scientific, and military institutions responsible for geospatial data production in the country. Without a nationally agreed-upon unified model, it becomes difficult to integrate data produced by different actors. Thus, accuracy and continuity in environmental and hydrographic studies are lost, and the national capacity to generate knowledge about the territory is compromised. The direct implications of this lack of rigorous correlation are reflected in significant errors in coastal flood modeling, inconsistencies in environmental licensing of maritime and port structures, and difficulties in establishing precise limits on maritime sovereignty.

In this sense, the creation of the National Commission on Geoinformation (CONGEO) in 2025, with a focus on its Thematic Committee for Coastal Mapping (CT-MAPCOST), represents an opportunity to restructure the governance of geoinformation in Brazil and strengthen integration between geodesy, oceanography, and marine spatial planning (Portaria GM/MPO n° 32, 2025). As part of this initiative, the thematic committee will propose a pilot area for high-precision coastal mapping, with the aim of subsidizing the future standardization of these activities at the national level. It is expected that this activity will contribute to standardizing methodologies, evaluating new technologies, and improving the accuracy of geoidal and hydrodynamic models.

Among the expected results, we highlight the strengthening of coastal planning and management, the improvement of risk management and disaster response strategies, and the reduction of the so-called "coastal observational gap". In addition, such actions can contribute to the development of more robust mechanisms for adaptation to climate change (Portaria GM/MPO n° 32, 2025).

The precise determination of SSTop is a complex but essential scientific challenge for understanding ocean circulation and establishing consistent connections between different vertical references. The various approaches, whether oceanographic or geodetic, offer different estimation strategies. Each method has its own advantages and limitations, so the integrated combination of these approaches is fundamental for reducing uncertainties and achieving more precise, spatially detailed representations of the ocean surface.

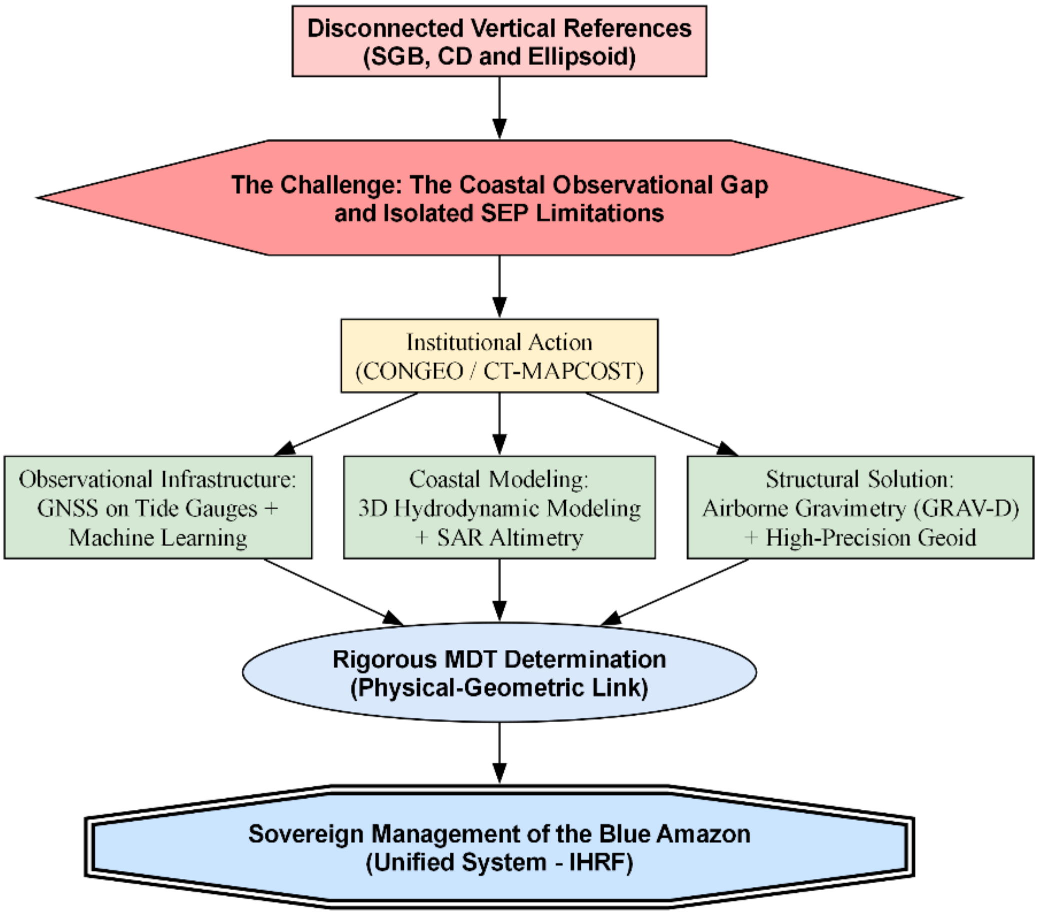
International experience shows that implementing a consistent national system requires cooperation among multiple institutions, harmonization of historical datasets, rigorous model validation, and the development of operational tools capable of integrating diverse data types. In this context, an interdisciplinary approach combining geodesy and physical oceanography becomes indispensable.

The analysis of revised international projects reveals recurring challenges, including the absence or insufficiency of metadata, the predominance of short-lived tide gauges, the need for additional GNSS tracking campaigns, and the limited availability of coastal gravimetric data. Regarding methods for connecting vertical references, the most robust results have been obtained in studies combining long-term tidal series, properly calibrated high-resolution hydrodynamic modeling, consistent geoidal models, and satellite altimetry data.

The integration of the GBVP approach, satellite altimetry data, and hydrodynamic models constitutes a robust alternative for estimating SSTop. Such a strategy allows for exploring the complementarities between different sources of information, particularly relevant in contexts of scarcity of gravimetric data. Although recent advances point to obtaining gravity in the coastal zone through aerogravimetric surveys, which is still under development in several countries (VU et al., 2024; WU et al., 2025), integration between geodetic and oceanographic methods remains a viable and operational solution.

To synthesize the complexity of this scenario and outline the technological path to overcome the country's coastal observational gap, Figure 5 presents a strategic flowchart. The scheme shows that the barriers inherent to classical methods require an integrated institutional governance (CONGEO), culminating in a progression of solutions based on stochastic inference, High-resolution modeling, and geopotential control to enable rigorous SSTop determination.

Figure 5 – Proposal of a strategic flowchart for overcoming the coastal observational gap, aiming at unifying the Brazilian vertical framework applied to the management of the Blue Amazon.



Elaboration: The authors (2026).

6 FINAL CONSIDERATIONS

In this context of data scarcity and geodesic complexity in vertical datums unification, overcoming the Brazilian coastal vacuum requires a multifaceted strategic approach. Within the observation infrastructure, it is urgent to integrate tide gauge networks into the ellipsoidal framework by expanding RBMC and episodic GNSS campaigns. This integration must go beyond the boundaries of the network managed by IBGE (RMPG) and incorporate the stations of the Directorate of Hydrography and Navigation (DHN), the Brazilian Coast Monitoring System (Sistema de Monitoramento da Costa Brasileira – SiMCosta) (FURG, 2026), and state networks, such as that of EPAGRI/CIRAM (2026) in Santa Catarina, ensuring national interoperability. In addition, the Geodetic Control of Tide Stations lacks a normative periodicity to attest to sensor stability. It is recognized that, given the vast extent of the Brazilian coast, this periodicity encounters severe logistical and budgetary constraints, requiring strategic approaches and prioritizing fundamental stations.

For quality control and spatial integration of tidal observations, it is recommended to explore machine learning techniques and Bayesian inference. Stochastic modeling has immense potential not only to standardize input data but, more importantly, to transcend the coastal exclusion zone in satellite altimetry. The coupling of these geostatistical techniques with high-resolution hydrodynamic and geoidal models represents the state of the art for overcoming physical seasonality breaks in complex estuaries, as observed in the evolution of

VDatum.

In parallel with the stochastic advance, coastal modeling activities should focus on expanding and calibrating regional hydrodynamic models, with special attention to the origins of BGS vertical datums (Imbituba and Santana) in candidate IHRF stations and in regions already facing adversity. The current scarcity of precise local models imposes reliance on global models, whose resolution often falls short of the baroclinic and morphological specificities of complex tidal zones. This hydrodynamic enhancement should go hand in hand with the exploration of new altimetric missions using SAR technology, which promise to reduce the observational gap near the coastline.

As a structural and final solution for the country, the non-negotiable strategy is to design a national aerogravimetry project for the coastal zone and shallow waters, inspired by the successful US project GRAV-D. Even though it requires high investments, this survey is the only way to determine a high-consistency coastal geoidal model aligned with IHRF. Such an initiative would directly resolve the GBVP at the ocean-continent interface, providing the absolute anchor needed for the Brazilian vertical reference frame to reach centimeter accuracy. This effort becomes even more critical in the context of missions such as SWOT, which require a rigorous geoidal model to fully exploit SSTop's observation potential.

Management of the Amazon Blue requires vertical accuracy, data continuity, and integration between different technical domains. The current disconnection of vertical references makes this task difficult and imposes limits on the sovereignty of the Brazilian state in its maritime territory. The unification of heights and depths in Brazil, in the context of IHRS/IHRF, will represent an essential advance in consolidating geoinformation based on the most recent vertical references. It is not just about aligning measures; it is about establishing a continuous Unified Vertical Reference System on which the country can observe, model, and protect its territory and its ocean.

Acknowledgments

The main author thanks the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística – IBGE) for granting temporary leave to carry out a Postgraduate Program.

Authors' contribution

Conceptualization: Soares, S. and Dalazoana, R.; Curatorship of the data: Soares, S.; Formal analysis and investigation: Soares, S. and Dalazoana, R.; Methodology: Soares, S.; Supervision: Dalazoana, R.; Writing – original draft: Soares, S.; Writing – review and editing: Soares, S. and Dalazoana, R.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

References

Andersen, O. B., & Nilsson, B. (2025). *DTU25MSS Mean Sea Surface*. [Dataset]. Technical University of Denmark. https://doi.org/10.11583/DTU.29412275.v1

Andersen, O. B., & Scharroo, R. (2011). Range and geophysical corrections in coastal regions: and implications for mean sea surface determination. In: S. Vignudelli, A. Kostianoy, P. Cipollini, & J. Benveniste (Eds.), *Coastal Altimetry*. Springer. https://doi.org/10.1007/978-3-642-12796-0_5

AVISO. (2025). *Mean Dynamic Topography - AVISO altimetry*. https://www.aviso.altimetry.fr/en/applications/ocean/large-scale-circulation/mean-dynamic-topography.html

Birol, F., Bignalet-Cazalet, F., Cancet, M., Daguze, J.-A., Fkaier, W., Fouchet, E., Léger, F., Maraldi, C., Niño, F., Pujol, M.-I., & Tran, N. (2025). Understanding uncertainties in the satellite altimeter measurement of coastal sea level: insights from a round-robin analysis. *Ocean Science*, *21*, 133–150. https://doi.org/10.5194/os-21-133-2025

Bosch, W. (2002). The Sea Surface Topography and its Impact to Global Height System Definition. In: H. Drewes, A. H. Dodson, L. P. S. Fortes, L. Sánchez, & P. Sandoval (Eds.), *Vertical Reference Systems* (pp. 225-230). Springer-Verlag. https://doi.org/10.1007/978-3-662-04683-8_43

Calado, L. G. L. P. (2023). *Estimativa do deslocamento vertical de estações maregráficas a partir da modelagem de séries temporais de coordenadas GNSS*. [Tese de doutorado, Universidade Estadual Paulista]. Repositório Institucional UNESP. https://hdl.handle.net/11449/253514

Chelton, D. B., Ries, J. C., Haines, B. J., Fu, L.-L., & Callahan, P. S. (2001). Satellite altimetry. In: L.-L. Fu & A. Cazenave (Eds.), *Satellite altimetry and the earth sciences: A handbook of techniques and applications* (pp. 1–131). Academic Press. https://www.sciencedirect.com/bookseries/international-geophysics/vol/69

Cressie, N. A. C. (1993). *Statistics for Spatial Data*. John Wiley & Sons, Inc.

Dalazoana, R., Luz, R. T., & Freitas, S. R. C. de. (2009). Estudos do NMM a partir de séries temporais maregráficas e de altimetria por satélites visando a integração da rede vertical brasileira ao SIRGAS. *Revista Brasileira De Cartografia*, *57*(2). https://doi.org/10.14393/rbcv57n2-44953

Decreto nº 9.759, de 11 de abril de 2019. (2019). Extingue e estabelece diretrizes, regras e limitações para colegiados da administração pública federal. Presidência da República. http://www.planalto.gov.br/ccivil_03/_ato2019-2022/2019/decreto/d9759.htm

Diretoria de Hidrografia e Navegação (DHN). (2017). *NORMAM 25: Normas da Autoridade Marítima para Levantamentos Hidrográficos* (2a ed.). Marinha do Brasil. https://www.marinha.mil.br/dpc/sites/www.marinha.mil.br.dpc/files/bibliografia/qt/NORMAN-25-DHN.pdf

Dong, X., Zhang, R.-H., Hu, J., Gao, C., & Chen, M. (2025). Thermodynamic processes prolong triple La Niña events in a hybrid coupled ocean-atmosphere model. *Climate Dynamics*, 63(2). https://doi.org/10.1007/s00382-024-07564-w

Dos Santos, M. C. (2019). Tendências modernas e questões relacionadas com a definição e realização de sistemas verticais: a experiência canadense. *Revista Brasileira de Cartografia*, *67*, 1627–1639. https://doi.org/10.14393/rbcv67n0-49252

Drewes, H., Kuglitsch, F., Adám, J., & Rózsa, S. (2016). The geodesist's Handbook 2016. *Journal of Geodesy*, *90*(10), 907–1205. https://doi.org/10.1007/s00190-016-0948-z

Ekman, M. (1989). Impacts of geodynamic phenomena on systems for height and gravity. *Bulletin Géodésique*, *63*, 281–296. https://doi.org/10.1007/BF02520477

Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina (EPAGRI). (2026). *Litoral On-line*. Centro de Informações de Recursos Ambientais e de Hidrometeorologia. https://ciram.epagri.sc.gov.br/litoral-online

Fédération Internationale des Géomètres (FIG). (2006). *FIG Guide on the Development of a Vertical Reference Surface for Hydrography* (No. 37). https://www.fig.net/resources/publications/figpub/pub37/pub37.pdf

Fédération Internationale des Géomètres (FIG). (2014). *Ellipsoidally Referenced Surveying for Hydrography* (No. 62). https://www.fig.net/resources/publications/figpub/pub62/Figpub62.pdf

Feng, G., Jin, S., & Zhang, T. (2013). Coastal sea level changes in Europe from GPS, tide gauge, satellite altimetry and GRACE, 1993–2011. *Advances in Space Research*, *51*(6), 1019-1028. https://doi.org/10.1016/j.asr.2012.09.011

Ferreira, V. G. (2011). *Solução do tipo Brovar para o Segundo Problema de Valor de Contorno da Geodésia com vistas à modernização de Sistemas de Altitudes*. [Tese de doutorado, Universidade Federal do Paraná]. Acervo Digital UFPR. https://hdl.handle.net/1884/25954

Filmer, M. S., Hughes, C. W., Woodworth, P. L., Featherstone, W. E., & Bingham, R. J. (2018). Comparison between Geodetic and Oceanographic Approaches to Estimate Mean Dynamic Topography for Vertical Datum Unification: Evaluation at Australian Tide Gauges. *Journal of Geodesy*, *92*(12), 1413–1437. https://doi.org/10.1007/s00190-018-1131-5

Filmer, M. S., Johnston, P. J., Jayaswal, Z., Taylor, A., Chittleborough, J., Claessens, S. J., Seifi, F., Kuhn, M., Mccubbine, J., & Entel, M. (2024). Connecting Land and Sea Vertical Datums: A Data Evaluation for Developing Australia's AUSHYDROID Model. *Marine Geodesy*, *47*(3), 183-213. https://doi.org/10.1080/01490419.2024.2305898

Freitas, S. R. C., & Blitzkow, D. (1999). Altitudes e Geopotencial. *IGeS Bulletin*, *9*, 47-62. https://cartografica.ufpr.br/home/wp-content/uploads/2015/06/altitudesegeopotencial.pdf

Freitas, S. R. C., Medina, A. S., & Lima, S. R. S. (2002). Associated Problems to Link South American Vertical Networks and Possible Approaches to Face Them. In: H. Drewes, A. H. Dodson, L. P. S. Fortes, L. Sánchez, & P. Sandoval (Eds.), *Vertical Reference Systems* (pp. xx-xx). Springer. https://doi.org/10.1007/978-3-662-04683-8_59

Fundação Universidade Federal do Rio Grande (FURG). (2026). *Sistema de Monitoramento da Costa Brasileira (SiMCosta)*. Centro de Estudos dos Oceanos e Clima. https://www.simcosta.furg.br/home

Guimarães, G. N., & Blitzkow, D. (2011). Problema de valor de contorno da Geodésia: uma abordagem conceitual. *Boletim de Ciências Geodésicas*, *17*(4). https://doi.org/10.1590/S1982-21702011000400007

Guimarães, G. N., Blitzkow, D., Matos, A. C. O. C. de, Castro Junior, C. A. C., & Inoue, M. E. B. (2020). 30 anos de Medições Gravimétricas Absolutas no Brasil. *Revista Brasileira De Cartografia*, *72*(1), 159-176. https://doi.org/10.14393/rbcv72n1-50229

Guimarães, G. N., Blitzkow, D., Matos, A. C. O. C. de, Silva, V. C., & Inoue, M. E. B. (2022a). O Estabelecimento do IHRF no Brasil: Situação Atual e Perspectivas Futuras. *Revista Brasileira De Cartografia*, *74*(3), 651-670. https://doi.org/10.14393/rbcv74n3-64949

Guimarães, G. N., Blitzkow, D., Matos, A. C. O. C. de, Silva, V. C., & Inoue, M. E. B. (2022b). O estabelecimento do IHRF e do ITGRF no Brasil: situação e perspectivas. [Trabalho apresentado]. *XII Colóquio Brasileiro de Ciências Geodésicas*, Curitiba.

Guimarães, G. N., Matos, A. C. O. C. de, & Blitzkow, D. (2024b). Connecting the Brazilian Vertical System to the International Height Reference Frame by estimating the vertical datum parameters. *Journal of South American Earth Sciences*, *142*, 104990. https://doi.org/10.1016/j.jsames.2024.104990

Guimarães, G. N., Matos, A. C. O. C. de, & Blitzkow, D. (2025). High-resolution regional gravity field modeling to connect the local vertical systems in South America to the IHRF. *Earth, Planets and Space*, *77*, 98. https://doi.org/10.1186/s40623-025-02226-5

Guimarães, G. N., Tocho, C., Piña, W. H. S., Matos, A. C. O. C. de, Gómez, A., Antokoletz, E. D., & Blitzkow, D. (2024a). *Guía 06: Directrices para el cálculo de los valores de potencial de gravedad en las estaciones IHRF de la región SIRGAS* (1a ed.). https://doi.org/10.5281/zenodo.15476094

Guo, J., Wei, X., Li, Z., Jia, Y., Chang, X., & Liu, X. (2025). SDUST2023GRA_MSS: the new global marine gravity anomaly model determined from mean sea surface model. *Scientific Data*, *12*, 108. https://doi.org/10.1038/s41597-025-04394-1

Heck, B. (2004). Problems in the Definition of Vertical Reference Frames. In: F. Sansò (Ed.), *V Hotine-Marussi Symposium on Mathematical Geodesy*. Springer. https://doi.org/10.1007/978-3-662-10735-5_22

Heck, B., & Rummel, R. (1990). Strategies for Solving the Vertical Datum Problem Using Terrestrial and Satellite Data. In: H. Siinkel & T. Baker (Eds.), *Sea Surface Topography and the Geoid* (pp. 116-128). Springer.

Heiskanen, W. A., & Moritz, H. (1967). *Physical Geodesy*. W. H. Freeman.

Hess, K. W., Schmalz, R. A., Zervas, C., & Collier, W. C. (1999). *Tidal constituent and residual interpolation (TCARI): A new method for the tidal correction of bathymetric data* (NOAA Technical Report NOS CS 4).

Huang, J. (2017). Determining coastal mean dynamic topography by geodetic methods. *Geophysical Research Letters*, *44*, 11125–11128. https://doi.org/10.1002/2017GL076020

Huang, J., & Ågren, J. (2024). *IHRF CONVENTIONS – SIMPLIFIED* (Version 1.0). https://ihrfcc.topo.auth.gr/wp-content/uploads/2024/08/IHRF_Conventions_Simplified_Jonas_v2.pdf

Idžanović, M., Ophaug, V., & Andersen, O. B. (2017). The coastal mean dynamic topography in Norway observed by CryoSat-2 and GOCE. *Geophysical Research Letters*, *44*, 5609–5617. https://doi.org/10.1002/2017GL073777

Iliffe, J. C., Ziebart, M. K., & Turner, J. F. (2007). A new methodology for incorporating tide gauge data in sea surface topography models. *Marine Geodesy*, *30*(4), 271–296. https://doi.org/10.1080/01490410701568384

Iliffe, J. C., Ziebart, M. K., Turner, J. F., Talbot, A. J., & Lessnoff, A. P. (2013). Accuracy of vertical datum surfaces in coastal and offshore zones. *Survey Review*, *45*(331), 254–262. https://doi.org/10.1179/1752270613y.0000000040

Instituto Brasileiro de Geografia e Estatística (IBGE). (2009). *Esclarecimento sobre a relação entre o Datum Vertical do SGB (Imbituba e Santana) e os Níveis de Redução e "Zeros" Hidrográficos no Litoral Brasileiro*. https://geoftp.ibge.gov.br/metodos_e_outros_documentos_de_referencia/outros_documentos_tecnicos/rmpg/relacao_dvsgb_nr_zh.pdf

Instituto Brasileiro de Geografia e Estatística (IBGE). (2010). *Instruções técnicas para controle geodésico de estações maregráficas - CGEM e sua vinculação vertical ao Sistema Geodésico Brasileiro - SGB*. (Manuais técnicos em Geociências, n. 11). https://www.ibge.gov.br/geociencias/metodos-e-outros-documentos-de-referencia/revista-e-manuais-tecnicos/15826-manual-tecnico-em-geociencias.html?edicao=16446&t=publicacoes

Instituto Brasileiro de Geografia e Estatística (IBGE). (2017). *Especificações e Normas para Levantamentos Geodésicos associados ao Sistema Geodésico Brasileiro*. https://geoftp.ibge.gov.br/metodos_e_outros_documentos_de_referencia/normas/normas_levantamentos_geodesicos.pdf

Instituto Brasileiro de Geografia e Estatística (IBGE). (2019). *Reajustamento da rede altimétrica com números geopotenciais* (2a ed.). Coordenação de Geodésia. https://biblioteca.ibge.gov.br/visualizacao/livros/liv101666.pdf

Instituto Brasileiro de Geografia e Estatística (IBGE). (2022, 28 de junho). *Censo 2022: informações de população e domicílios por setores censitários auxiliam gestão pública*. Notícias. https://agenciadenoticias.ibge.gov.br/agencia-noticias/2012-agencia-de-noticias/noticias/39525-censo-2022-informacoes-de-populacao-e-domicilios-por-setores-censitarios-auxiliam-gestao-publica

Instituto Brasileiro de Geografia e Estatística (IBGE). (2023). *Modelo hgeoHNOR2020 para conversão de altitudes geométricas em altitudes normais* (2a ed.). Coordenação de Geodésia. https://biblioteca.ibge.gov.br/visualizacao/livros/liv102048.pdf

Instituto Brasileiro de Geografia e Estatística (IBGE). (2024). *Adequação do limite leste do Sistema Costeiro-Marinho à Amazônia Azul*. https://www.ibge.gov.br/geociencias/cartas-e-mapas/informacoes-ambientais/15842-biomas.html?edicao=41055&t=acesso-ao-produto

Instituto Brasileiro de Geografia e Estatística (IBGE). (2026). *Banco de Dados Geodésicos (BDG)*. https://www.bdg.ibge.gov.br/appbdg/

Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA). (2025). *Ibama emite licença de operação para perfuração marítima no bloco FZA-M-59, na bacia da Foz do Amazonas*. Notas. https://www.gov.br/ibama/pt-br/assuntos/notas/2025/ibama-emite-licenca-de-operacao-para-perfuracao-maritima-no-bloco-fza-m-59-na-bacia-da-foz-do-amazonas

Intergovernmental Oceanographic Commission of UNESCO (IOC–UNESCO). (2024). *State of the Ocean Report*. (IOC Technical Series, 190). https://doi.org/10.25607/4wbg-d349

International Hydrographic Organization (IHO). (2024). *Resolutions of the International Hydrographic Organization*. (Publication M-3 – 2nd Edition 2010 - Updated July 2024). https://iho.int/uploads/user/pubs/misc/M3-E-2024_July.pdf

Jahanmard, V., Delpeche-Ellmann, N., & Ellmann, A. (2021). Realistic dynamic topography through coupling geoid and hydrodynamic models of the Baltic Sea. *Continental Shelf Research*, *222*. https://www.sciencedirect.com/science/article/pii/S0278434321000789

Keysers, J. H., Quadros, N. D., & Collier, P. A. (2015). Vertical Datum Transformations across the Australian Littoral Zone. *Journal of Coastal Research*, *31*(1), 119–128. https://doi.org/10.2112/JCOASTRES-D-12-00228.1

Lary, D. J., Alavi, A. H., Gandomi, A. H., & Walker, A. L. (2016). Machine learning in geosciences and remote sensing. *Geoscience Frontiers*, *7*(1), 3-10. https://doi.org/10.1016/j.gsf.2015.07.003

Le Traon, P. Y., Nadal, F., & Ducet, N. (1998). An Improved Mapping Method of Multisatellite Altimeter Data. *Journal of Atmospheric and Oceanic Technology*, *15*(2), 522–534. https://doi.org/10.1175/1520-0426(1998)015<0522:aimmom>2.0.co;2

Luz, R. T. (2008). *Estratégias para modernização da componente vertical do Sistema Geodésico Brasileiro e sua integração ao SIRGAS*. [Tese de doutorado, Universidade Federal do Paraná]. Acervo Digital UFPR. https://acervodigital.ufpr.br/handle/1884/17075

Luz, R. T. (2016, 16 a 18 de novembro). Atividades para Integração das Superfícies de Referência Vertical na Zona Costeira Brasileira. [Trabalho apresentado]. *Simpósio SIRGAS*, Quito, Equador. https://www.sirgas.org/fileadmin/docs/Boletines/Bol21/48_Luz_2016_IntegracionSuperficiesVerticalesCosteras.pdf

Mäkinen, J. (2021). The permanent tide and the International Height Reference Frame IHRF. *Journal of Geodesy*, *95*, 106. https://doi.org/10.1007/s00190-021-01541-5

Marinha do Brasil. (2023). *Amazônia Azul*. https://www.mar.mil.br/hotsites/amazonia_azul/index.html

Marinha do Brasil. (2024). *Sondagem Batimétrica*. Centro de Hidrografia da Marinha. https://www.marinha.mil.br/chm/dados-do-segnav-lev-hidro/sondagem-batimetrica

Mather, R. S. (1974). On the Solution of the Geodetic Boundary Value Problem for the Definition of Sea Surface Topography. *Geophysical Journal International*, *39*(1), 87–109. https://doi.org/10.1111/j.1365-246X.1974.tb05440.x

Mazloff, M. R., Gille, S. T., & Cornuelle, B. (2014). Improving the geoid: Combining altimetry and mean dynamic topography in the California coastal ocean. *Geophysical Research Letters*, *41*, 8944–8952. https://doi.org/10.1002/2014GL062402

Michalski, M. (2023). *Introduction to tidal & geodetic vertical datums*. NOAA/National Ocean Service. https://tidesandcurrents.noaa.gov/datum-updates/assets/pdf/VA_April_2023_Tidal_geodetic_Presentation.pdf

Ministério do Meio Ambiente (MMA). (2018). *Programa Nacional para Conservação da Linha de Costa – PROCOSTA*. Secretaria de Recursos Hídricos e Qualidade Ambiental. https://antigo.mma.gov.br/images/arquivos/gestao_territorial/Procosta/PROCOSTA-versao_digital.pdf

Mulet, S., Rio, M.-H., Etienne, H., Artana, C., Cancet, M., Dibarboure, G., Feng, H., Husson, R., Picot, N., Provost, C., & Strub, P. T. (2021). The new CNES-CLS18 global mean dynamic topography. *Ocean Science*, *17*, 789–808. https://doi.org/10.5194/os-17-789-2021

Myers, E. P., Wong, A., & Hess, K. (2005). Development of a national VDatum, and its application to sea level rise in North Carolina. [Trabalho apresentado]. *U.S. Hydrographic Conference*, San Diego, CA, USA.

Myers, E., Hess, K., & Yang, Z. (2007). VDatum and strategies for national coverage. [Trabalho apresentado]. *Marine Technology Society/IEEE Oceans Conference*, Vancouver, British Columbia, Canada.

Nações Unidas. (2019). *The Global Fundamental Geospatial Data Themes*. Department of Economic and Social Affairs, Statistic Division. https://ggim.un.org/meetings/GGIM-committee/9th-Session/documents/Fundamental_Data_Publication.pdf

National Geodetic Survey (NGS). (2025). *Research Geoids — USGG and xGEOID*. https://www.ngs.noaa.gov/research/geopotential-datums/research-geoids.shtml

National Oceanic and Atmospheric Administration (NOAA). (2012). *VDatum Manual for Development and*

Support of NOAA's Vertical Datum Transformation Tool, VDatum (Version 1.01). https://vdatum.noaa.gov/download/publications/Manual_2012.06.26.pdf

National Oceanic and Atmospheric Administration (NOAA). (2023). *GRAV-D Project Homepage*. National Geodetic Survey. https://geodesy.noaa.gov/GRAV-D/

National Oceanic and Atmospheric Administration (NOAA). (2025). *VDatum: Current Events*. https://vdatum.noaa.gov/about/currentevents.html

Nilsson, B., Andersen, O. B., & Knudsen, P. (2025). Assessment of the performance of SWOT for observing the static ocean topography. *Geophysical Research Letters*, *52*, e2024GL112290. https://doi.org/10.1029/2024GL112290

Padilha, T. K. (2025). *Análise do uso da solução do tipo Brovar no PVCG fixado para a modelagem do geopotencial na estação IHRF PPTE*. [Dissertação de mestrado, Universidade Federal do Paraná]. Acervo Digital UFPR. https://hdl.handle.net/1884/96848

Parker, B., Milbert, D. G., Wilson, R., Hess, K. W., Bailey, J., Berry, R., Fowler, C., & Gesch, D. (2001). A Tampa Bay bathymetric / topographic digital elevation model with internally consistent shorelines for various datums. [Trabalho apresentado]. *Twelfth Biennial International Symposium of the Hydrographic Society*, University of East Anglia, Norwich, UK. https://vdatum.noaa.gov/download/publications/2001_parker_TampaDEM.pdf

Parker, B., Milbert, D., Hess, K., & Gill, S. (2003). *National Vdatum - The Implementation of a National Vertical Datum Transformation Database* [Relatório Técnico]. National Ocean Service. https://vdatum.noaa.gov/download/publications/2003_parker_USHydro_nationalvdatum.pdf

Passaro, M., Cipollini, P., Vignudelli, S., Quartly, G. D., & Snaith, H. M. (2014). ALES: A multi-mission adaptive subwaveform retracker for coastal and open ocean altimetry. *Remote Sensing of Environment*, *145*, 173–189. https://doi.org/10.1016/j.rse.2014.02.008

Pineau-Guillou, L., & Dorst, L. (2013). Creation of Vertical Reference Surfaces at Sea Using Altimetry and GPS. In: Z. Altamimi & X. Collilieux (Eds.), *Reference Frames for Applications in Geosciences* (pp. xx-xx). Springer. https://doi.org/10.1007/978-3-642-32998-2_33

Plag, H.-P., & Pearlman, M. (Eds.). (2009). *Global Geodetic Observing System: Meeting the requirements of a global society on a changing planet in 2020*. Springer.

Ponte, M. R. (2006). Low-Frequency Sea Level Variability and the Inverted Barometer Effect. *Journal of Atmospheric and Oceanic Technology*, *23*(4), 619-629. https://doi.org/10.1175/JTECH1864.1

Portaria GM/MPO nº 32, de 14 de março de 2025. (2025). Institui a Comissão Nacional de Geoinformação (CONGEO). Diário Oficial da União. https://www.in.gov.br/en/web/dou/-/portaria-gm/mpo-n-32-de-14-de-marco-de-2025-617960249

Pugh, D. T. (1987). *Tides, Surges and Mean Sea-Level*. John Wiley & Sons.

Pugh, D. T. (2004). *Changing Sea Levels: Effects of Tides, Weather and Climate*. Cambridge University Press.

Rasmussen, C. E., & Williams, C. K. I. (2006). *Gaussian Processes for Machine Learning*. MIT Press. http://www.GaussianProcess.org/gpml

Renganathan, V. (2010). *Arctic Sea Ice Freeboard Heights from Satellite Altimetry*. [Tese de doutorado, University of Calgary]. Repositório Institucional. https://www.ucalgary.ca/engo_webdocs/AB/10.20301_VRenganathan.pdf

Ribeiro, L. C., Guimarães, G. N. do, & Marotta, G. S. (2023). Combining terrestrial, marine, and satellite gravity data to compute gravity potential values at IHRF stations. *Applied Geomatics*, *15*, 455–472. https://doi.org/10.1007/s12518-023-00507-w

Ribeiro, L. C., Marotta, G. A., & Guimarães, G. N. (2022). Analysis of marine gravity data: study to the brazilian near coast geodetic stations in the context of the International Height Reference Frame. *Geociências*, *41*(4), 943-961. https://doi.org/10.5016/geociencias.v41i04.16937

Rio, M. H., & Hernandez, F. (2004). A mean dynamic topography computed over the world ocean from altimetry, in situ measurements, and a geoid model. *Journal of Geophysical Research: Oceans*, *109*(C12).

https://doi.org/10.1029/2003JC002226

Robin, C., Nudds, S., MacAulay, P., Godin, A., De Lange Boom, B., & Bartlett, J. (2016). Hydrographic Vertical Separation Surfaces (HyVSEPs) for the Tidal Waters of Canada. *Marine Geodesy*, *39*(2), 195–222. https://doi.org/10.1080/01490419.2016.1160011

Sánchez, L. (2002). *Determinación de alturas físicas en Colombia*. Institut Für Planetare Geodäsie Technische Universität Dresden. https://www.sirgas.org/fileadmin/docs/Determinacion_de_alturas_fisicas_en_Colombia.pdf

Sánchez, L., & Sideris, M. G. (2017). Vertical datum unification for the International Height Reference System (IHRS). *Geophysical Journal International*, *209*(2), 570-586. https://doi.org/10.1093/gji/ggx025

Sánchez, L., Ågren, J., Huang, J., Wang, Y. M., Mäkinen, J., Pail, R., Barzaghi, R., Vergos, G. S., Ahlgren, K., & Liu, Q. (2021). Strategy for the realisation of the international height reference system (IHRS). *Journal of Geodesy*, *95*(3), 33. https://doi.org/10.1007/s00190-021-01481-0

Sánchez, L., Barzaghi, R., & Vergos, G. S. (2024, 4-6 de setembro). Towards a first solution for the International Height Reference Frame (IHRF). [Trabalho apresentado]. *GGHS2024 Joint Section 2, IGFS and GGOS Symposium "Gravity, Geoid and Height System 2024"*, Thessaloniki, Greece. https://ihrfcc.topo.auth.gr/wp-content/uploads/2024/10/Sanchez_etal_IHRF_Solution_GGHS2024.pdf

Santamaría-Gómez, A., Gravelle, M., Dangendorf, S., Marcos, M., Spada, G., & Wöppelmann, G. (2017). Uncertainty of the 20th century sea-level rise due to vertical land motion errors. *Earth and Planetary Science Letters*, *473*, 24-32. https://doi.org/10.1016/j.epsl.2017.05.038

Santana, F. R., Krueger, C. P., Santana, T. A., Nascimento, G. A. G., & Oliveira Junior, A. M. (2020). Cartas Náuticas com Modelos SEP: Evolução Histórica, e Perspectivas para Hidrografia Brasileira. *Revista Brasileira De Cartografia*, *72*, 1299-1328. https://doi.org/10.14393/rbcv72nespecial50anos-56616

Santana, T. A. (2024). *Desafios e perspectivas para a vinculação dos data verticais oceânicos a um referencial geodésico global*. [Tese de doutorado, Universidade Federal do Paraná]. Acervo Digital UFPR. https://acervodigital.ufpr.br/handle/1884/89992

Santana, T. A., & Dalazoana, R. (2020). Integração dos Referenciais Verticais Terrestre e Oceânico: Conceitos Relacionados, Projetos Desenvolvidos e Desafios. *Revista Brasileira De Cartografia*, *72*(2), 345-364. https://doi.org/10.14393/rbcv72n2-52611

Santana, T. A., & Dalazoana, R. (2022). Analysis of vertical reference levels in the brazilian coast: comparing local and global approaches. *Bulletin of Geodetic Sciences*, *28*(3), e2022012. https://doi.org/10.1590/s1982-21702022000300012

Santos, E. G. dos, Soares, S., & Klein, I. (2022). Avaliação da Variação Vertical Local Voltada à Integridade de Séries Temporais Maregráficas. *Revista Brasileira de Cartografia*, *74*(4), 1003-1028. https://doi.org/10.14393/rbcv74n4-66090

Seeber, G. (2003). *Satellite geodesy* (2a ed.). Walter de Gruyter.

Service Hydrographique Et Océanographique De La Marine (SHOM). (2023). *Surfaces BathyElli v2.1 Descriptif de contenu du produit externe*. https://services.data.shom.fr/static/specifications/Descriptif_Contenu_ProduitExterne_Bathyelli_v2_1.pdf

Shi, L., & Myers, E. (2016). Statistical Interpolation of Tidal Datums and Computation of Its Associated Spatially Varying Uncertainty. *Journal of Marine Science and Engineering*, *4*(4), 64. https://www.mdpi.com/2077-1312/4/4/64/pdf

Silva, V. C. (2020). *Sistema Gravimétrico de Referência do estado de São Paulo: contribuição ao referencial geodésico*. Dissertação de Mestrado, Escola Politécnica, Universidade de São Paulo, São Paulo. http://doi.org/10.11606/D.3.2020.tde-05042021-153203

Silva, R., Noernberg, M., & Lopes, A. (2024). Challenges and responses to sea level rise in the context of climate change: A case study of the Paranaguá Estuarine Complex. *Ocean and Coastal Research*, *72*(suppl 1), e24062. https://doi.org/10.1590/2675-2824072.22127

Slobbe, D. C., Verlaan, M., Klees, R., & Gerritsen, H. (2013). Obtaining instantaneous water levels relative to a geoid with a 2D storm surge model. *Continental Shelf Research*, *52*, 172-189. https://doi.org/10.1016/j.csr.2012.10.002

Slobbe, D. C., Sumihar, J., Frederikse, T., Verlaan, M., Klees, R., Zijl, F., Farahani, H. H., & Broekman, R. (2018a). A Kalman Filter Approach to Realize the Lowest Astronomical Tide Surface. *Marine Geodesy*, *41*(1), 44-67. https://doi.org/10.1080/01490419.2017.1391900

Slobbe, D. C., Klees, R., Verlaan, M., Zijl, F., Alberts, B., & Farahani, H. H. (2018b). Height system connection between island and mainland using a hydrodynamic model: a case study connecting the Dutch Wadden islands to the Amsterdam ordnance datum (NAP). *Journal of Geodesy*, *92*, 1439–1456. https://doi.org/10.1007/s00190-018-1133-3

Soares, S., Dalazoana, R., & Araki, H. (2025). Uma abordagem baseada em lógica fuzzy para o diagnóstico e planejamento da rede de nivelamento do Sistema Geodésico Brasileiro. *Revista de Geociências do Nordeste*, *11*(2), 225–240. https://doi.org/10.21680/2447-3359.2025v11n2ID40465

Souza, L. M. de, Dalazoana, R., & Santana, T. A. (2025). Estimativas da Topografia do Nível Médio do Mar na costa brasileira por meio da Altimetria por Satélites: Estimates of Average Mean Dynamic Topography on the Brazilian coast using Satellite Altimetry. *Revista de Geociências do Nordeste*, *11*(1), 922–935. https://doi.org/10.21680/2447-3359.2025v11n1ID38308

Tang, L., Shi, L., Meyers, E., Jeong, I., White, S., Riley, J., Peeri, S., Murry, N., Huang, L., Michalski, M., Fanelli, C., Hoang, C., & Graham, D. (2025). *Regional VDatum Upgrade for the U.S. West Coast: Tidal Datums, Tides Assimilation, Spatially Varying Uncertainty, and Topography of the Sea Surface* [Relatório Técnico]. NOAA Technical Memorandum NOS CS 61. https://vdatum.noaa.gov/download/publications/TM-61_VDatum_WestCoast_SVU.pdf

Tanguy, Y.-M., Jan, G., & Pastol, Y. (2014). Les références verticales maritimes en France: méthodologie de création des surfaces BATHYELLI. *Revue XYZ*, (140). https://diffusion.shom.fr/shom_downloadable/download/freelink/product_id/412/

Todd, P., Martin, R. J., & Broadbent, G. J. (2004). Infrastructure supporting mapping of tidal planes and lines. [Trabalho apresentado]. *2004 Trans Tasman Surveyors Conference*, Auckland, New Zealand. https://legacy.iho.int/mtg_docs/com_wg/IHOTC/IHOTC7/Infrastructure_Supporting_Mapping_of_Tidal_Planes_and_Lines_Paper.pdf

Tolkova, E., Tang, L., Riley, J., Jeong, I., & White, S. (2023). *VDatum Update for Chesapeake Bay, Delaware Bay, and Adjacent Waters: Tidal Datums, Sea Surface Topography, and Their Spatially Varying Uncertainties* [Relatório Técnico]. NOAA Technical Memorandum NOS CS 55. https://vdatum.noaa.gov/download/publications/noaa_48085_DS1.pdf

Torge, W., & Müller, J. (2012). *Geodesy* (4a ed.). Walter de Gruyter.

Turner, J. F., Iliffe, J. C., Ziebart, M. K., & Jones, C. (2010). Interpolation of tidal levels in the coastal zone for the creation of a hydrographic datum. *Journal of Atmospheric and Oceanic Technology*, *27*, 605–613. https://doi.org/10.1175/2009JTECHO645.1

United Kingdom Hydrographic Office (UKHO). (2015). Admiralty VORF Notes and Caveats – Version 2.2 [Relatório Técnico]. UKHO. https://data.admiralty.co.uk/portal/sharing/rest/content/items/d7b4de45ac4b4a7ca9aaecab37a59194/data

Vergos, G. S., Sánchez, L., & Barzaghi, R. (2024, 10-11 de outubro). Coordination Center for the IHRF. [Trabalho apresentado]. *GGOS Days 2024 Symposium*, Potsdam, Germany. https://ihrfcc.topo.auth.gr/wp-content/uploads/2024/10/IHRFCC_GGOSDays2024.pdf

Vignudelli, S., Cipollini, P., Roblou, L., Lyard, F., Gasparini, G. P., Manzella, G., & Astraldi, M. (2005). Improved satellite altimetry in coastal systems: Case study of the Corsica Channel (Mediterranean Sea). *Geophysical Research Letters*, *32*, L07608. https://doi.org/10.1029/2005GL022602

Vu, D. T., Bonvalot, S., Seoane, L., Gabalda, G., Remy, D., Bruinsma, S., Bidel, Y., Bresson, A., Zahzam, N., Rouxel, D., Salaün, C., Lalancette, M.-F., Forsberg, R., Jensen, T., & Jamet, O. (2024). Potential of coldatom airborne gravimetry to improve coastal gravity field and quasigeoid modelling. *Journal of Geodesy*, 98(4). https://doi.org/10.1007/s00190-024-01839-0

Woodworth, P. L., Hughes, C. W., Bingham, R. W., & Gruber, T. (2012). Towards worldwide height system unification using ocean information. *Journal of Geodetic Science*, *2*(4), 302–318. https://doi.org/10.2478/v10156-012-004-8

Wöppelmann, G., & Marcos, M. (2016). Vertical land motion as a key to understanding sea level change and variability: vertical land motion and sea level change. *Reviews of Geophysics*, *54*(1), 64–92. https://doi.org/10.1002/2015RG000502

Wöppelmann, G., Zerbini, S., & Marcos, M. (2006). Tide gauges and Geodesy: a secular synergy illustrated by three present-day case studies. *Comptes Rendus Geoscience*, *338*(14-15), 980–991. https://doi.org/10.1016/j.crte.2006.07.006

Wu, Y., Andersen, O. B., Abulaitijiang, A., Wang, B., He, X., Shi, H., Luo, Z., & Wang, H. (2025). Marine quasi-geoid enhancement from SWOT wide-swath data and its mapping of mean dynamic topography over island areas. *IEEE Transactions on Geoscience and Remote Sensing*, *63*, 4209920. https://doi.org/10.1109/TGRS.2025.3592243

Biography of the main author

Salomão Soares, born in Rio de Janeiro, 1980. He is a cartographic engineer from the State University of Rio de Janeiro (UERJ, 2003) and a master's degree in population studies and social research from the National School of Statistical Sciences (ENCE, 2006). Currently, he is a PhD student in Geodetic Sciences at the Federal University of Paraná (UFPR). He works as a technologist at the Brazilian Institute of Geography and Statistics (IBGE), in the Coordination of Geodesy. His research interests include vertical reference systems, satellite altimetry and tide gauge data analysis.