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

# Nautical Charts with SEP Models: Historic Evolution and Perspectives for the Brazilian Hydrography

## *Cartas Náuticas com Modelos SEP: Evolução Histórica, e Perspectivas para Hidrografia brasileira*

Felipe Rodrigues Santana [1], Claudia Pereira Krueger [2], Tulio Alves Santana [3], Guilherme Antonio Gomes Nascimento [4] e Aluízio Maciel Oliveira Junior [5]

1 Federal University of Parana, Graduate Program in Geodetic Sciences, Curitiba, Brazil. felipesantana33@gmail.com.
ORCID: https://orcid.org/0000-0001-6410-7999
2 Federal University of Parana, Graduate Program in Geodetic Sciences, Curitiba, Brazil. cpkrueger64@gmail.com.
ORCID: http://orcid.org/0000-0002-4839-1317
3 Federal University of Uberlandia/ Federal University of Parana, Monte Carmelo, Brazil. tulio.santana@ufu.br.
ORCID: https://orcid.org/0000-0002-4429-9409
4 Brazilian Navy, Navy's Hydrographic Center, Niteroi, Brazil. guilhermenascimento@hotmail.com.
ORCID: https://orcid.org/0000-0003-0579-2070
5 Delfos Counseling and Maritime Services, Technical Board, Niteroi, Brazil. aluizio94@outlook.com.
ORCID: https://orcid.org/0000-0003-3625-5809

Received: 08.2020 | Accepted: 11.2020

**Abstract**: Advances in high-precision GNSS techniques have allowed the reduction of vertical uncertainties in bathymetric surveys, with a better determination of the heave, the dynamic draft and the reduction of co-tidal errors. However, it is necessary to determine a separation model (SEP) between the Chart Datum and the reference ellipsoid. This article will present a historical evolution on the development of SEP models in the world across seven countries: the United States, Canada, Netherlands, Saudi Arabia, Colombia, England and Brazil. Research from foreign countries shows uncertainties in SEP models ranging from 6.6 cm to 22.6 cm in relation to the ITRF. In the case of Brazil, a pioneering study for the SEP of Guanabara Bay is described, where an average difference of 2.5 cm was found with a standard deviation of 5.1 cm between the surface generated with the traditional reduction method and by GPS-tide. For national coverage, the Alt-Bat project is presented, which provides the use of the geoid as a vertical reference for hydrodynamic models. As for the prospects, there is a virtuous cycle for port development: investment in environmental data, provides greater accuracy of SEP models and less uncertainty of surveys, providing greater draft, possibility of increased cargo flow in ports and more resources for investment. SEP models are fundamental for the gathering of information from different vertical references, providing safe navigation and management of coastal process.

**Keywords**: Hydrography. GNSS. Modeling. GPS-Tide. Satellite Altimetry.

**Resumo**: Os avanços das técnicas GNSS de alta precisão permitiram a diminuição das incertezas verticais dos levantamentos batimétricos, com uma melhor determinação do *heave*, do calado dinâmico e redução dos erros cotidais. Contudo, é necessário a determinação de um modelo de separação (SEP) entre o *Datum* da Carta Náutica (DCN) e o elipsoide de referência. Neste artigo será apresentada uma evolução histórica sobre o desenvolvimento de modelos SEP no mundo através de sete países: Estados Unidos, Canadá, Holanda, Arábia Saudita, Colômbia, Inglaterra e Brasil. O resultado das estratégias adotadas por países estrangeiros mostram incertezas de modelos SEP variando de 6,6 cm a 22,6 cm em relação ao ITRF. No caso do Brasil, é descrito um estudo pioneiro para o SEP da Baía de Guanabara, onde foi encontrada uma diferença média de 2,5 cm com um desvio padrão de 5,1 cm entre a superfície gerada com método de redução tradicional e por maré-GPS. Para uma cobertura nacional, é apresentado o projeto Alt-Bat, que prevê a utilização do geoide como referência vertical para os modelos hidrodinâmicos. Quanto às perspectivas, percebe-se um ciclo virtuoso para o desenvolvimento portuário: o investimento em dados ambientais, fornece uma maior acurácia de modelos SEP e menor incerteza dos levantamentos, propiciando maior calado, possibilidade do aumento no fluxo de cargas em portos e mais recursos para investimento. Por fim são apresentados os desafios a serem superados para a Hidrografia brasileira visando a determinação do DCN com uma acurácia de 10 cm em relação ao ITRF. Os modelos SEP são fundamentais para a integração de informações provenientes de diferentes referenciais verticais proporcionando uma navegação segura e gestão de processos costeiros.

## 1 INTRODUCTION

In 2019 the United Nations (UN) considered the period from 2021 to 2030 as the Decade of Ocean Science for Sustainable Development, having among its goals a safe, predictable, clear and productive ocean, where the maritime data could be mapped, predicted and released its resources to be explored in a sustainable way. In this context of the Blue Economy, aiming to increase the navigation's security and reduce the probability of nautical accidents, the International Hydrographic Organization (IHO) started to include the Standards for Hydrographic Surveys (S-44 6$^{th}$ edition), with stricter parameters of vertical uncertainties where the vessel's Underkeel Clearance (UKC) is critical. (IOC/UNESCO et al., 2011; UNESCO, 2019; OHI; 2020a).

Some countries already adopted these criteria in its specifications (Table 1). In Brazil, the NORMAN-25 internalizes the international's standards, although it includes those up to the Special Order (DHN, 2017).

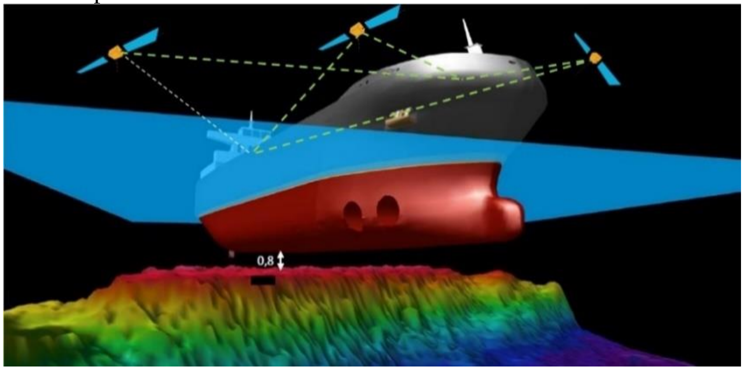
Table 1 – Minimal uncertainty standard for hydrographic surveys up to 10m deep, with a confidence level of 95%.

| **Criteria (m)** | **Order 2** | **Order 1b** | **Order 1a** | **Special Order** | **Exclusive Order** |
|---|---|---|---|---|---|
| Total vertical uncertainty | 1,03 | 0,52 | 0,52 | 0,26 | 0,17 |
| Total horizontal uncertainty | 21,00 | 5,25 | 5,25 | 2,00 | 1,00 |
| Shore line | 10 | 10 | 10 | 10 | 5 |

Source: DHN (2017) e CHS (2013).

The reduction of uncertainties of the surveys has become more important with the advent of the Electronic Chart Display and Information System (ECDIS) and of the S-10X nautical charts, in which information such as floor type, tide, wind, current and waves can be integrated in real time and the depth can be visualized dynamically. These environmental data, used together with the Global Navigation Satellite System (GNSS) high-precision techniques, such as GPS-RTK (OTF – On The Fly), allow the vessels to navigate safely according to the UKC (Figure 1), evaluating continuously the risk of contact of the vessel with the seabed, increasing its load capacity, reducing travel costs and the environment's pollution, which is already a reality in seaports such Rotterdam, in the Netherlands, and Santos, in Brazil. Nonetheless, it is urgent to establish the uncertainty level of the environmental monitoring sensors used and the available bathymetric data, as well as the frequency of the surveys (WELLS; KLEUSBERG; VANÍČEK, 1996; KRUEGER, 1996; DPC, 2019; CONAPRA, 2020).

Figure 1 – The safety margin due to the type of floor is obtained trustworthily, through the knowledge of the measurement of the water depth, of the zero level for water depth measurements, the vessel's vertical position and the pre-calculated level of water surface at sea.

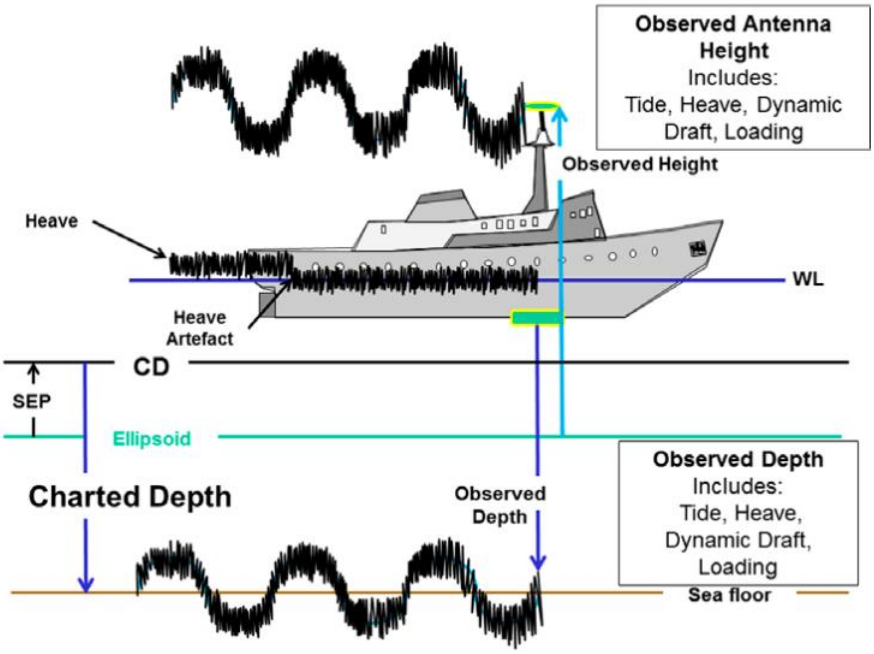


Source: FAMOS (2020)

The use of high-precision GNSS receivers allows to reduce the uncertainties of bathymetry, once it is known that heave corrections, dynamic draft and tides can be performed from the variation of the ellipsoidal height of the vessel, which reduces the co-tidal errors. These errors consist of the difference between the tide measured on the tide station and on the place where the survey is being held. Therefore, the logistic efforts of the hydrographic surveys are reduced considerably once these dismiss the necessity of maintenance of the tide stations on the shore. Therewith, the surveys became quicker, cheaper and with less data uncertainty (ZIEBART et al. 2007; RAMOS, 2007; FIG, 2014).

However, to perform the tidal reduction necessary in hydrographic surveys, through GPS tide, the development of a separation model (SEP) between the Chart Datum (CD) and the reference ellipsoid is necessary. This ellipsoid must be oriented and fixed to a particular period related to the International Terrestrial Reference Frame (ITRF) (FIG, 2006).

Figure 2 –Scheme of the vertical components involved in the hydrographic survey.



Source: FIG (2014).

Besides hydrography, SEP is also useful to integrate the terrestrial and maritime vertical references. In Brazil, for example, the bathymetric data is referenced to the Chart Datum, of the nautical chart, corresponding to the average of the spring low tides; the coastline data is collected in relation to the average of the high tide's spring (DHN, 2017); the topography data, in reference to the Mean Sea Level (MSL), observed in Imbituba-SC and Santana-AP, and materialized over the country through the Brazilian Reference Network (*RVRB – Rede Vertical de Referência do Brasil*) of the Brazilian's Geodetic System (*SGB – Sistema Geodésico Brasileiro*) (LUZ, 2016). All of them reference the tide station, determined in a specific point and period, varying from place to place, making it difficult to integrate data in large areas. Whereas the use of SEP in a coast zone allows the integration of the data to a single and stable reference, such as the Geodetic Reference System (GRS80), oriented and fixed to a specific epoch of the ITRF (FIG, 2006).

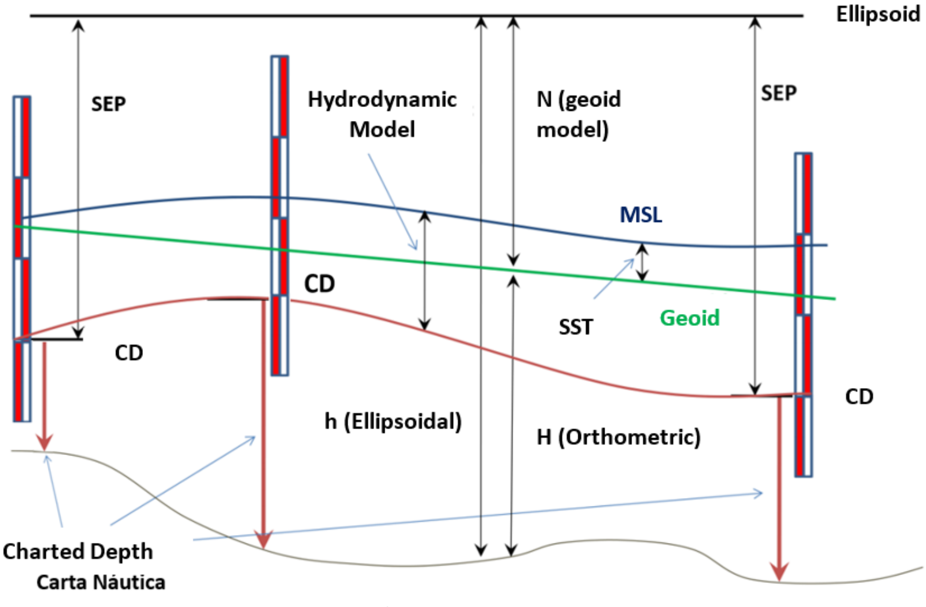
Regarding the definition of a SEP, it is possible to estimate more precise digital elevation models that are used in several purposes, such as the reconstruction of habitats, mapping of corals and the seabed, erosion studies, civil construction, measurement of the elevation of sea level, and modelling of the impact of waves and storms in the coast, flood and evacuation plans. The measurement of the change of coastline and delimitation of the maritime border can also be mentioned. In regions such as Maricá-RJ, for example, where a variation of 1.7 m was measured within a year, the accuracy of the model is essential (PARKER, 2002; OSILIERI; SEOANE; DIAS, 2020). In terms of the hydrographic surveys, the reduction of uncertainties enhances a virtuous circle for the countries' economy, since the safer the sailing is, the bigger the load movement potential in a harbor, which may contribute even more to the modernization of harbor infrastructures. In this scenario, SEP models are essential for the development of the Blue Economy of a nation. However, the investment in an infrastructure that allows obtaining constant tide, geodetic, and gravimetric data is necessary (MMA, 2018; SUPRG, 2018).

For the further development of these themes, a revision about the verticals reference surfaces that are needed to define a SEP will be presented in section 2. Section 3 will present a historical-scientific evolution over two decades with a panorama of SEP models developed around the world. Internationally, the international strategies employed by some countries to calculate the uncertainties in relation to ITRF will be explained. In the national scene, a pioneer work accomplished in 2010 by the Directorate of Hydrography and Navigation (DHN - *Diretoria de Hidrografia e Navegação*), to calculate the SEP for Guanabara Bay will be presented. In this research, a difference of 2.5 cm between the conventional reduction of the survey and the one obtained via GPS-tide was detected. Additionally, the Alt-Bat project, proposed by the Integration of Vertical Terrestrial and Maritime Components Committee (CICVTM - *Comitê de Integração dos Componentes Verticais Terrestre e Marítimos*) that foresees the adoption of the geoid as vertical reference for hydrodynamical models is presented, thus providing the national SEP for hydrographic surveys. This article presents the perspectives and challenges that Brazil needs to overcome in section 4. And in section 5 there are the final considerations about this theme.

## 2 VERTICAL REFERENCE SURFACES TO CALCULATE SEP MODELS

In coastal zones different vertical reference surfaces can be utilized for SEP determination. They can be mathematical, such as the revolution ellipsoid; or physical, resulting from the tide or the terrestrial gravitational field. In figure 3, the relation between these surfaces involving the determination of the Sea Surface Topography (SST) is noted, where SEP refers to the separation between the CD and the ellipsoid on the tide stations. The green line represents the geoid. The corrugated lines represent the SST and the CD and similar trends can be verified. This indicates that although they have a relation, the separation between these surfaces will be different from one place to another. The hydrodynamic model represents this difference. In this figure the separation between the geoid and the MSL, known as SST (FIG, 2014), is also indicated.

Figure 3 – Relation between the geoid, the ellipsoid and the Chart Datum.



Source: Adapted from DODD and MILLS (2012).

Some northern European countries, use the geoid as the vertical reference of the hydrodynamic models (ELLMER; GOFFINET, 2006) instead of the MSL. Canada (NUDDS; ROBIN; MACAULY, 2016) and the United Kingdom (ILIFFE et al., 2013) use data from satellite altimetry and ocean models, calculating the relation between the oceanic vertical reference, for example LAT (Lowest Astronomical Tide) and the CD. Other methods and details will be seen in section 3.

### 2.1 Ellipsoidal surface

The Revolution Ellipsoid is a mathematical surface, based on conventions, representations and estimations that are closest to the terrestrial surface, not to mention topography. From this surface, the ellipsoidal heights are measured through the observables transmitted by satellites. To ensure a higher accuracy, the ellipsoid must be oriented and fixed in a certain epoch of the ITRF, which materializes the terrestrial surface from a series of observations performed by several systems such as GNSS, SLR (Solar Laser Range), LLR (Lunar Laser ranger), VLBI (Very Long Baseline Interferometry) and others (SIMON, 2013).According to Altamini et al (2017), the difference between the ITRF 2008 and the ITRF 2014, at the 2010.0 period, for x, y and z axis were of 1.6mm, 1.9mm and 2.4mm. Thus, the GNSS observations over tide stations and level references, promote ellipsoidal heights (h) that allow the transformations between the terrestrial and ocean reference systems. (KEYSERS; QUADROS; COLLIER, 2015).

## 2.2 Geoidal surface

In a current definition, presented by Sánches et al. (2016) and which is based on the classical definitions of Gauss (1876) and Listing (1873), the geoid is given by $W_0$, which is the geopotential value in a level surface that is closest (regarding the least square method) to the average global sea level surface, when this is found totally calm. The value of $W_0$ agreed for the 2010.0 period and adopted in resolution by IAG (International Association of Geodesy) is 62.636.853,4 $m^2s^{-2}$ with a formal error of ±0,02 $m^2s^{-2}$ (IAG, 2015; SÁNCHEZ et al., 2016). The modelling of the gravity field is laborious and leads to an investigation based on *in-situ* surveys with relative and/or absolute superconducting gravimeters.

Besides of the *in-situ* determinations, it is possible to make observations with on-board gravimeters on aircrafts, ships and orbital platforms (PLAG et al., 2009). On this sphere, the contributions of the Challenging Mini-satellite Payload (CHAMP), Gravity Recovery and Climate Experiment (GRACE) e Gravity Field and steady state Ocean Circulation Explorer (GOCE) (FLECHTNER; SCHUH; SNEEUW, 2014) missions can be highlighted. Throughout the years, with the missions for modelling the gravity field, the bigger availability of the terrestrial geodetic observations and development of computing allowed the calculation of more than hundreds of Earth models, called Global Geopotential Models (GGM), that have the geoid and the quasi-geoid as one of the of the gravity field functional, like EGM2008 (SÁNCHEZ; SIDERIS, 2017).

## 2.3 Surface from MSL

According to Feng, Jin e Zhang (2012), sea level measurements are made by two main techniques: observations with tide stations and satellite altimetry. The tide stations fixed to the Earth crust measure the sea level in a punctual manner, whose measurements are influenced by the dynamic of the Earth crust, thus, needing corrections. (FENG; JIN; ZHANG, 2012). Besides that, it is observed that a low spatial distribution of tide gauges and the observations are made relative to the level zero of the measurement instrument.

Aiming the monitoring of sea level in regions close to the coast, estuaries or bays, Pineau-Guillou and Dorst (2012) presented a solution that consist in the use of buoys or ships equipped with GNSS receivers. Comparably, the publication from FIG (2014) describes the use of bottom mounted pressure gauges, using vessels with GNSS receivers over the bottom mounted gauges to reference its measurements to the reference ellipsoid.

The products obtained by satellite altimetry are made available by several research institutes. With the launch of the Topex/Poseidon (T/P) altimetric mission, in 1992, absolute observations of the sea level started to be done directly in the oceans and referred to a reference ellipsoid (SLOBBE; KLEES, 2012). This technique, although having loss of precision on the shore due to the ocean/continent interaction, provides a spatial covering unprecedented in the sea level observations. For example, the National Space Institute at the Technical University of Denmark (DTU Space), a Danish research institute linked to the Technical University of Denmark produces several products such as: estimations on the sea level change, global bathymetry models, global gravity field models, global ocean tide models, LAT surface model, Global Mean Sea Surface, Global Mean Dynamic Topography (DTU, 2020).

The surface models resulting from altimetric missions have loss of precision on the shore, according to what was mentioned previously, although they can be rectified by hydrodynamic models. These models describe the reaction of the water body introducing outline conditions (bathymetry and coastline) and external forces (solar/lunar system/meteoceanographic effects). It uses a set of algorithms based of the fluid dynamic, resulting from Newton's laws of movement, though they need to be calibrated by tide and meteoceanographic stations (FIG, 2014; MMA, 2018; DTU, 2020).

Thus, the Sea Surface Topography (SST) can be measured through the average of the deviation between the ocean surface in relation to the geoid, influenced by several oceanographic and meteorological conditions. It can be determined on the shore by tide stations where the average sea level was observed and leveled to the terrestrial altimetric referential; or on the ocean, by altimetric satellite, obtained by the difference between the Mean Sea Surface (MSS) and the geoid, case where it is also called Mean Dynamic Ocean Topography (MDOT) or Mean Dynamic Topography *(MDT*) (FIG, 2014).

## 2.4 Chart Datum

According to the C-32 publication from the International Hydrography Dictionary, the Chart Datum is a permanently stable surface, usually at low water, which are referenced to the surveys or tide heights, also being called as reference level or reference plan (OHI, 2020c).

Aiming the sailing security, OHI recommends that, in ocean areas under the tide influence, the Lowest Astronomical Tide (LAT) or a near similar level, to be adopted as the CD for the depth. LAT is defined as the lowest water expected to occur under average meteorological conditions and under any astronomical conditions (OHI, 2018). Simon (2013) highlights that LAT is an approximate value and that it is not possible to calculate it in a stable and accurate way, once it depends on the quality and duration of the observed data, on the correction of the meteorological and oceanographic effects, on the method used for the calculation and on the type and amplitude of the tide. However, once it is defined, it can be used as the CD.

Some countries like Canada use other reference levels, based on astronomical criteria, such as the mean of the predicted low water of each year (LLWLT - Lower Low Water, Large Tide), in a 19 years cycle (CHS, 2013). For the United States and Japan, instead of tide predictions, CD is based on the average of the lowest low water (MLLW - *Mean Lower low Water*) observed in a period called National Tidal Datum Epoch (NTDE) (NOAA, 2020a; ROEBER, 2016). In Brazilian nautical charts, CD is known as a reduction level and corresponds approximately to the mean low water springs (MLWS) (MARINHA DO BRASIL, 2020).

In the CD's definition it may occur that the register of the variation of the tide curve in a single station is not enough to represent the whole area of a hydrographic survey. An alternative would be to realize the tidal zoning, which consists of the linear interpolation or extrapolation of the data observed between two tide stations located on the edges of the area, dividing it into zones (DNH, 2017). Although, "*depending on the region this method can be imprecise once it assumes that the components that are no astronomical vary on time and space the same way the tide components."* (HESS et al., 1999, p.11). Foreign countries use other techniques, integrating tide stations; hydrodynamic and ocean global models; local geoidal models and global models of the geopotential to define the SEP.

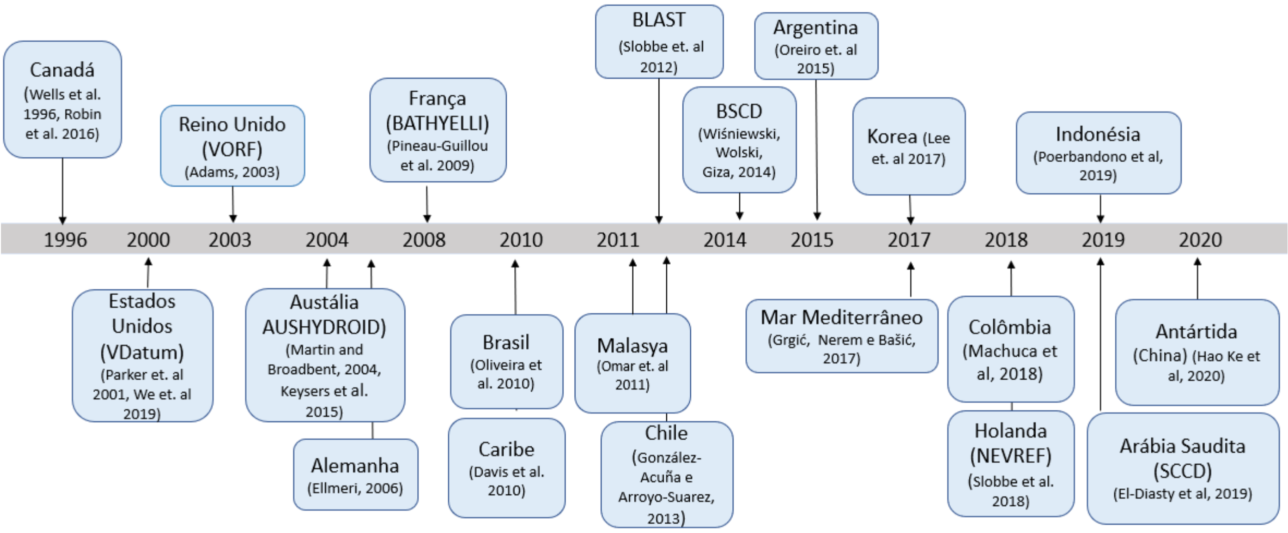
## 3 HISTORIC REVOLUTION IN TERMS OF STRATEGIES TO CALCULATE SEP MODELS

It is verified that the calculus of SEP began in the 90's, in Canada, according to Wells, Kleusberg e Vaniček, (1996). According to these authors, there is the need in the evaluation of a continuous reference surface for visualization, management and acquisition of hydrographic data on ECDIS, in a way that the system is able to inform the depths in real time to the sailor, instead of the lowest tide situation possible, as well as the uncertainties of these measures. Other authors highlight not only the significance on determining SST through hydrodynamic models and altimetric satellites, but also the significance of these models to the process management on the coastal zone. (FIG, 2014; ODAMAKI, 2003). Thus, it is highlighted the necessity of developments in terms of SEP, once in June 2020, OHI published the Guidelines for creating S-100 Product Specification - S-97, about electronic charts of the S-10X class, in which the depths can be informed in real time, in relation to different vertical references (OHI, 2020b).

The historic evolution, in terms of the main strategies developed in the SEP definition, can be grouped in two distinct periods: a creation period, comprehended from 1995 to 2010, and other of consolidation, comprehended from 2010 to 2020 (Figure 4).

On these two decades several models were developed, such as AUSHYDROID, in Australia (MARTIN; BROADBENT, 2004); the Bathyelli project in France, (PINEAU-GUILLOU et al., 2009); in the Baía da Concepcion and Golfo de Arauco, in Chile (GONZÁLEZ ACUÑA; ARROYO SUAREZ, 2013); in Rio da Prata, in Argentina (OREIRO; D'ONOFRIO; FIORE, 2016); near the borders of Singapore and Malaysia (ABDULLAH; OMAR, 2011); in the Baltic Sea (BSCD – Baltic Sea Chart Datum) (FAMOS, 2020); in the Mediterranean Sea (GRGIć, NEREM, BAšIć, 2017); or even near the King George Island, in Antarctica (KE et al., 2020).

Figure 4 – Historic-Scientific Evolution of SEP models in the world.



Fonte: The authors (2020).

In section 3.1, the strategies adopted by Canada, the United States, United Kingdon will be presented and those by northern European countries, Colombia and Saudi Arabia and posteriorly nationwide in section 3.2.

## 3.1 International Overview

### 3.1.1 PERIOD FROM 1995 TO 2010

Canada was one of the pioneers on research related to the separation models between vertical reference surfaces, beginning in 1995, in St. Lawrence, the hydrographic surveys using GPS tide. In this research throughout the canal a network of stations were established to allow the use of RTK positioning, using the Hypack software to real time navigation and measurement of GPS tide with RTK solutions. Thus, GNSS surveys in each primary tide station were performed and SEP was determined through a linear interpolation between these tide stations in relation to the Canadian Geodetic Vertical Datum of 1928. The validation of the GPS tide data was made by comparing them to the hydrodynamic model (LEFAIVRE et al., 2010).

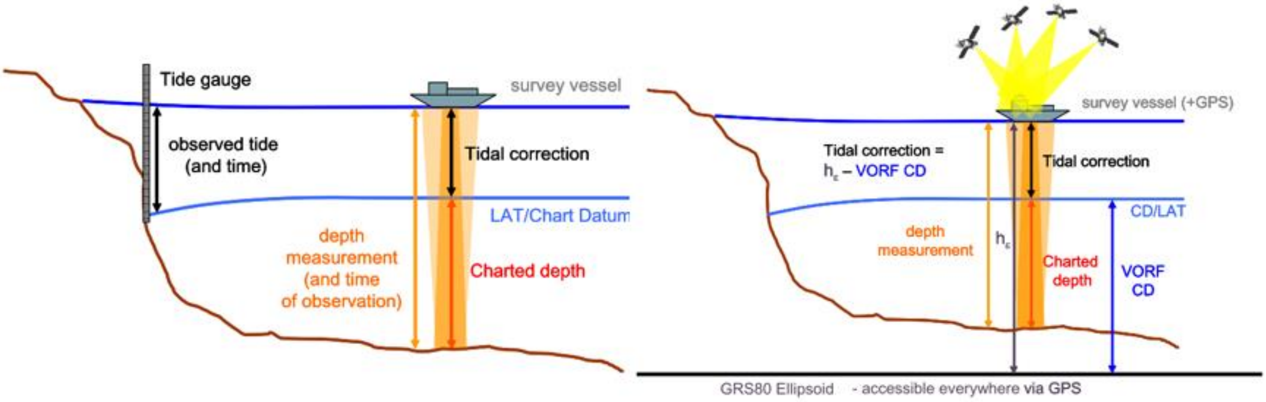
In the United States of America, the VDatum software was developed aiming to allow the conversion between three references: tide, ellipsoidal and orthometric. It is an algorithm of *Data* transformation, considered as traversing minimum spanning tree, in which each knot of the grid represents an individual Datum. The initial project was in the Tampa Bay, in Florida, with the aim to integrate bathymetry and topography. The Princeton Ocean Model hydrodynamic model was used, with a tide time series of 18.6 years and a grid varying from 100 to 1000 m. A standard deviation of 2.7 cm between the predicted data from the model and the ones observed in the region was accomplished. In the places where the models were not available or totally calibrated, as in a study carried out in the Delaware Bay, it was used the Tidal Constituent and Residual Interpolation (TCARI) technique. This technique consisted in the spatial interpolation of the range and phase of the harmonic components and the residuals originating from effects that are not related to the tide, through the numeric solution of Laplace equation (HESS, 2002; PARKER, 2002; PARKER et al., 2003; NOAA, 2004; NOAA, 2020b).

After the application of VDatum in local projects, like in *New York Bight, Puget Sound, Chesapeake Bay, New York Harbor*, the creation of a bathymetry and topography integrated database for all national territory, reaching to Alaska and Hawaii, was investigated. To do so, the strategy consisted in four steps: the bathymetry and coastline data were collected, verified and a grid of finite elements was created; the same outline conditions were applied in the advanced circulation model for oceanic, coastal and estuarine waters (ADCIRC - *ADvanced CIRCulation Model for Oceanic, Coastal and Estuarine Waters*) using computers from the National Oceanic and Atmospheric Administration (NOAA) department; the results were refined through TCARI; the data was sent to the National Geodetic Survey (NGS) for inclusion in the VDatum software with the algorithm of reference ellipsoid, the results from the geoidal model and the SST analysis (MYERS et. al., 2005; MYERS et al., 2007; NOAA 2020b).

In the northern Europe, in 2002, the Hydrographic German Service started a project to determine the CD surface in the Baltic Sea coast and reference it to the European Terrestrial Reference System 1989. GNSS surveys in references levels on the coast and in interior waters under the tidal influence waere carried out. The quasi-geoid EGG97 was used as a reference system to determine the sea level, resulting in a model of finite elements with 32 thousand knots. For each knot was determined the value of tidal range, resulting the SEP for each dot of the model's grid (ELLMER; GOFFINET, 2006).

In 2005, the UK Hydrographic Office started the project of the Vertical Offshore Reference Frame (VORF), with the aim to calculate separation models between the GRS80 ellipsoid, referenced to ERTF89 and the vertical surfaces on land and on the sea (ADAMS et al., 2006). According to Iliffe, Ziebart e Turner (2007), the data integration of tide stations and altimetric satellites was accomplished through the least squares collocation, using as a vertical reference the MSL calculated for the 2000 epoch, and data from the geoidal models OSGM02 and OSGM05, levelling, GNSS survey and data from the hydrodynamic models. According to Ziebart et al. (2007), VORF represented a revolution in the naval industry, once the offshore hydrographic surveys could be reduced without the help of tide stations or co-tidal charts (Figure 5).

Figure 5 – Comparison of bathymetry using a tide station (left) and using a GNSS and VORF (right).



Source: Adapted from ZIEBART et al. (2007).

In 2009, a group of 14 countries started the *Bring Land and Sea Together* (BLAST) project, that as one of its aims was the harmonization of CD of northern Europe. Following Germany's methodology, an equipotential surface of the Earth's gravity field was used as the vertical reference for the hydrodynamic model. With this, there was an advantage of dismissing the interpolation techniques, like the ones used in VORF, to fulfill the lack of data between the tide station and the altimetric satellite (HUGHES; BINGHAM 2008; SLOBBE et al., 2012, SLOBBE; KLEES; GUNTER, 2014; BOSCH 2016a).

### 3.1.2 PERIOD FROM 2010 TO 2020

From 2010, the VORF methodology was implemented by combining NISE10 hydrodynamic model data and the CSR4.0 Global Ocean Model, with data from tide stations of northern Europe and satellite altimetry. The Thin Plate Spline (TPS) algorithm was used for the interpolation, which resulted in an improvement of 23% in the error modelling (TURNER et al. 2010). Posteriorly, the use of seven global ocean models was evaluated aiming the LAT determination in relation to sea level, comparing data from 7.389 tide stations located in the United Kingdom (TURNER et.al. 2013). From 30 km away from the coast, it was verified that there was a decrease on the data's accuracy, however, with the use of TPS algorithm, it was obtained the standard deviation of 0.23 m. In the same year, Iliffe et al. (2013) presented the mathematical basis Eq. (1) necessary to determine the spatial uncertainty of the CD, in relation to the ERTF89 reference ellipsoid ($\sigma^2_{h_{DCN}}$). In equation 1, $k_c$ represents the degradation term calculated in function of $c$, in which $c$ is the distance to the coastline and h corresponds to the represented variable's height, in relation to ETRF89.

$$\sigma^2_{\mathrm{h_{DCN}}} = \sigma^2_{h_{LAT}} + k_c^2\sigma^2_{h_{DCN_0}} + k_c^2\sigma^2_{h_{LAT_0}} - 2k_c^2\sigma^2_{h_{LAT}} \tag{1}$$

In the USA, VDatum was also consolidated and developed from a extension of 25 to 75NM from the coast (NOAA, 2020b), Georgas, Wen and Zhao (2013), used, besides TCARI, the Spline with Barriers interpolation in the Hudson river. NOAA developed a procedure to realize the Ellipsoidal Referenced Zoned Tides (ERZT) in which, from the acquisition of data collected during a hydrographic survey, it was possible the development of new SEP models and the validation of other existing ones (RICE; RILEY, 2011). Shi, Hess and Myers (2013) used in the Chesapeake Bay the spatial interpolation method with harmonic equations of multiple orders for unstructured grids, which allowed representing in the hydrodynamic model complex regions such as water recessions and islands. In addition, Shi and Myers (2016) presented a method of statistical interpolation of tidal datum and the determination of its associated spatially varying uncertainty, which minimize a cost function similar to the assimilation of variational 3D data (3DVAR) or Optimal Interpolation (OI). This function is highly used in meteorological and oceanographic applications to integrate data from models and observations. The same authors applied this methodology in Chesapeake and Delaware Bays and found better results in relation to the interpolation when used the Laplace equation (Table 2).

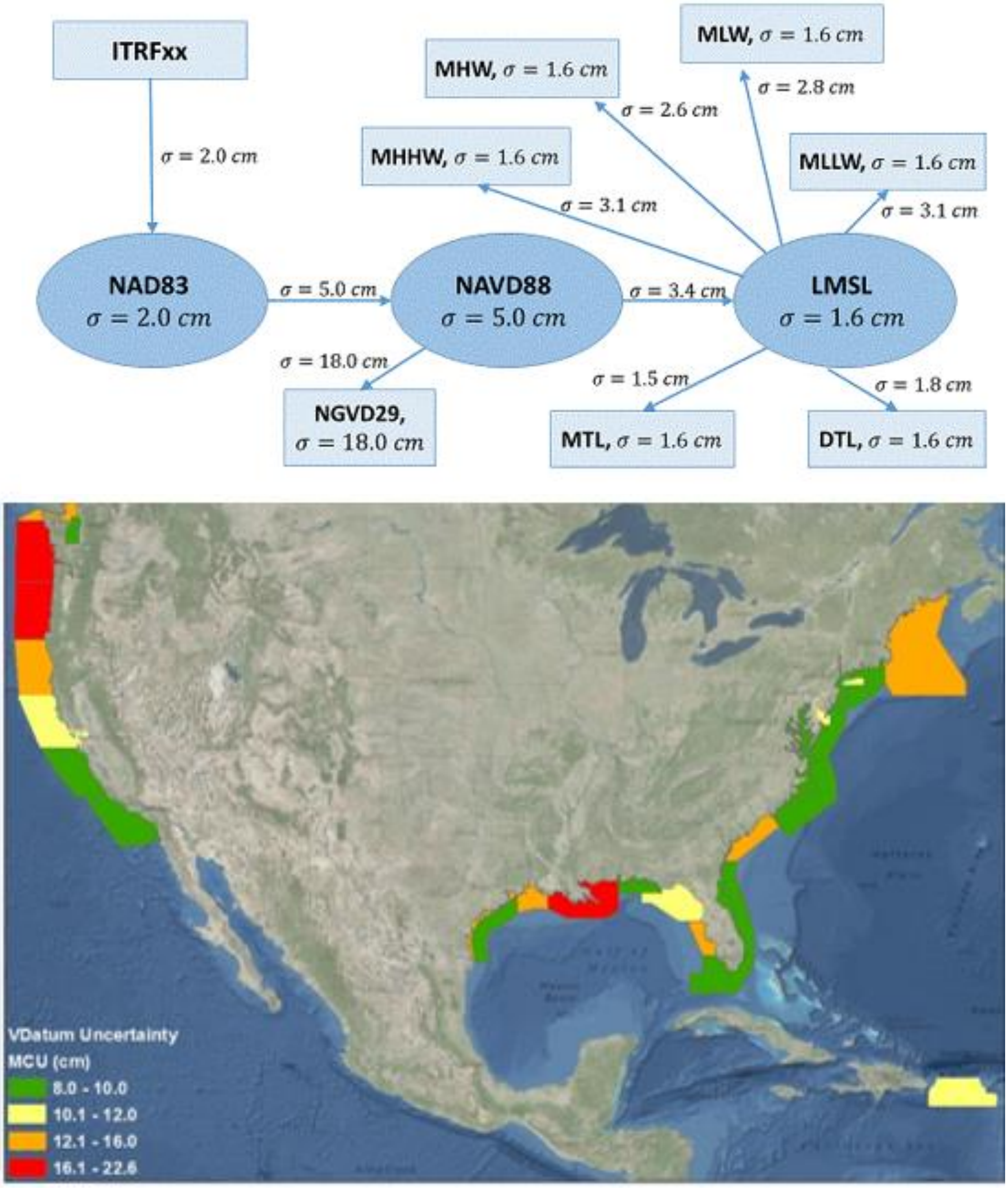
Table 2 - Case study on the Chesapeake and Delaware Bays with the measurement of 117 tide stations comparing the data observed with data from the model. Errors obtained with the application of Laplace's interpolation and statistical interpolation.

| **Result/error** | **Absolute maximum error (cm)** | **Absolute mean error (cm)** | **RMSE (cm)** |
|---|---|---|---|
| Model error | 28,35 | 4,98 | 7,0 |
| With Laplace's interpolation | 12,76 | 2,19 | 3,02 |
| With statistical interpolation | 7,63 | 1,28 | 1,86 |

Source: MYERS (2018).

In Figure 6, the calculus of the total uncertainty that is accumulated in each tidal datum in relation to a specific ITRF epoch is indicated, this calculated for the Chesapeake Bay in 2016, as well as the maximum cumulative uncertainty for each region in the United States (NOAA, 2020b).

Figure 6 – On the left diagram, the Maximum Cumulative Uncertainty (MCU) is presented. It is defined by the sum of the square roots of the individual uncertainties of each Datum and between each *Data* transformation, *as* ITRFxx, and the *North American Datum* 1983 (NAD83) ellipsoid, the orthometric *Datum* NAVD88, the Local mean sea level (LMSL) and each tidal *Datum* (MSL, MHWS and others). To the right is the MCU for each region in the USA.

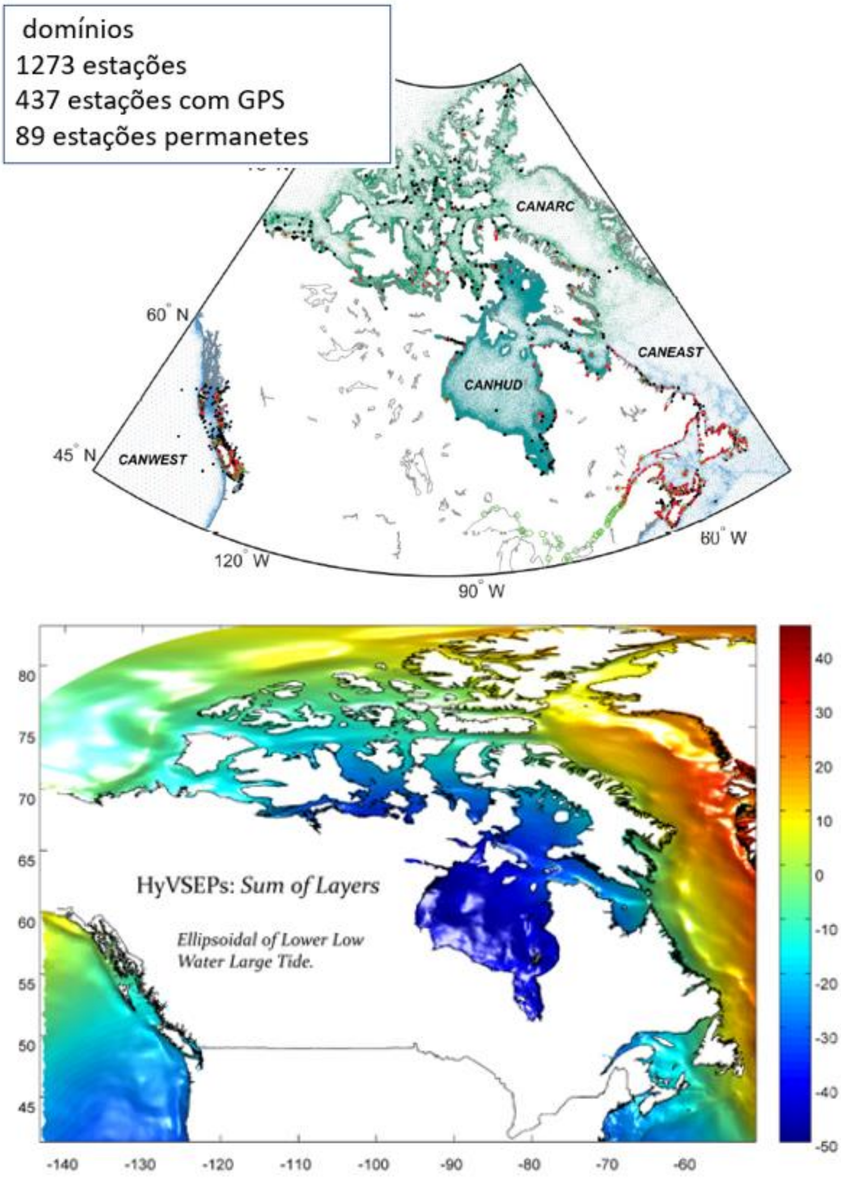


Source: MYERS (2018).

In 2010, Lefaivre et al. (2010) presented *the Continuous Vertical Datum Canadian Waters Project* (Canada) methodology. In this project a long-term planning, divided into several steps, was carried out: materialization of control points, tide and GNSS data survey and database for hydrodynamic models. The country was divided in regions with specific hydrographic aspects (Atlantic, Pacific, Quebec, Artic and Central). The works began regionally, like on St Lawrence's Gulf (ROBIN et al., 2012) and British Columbia's Coast (DE LANGE BOOM et al., 2012). In 2014, were generated, for all Canadian coast regions, Hydrographic Vertical Separation Surfaces (HyVSEPs) between the ellipsoid, the CD and other seven tide levels. Data from satellite altimetry, tide stations, dynamic ocean models (DOM), global ocean model and geoidal model – CGG2013 (with data from GRACE and GOCE satellites) were combined as layers.

VDatum and VORF's methodologies were combined using a Laplace interpolator in the unstructured grids with 30 to 100 m of resolution, besides a fine element smoother (FE). The non-linear variability while interpolating data from satellite altimetry and tide stations was also considerated. A new methodology to adjust the ocean vertical reference (LLWLT) to the local CD (LLWLT defined for an epoch) was implemented. The uncertainties from the SEP model were based on the sum of squares of individual's uncertainties of the the geoid, MDT and tide measurements– based on Iliffe (2013) and NOAA (2020b) formulations. Values in relation to ITRF equal to 7.5 cm (CANEAST), 6.9 cm (CANWEST), 6.6 cm (CANNORTH) and 17.7 (CANHUD) were found for each one of the regions (Figure 7) (ROBIN et al., 2014; ROBIN, 2016).

Figure 7 – To the left the hydrographic regions with specific characteristics and spatial distribution of the tide stations are indicated; To the right the Hydrographic Vertical Separation Surfaces.



Source: ROBIN et al. (2014) e ROBIN et al. (2016).

In the northern Europe, after the BLAST project, the Netherlands and Belgium launched the NEVREF project, aiming to calculate LAT with an accuracy of 10 cm in relation to ITRF, using the quasi-geoid as a vertical reference surface for the hydrodynamic model. In this project, LAT and quasi-geoid were calculated consistently and independently. Consistently, because for the accomplishment of both reference surfaces the same regional hydrodynamic model and the same forcing fields (tides, wind, sea level pressure, temperature, and salinity) were used. And independently, because the hydrodynamic model was used to determine the separation between the quasi-geoid and LAT and to obtain the quasi-geoid from measures of satellite altimetry. This difficulty to reference the hydrodynamic model to the quasi-geoid and the estimative of the quasi-geoid itself was solved by the following: using LAT values modelled in tide stations and hydrodynamic models, as well as gravimetry and altimetric radar data to increase the accuracy of the geoid and the MDT corrections. Thus, LAT's ellipsoidal heights were obtained with the sum of the quasi-geoidal heights to the modelled LAT values (SLOBBE; KLEES; GUNTER, 2014).

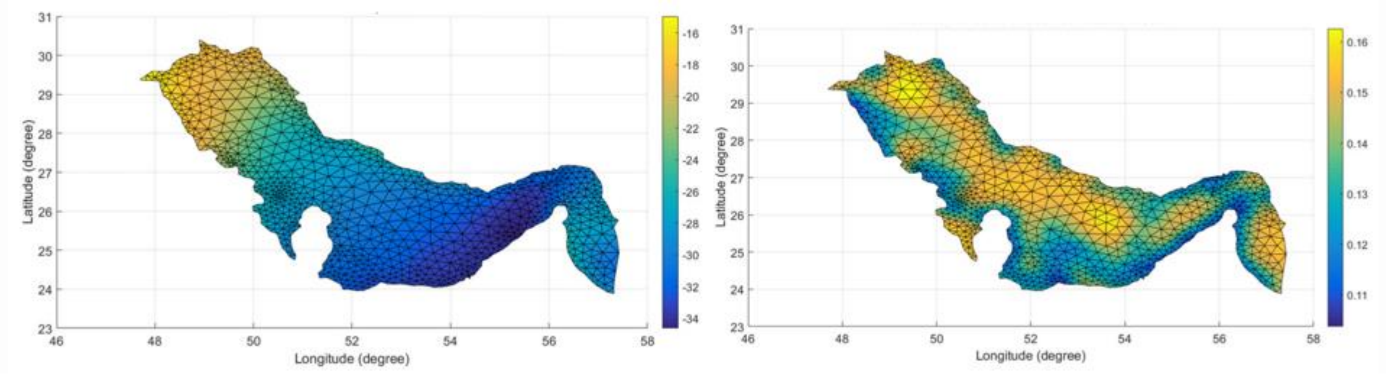
Comparing with other interpolation and calibration methodologies of models used, Slobbe et al. (2018a) stated that the Thin Spline techniques and Laplace's equations, used by Turner et al. (2010) and Robin et al. (2016), respectively, were not utilized in an ideal way. According to Slobbe et al. (2018a), the LAT in shallow waters is significantly altered by non-linear factors, thus they recommend a real time calibration and that the LAT's validation, obtained through the hydrodynamic model, would be accomplished according to Iliffe et al. (2013). When comparing, in terms of RMSE, LAT's variance obtained through the hydrodynamic model with tides stations, was found a total value of 15.1 cm.

Besides of the quasi-geoid as a reference for the hydrodynamic model, the authors suggest the use of the Kalman filter to calculate the LAT. Since this filter is a rugged estimator which weights are updated sequentially, therefore, ideal for long series of data that are susceptible to nonlinear variations, which is the case of the sea. For example, when comparing with the traditional method to calculate the LAT, for the linear solution of least squares, were found values up to 45% smallest in the British canal, in terms of RMSE.

Due to the high cost to realize marine gravimetric surveys in a short term, the hydrodynamic models DNSC06MSS-ZUNOv4 were also used by Slobbe et al. (2018b) to join the vertical references between the Wadden Sea islands and the European continent, with a resolution grid of 1/40º (E-W) and 1/60º (N-S). A discrepancy between the predicted and the observed smaller than 1 cm for 30% of the tide stations and smaller than 2 cm for 60% of the tide stations was found. It is highlighted that all tide stations had more than 18.6 years of data.

Continuing SEP's evolution, El-Diasty, Al-Harbi, Pagiatakis, (2019) developed the Saudi continuous Chat Datum (SCCD). Besides the definition of the CD in relation to ITRF, they also presented the spatial uncertainty of this measure, which had not been presented by the Netherlands. It was created to the Persian Gulf with resolution of 1/16 degrees (up to 75 NM from the shore) and 1/4 degrees (more than 75 NM from the shore). They applied the Canadian global ocean tide model WebTide TIN model, the EGM08 geoid model, the Global Mean Dynamic Topography model (MDT15DTU) and 114 tide stations on the coast, with a minimum of 1 year of observation each. The uncertainty of the SEP model was measured by the sum of geoid and the MDT's variance, and the adjustment of LAT to CD, using kriging interpolation. The final values found were between 11 and 16 cm (Figure 8).

Figure 8 – Final separation model CD – WGS84 (left); and final model uncertainty (right).

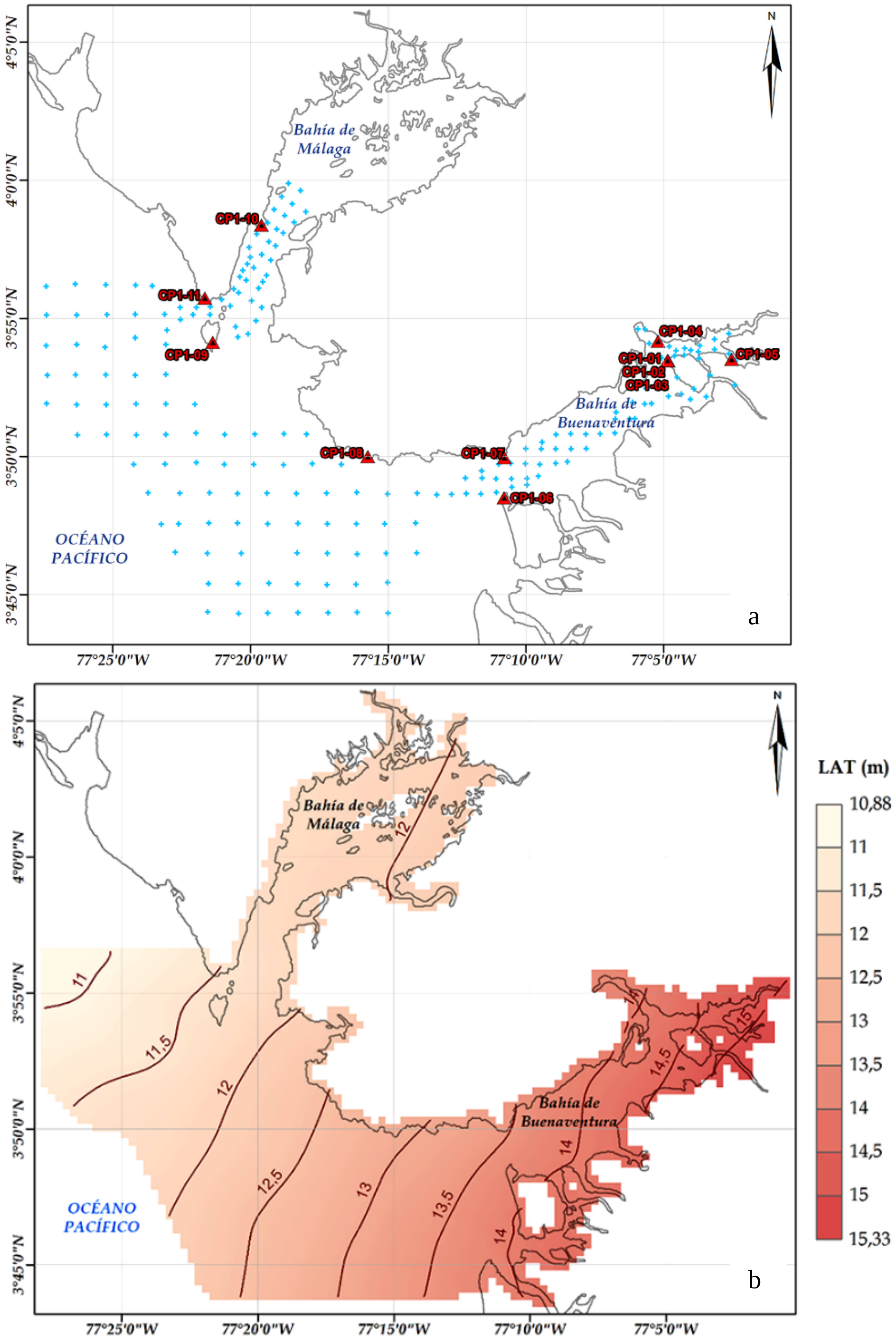


Source: EL-DIASTY, AL-HARBI e PAGIATAKIS (2019).

Besides using hydrodynamic and ocean global models, SEP can also be determined using only data from tide stations, GNSS tracking and geoidal models. For example, in Colombia, in Buenaventura and Málaga Bays, with the aim to calculate a hydrographic vertical reference surface (SHRV - *superfície hidrográfica de referência vertical*), it was stablished a first order geodetic network. This network was composed by 11 points providing support for the vertical control of the water level data of 5 tide stations. With the use of vessels, were added other 200 points through GNSS-RTK observations, these referenced to the zero of the closest tide stations (Figure 9).

For the shallow areas where the RTK survey was not viable due to the difficulty on measuring the water levels, new heights were created with the measurement of the separation between the tidal Datum and the GEOCOL2004 geoid. For the bays, the data was extrapolated, and it was used the same spatial interpolation technique through the geoid to obtain a total coverage of the area. With a resolution of 500 m, the total vertical uncertainty of the SHRV was calculated through the sum of the survey grid of the ellipsoidal heights on the water's surfaces, the materialization of the geodetic network and the vertical control of the trigonometric levelling, estimating a final value of ± 6 cm. When comparing the ellipsoidal height of the sea level Data obtained through trigonometric levelling and through GNSS-RTK, it was found an average of the differences of 5 cm with variation of -6 to 9 cm. (ALVAREZ MACHUCA et al., 2018).

Figure 9 – GNSS survey points (blue), vertex of the first order geodetic network (red) (Figure 9a); LAT's SEP model in relation to WGS-84 (Figure 9b).



Source: ALVAREZ MACHUCA et al. (2018).

## 3.2 National overview

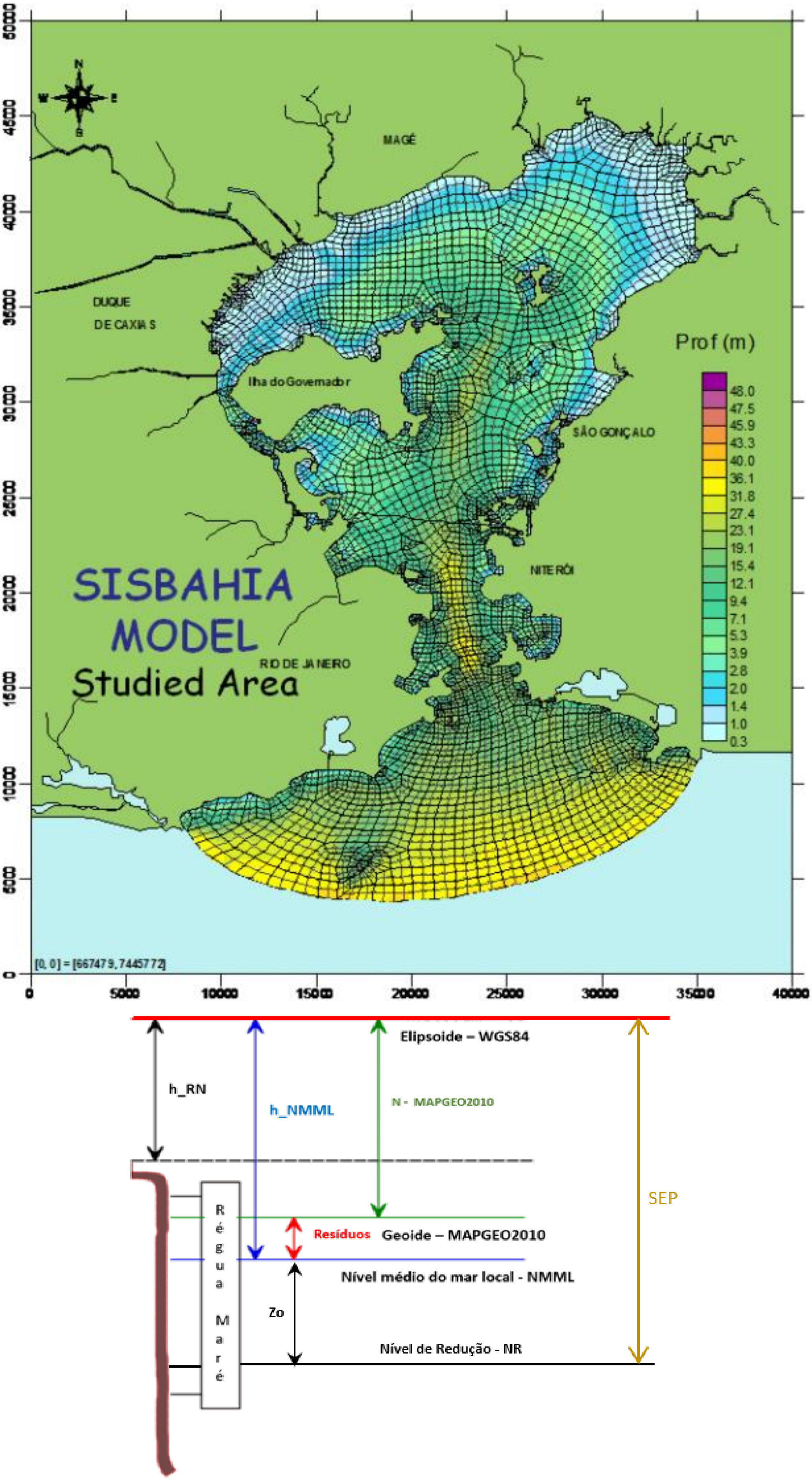
### 3.2.1 PERIOD FROM 2007 TO 2010

In Brazil, in 2007, was carried out in Guanabara Bay, Rio de Janeiro, a pilot work with the aim to lead a hydrographic survey with GPS-tide. The area comprehended the region between the tide stations of Ponta da Armação and Ilha Fiscal, which guaranteed a good knowledge of the CD and allowed to consider it constant due to the different of 2.3 cm between the values of $Z_0$ (separation between the local MSL and the CD) of the tide stations (RAMOS, 2007).

Arentz (2009) started the evaluation of the use of hydrodynamic models as a support to navigation on Amazonas's estuary, an outcome from a covenant between the Brazilian Navy and COPPE/UFRJ. The results found in the bathymetric data showed that in this small area, LAT and CD adopted in Brazil were coincident. When performing the comparison of the tidal zoning method, seen in DNH (2017), with the modelling accomplished, it was found a difference in absolute terms of 1.3 m.

In continuity to the work of Ramos (2007), Oliveira Junior et al. (2010) carried out another hydrographic survey on Guanabara's Bay, an outcome from a covenant between DNH and *Naval Oceanographic Office* (NAVOCEANO). It was used a real SEP for the whole Bay, generated from the SISBAHIA (*Sistema Base de Hidrodinâmica Ambiental – Base System of Environmental Dynamic*) hydrodynamic model of *Fundação Universidade Federal do Rio de Janeiro* and MAPGEO2010 (MATOS et al., 2012). In this methodology the difference between the LMSL (local mean sea level) and the geoid, called residual (hLMSL – N) was calculated in six tide stations. Afterwards a grid of residual values was generated using a polynomial interpolation of first order. This grid was summed to the geoid and thus, it was obtained the LMSL for the region. The ellipsoidal Heights (h_RN) of the tide stations were determined with the post-processing of the GPS data collected. The ellipsoidal height of LMSL (h_LMSL) was calculated by adding the value of h_RN to the distance of each level reference to MSL. The geoidal Heights (N) were given by MAPGEO2010 (Figure 10).

Figure 10 – Domain of the hydrodynamic model (left). With values of geoidal height (N) for each level reference it was possible to generate the geoid's residuals. (Residuals = hNMML – N) (right).

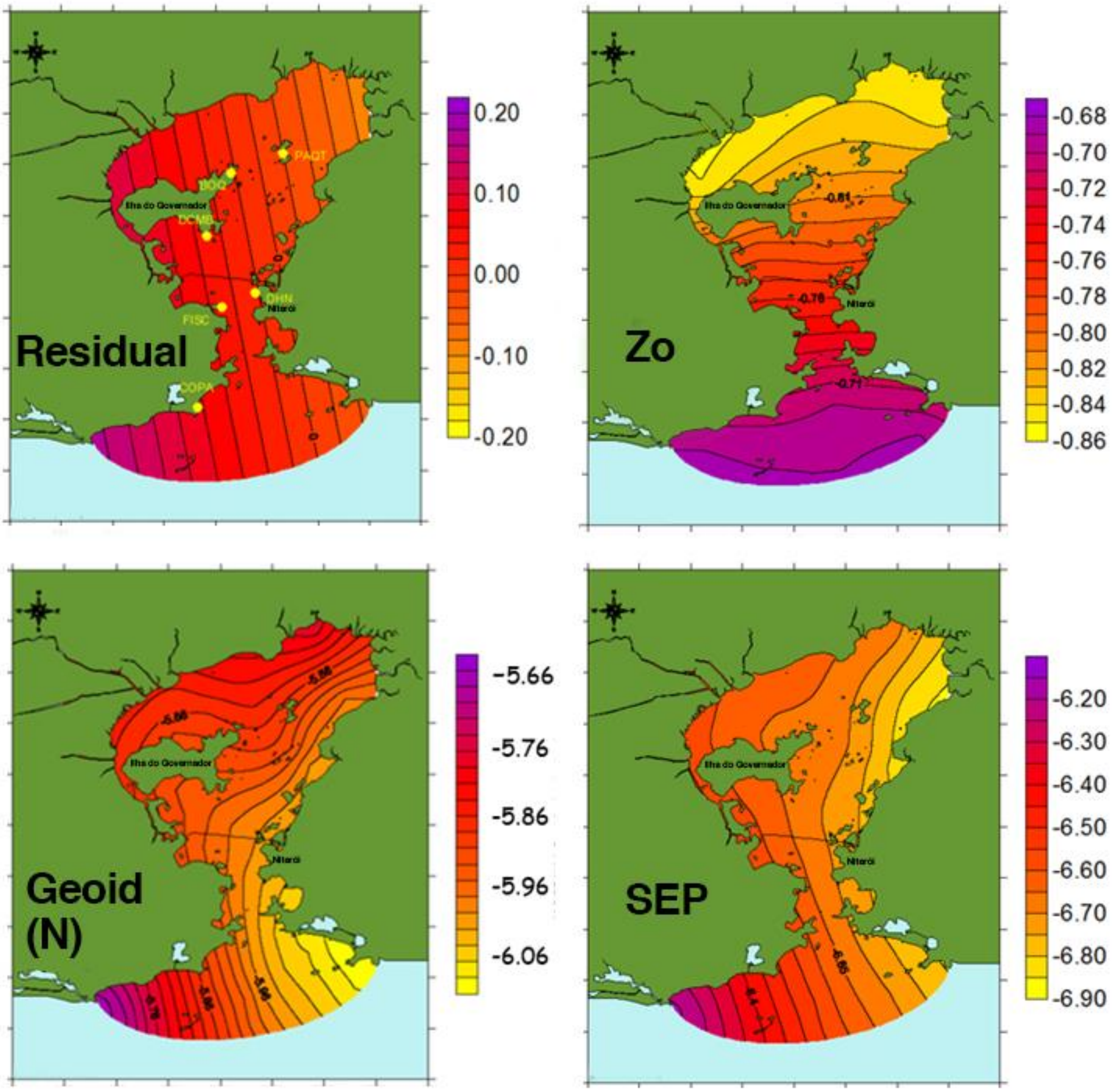


Source: OLIVEIRA JUNIOR et al. (2010).

The final separation model (SEP) between the ellipsoid and the CD was produced using Equation 2. In which $Z_0$ represents the separation from LMSL to CD, obtained for each tide station and each knot of the grid of the hydrodynamic model (Figure 11):

$$SEP = N + Z_0 + Residuals \tag{2}$$

Figure 11 – $Z_0$: Variations of the Chart *Datum* along the survey area; N: Geoidal Heights obtained by MAPGEO2010 (meters); Residuals: LMSL – Geoid MAPGEO2010 (meters) result of the six tide stations used; SEP: Separation Model (SEP) between CD and the ellipsoid.



Source: OLIVEIRA JUNIOR et al. (2010).

When comparing the bathymetrical surfaces, created using the traditional tide and GPS-tide (PPP) method, it was found an average difference of 2.5 cm, with a standard deviation of 5.1 cm. The comparison of the ADCIRC hydrodynamic model with SISBAHIA resulted in differences smaller than 5 cm in the region of the study.

### 3.2.2 PERIOD FROM 2010 TO 2020

In 2010 was given a first step to the communication of different institutions in direction to the link between topography and hydrography sectors, in relation to vertical references in coast zones, with the creation of the Integration of Terrestrial and Maritime Components Committee (CICVTM - *Comitê de Integração dos Componentes Verticais Terrestre e Marítima*), by the National Cartography Committee (CONCAR- *Comissão Nacional de Cartografia*). The accomplishment of one or two pilot studies in the Brazilian coast was also approached, as well as the necessity of technical capacitation for conducting the works and the project's funding in integrating vertical components (CONCAR, 2016).

With the conclusion of CICVTM's works, two proposals to unify vertical references were presented by Bosch (2016c). The first one adopting the MSL as reference for hydrodynamic models, used in VORF; and the second adopting a vertical stable surface, such as the quasi-geoid, used in BLAST. The response was given by National Program for CoastLine Conservation, (PROCOSTA - *Programa Nacional para a Conservação da Linha de Costa*), proposed by Ministry of the Environment (Ministério do Meio Ambiente) in 2018, having as one of the subprojects the Alt-Bat, whose objective is "*the integration of altimetric and bathymetric reference levels and the determination of the flood level as an intersection between the maximum water level projected and the topographical surface"* and follows the BLAST project line, using the geoid as a vertical reference for the hydrodynamic models (LUZ, 2018).

The methodology indicates the use of terrestrial, marine and aerial gravimetric data and data from global geopotential models, aiming the realization of a preliminary processing and calculation of a provisory geoid. In sequence, satellite altimetry information is used to refine the geoid (through vertical deviation). The coastal data will be corrected through regional hydrodynamic models referenced to the geoid, with the link of the tide stations to GNSS stations. Thus, products such as a refined geoid will be generated. Afterwards, the data from MSL, geodetic control of the tide stations (CGEM), level reference heights (RRNN) and from the geoid (N) are used aiming to calculate the MSL in relation to the ellipsoid that, through harmonical analysis, will allow to calcute LAT, as well as other surfaces (LUZ, 2018).

Alt-Bat preliminary actions were taken by Brazilian Institute of Geography and Statistics (IBGE - *Instituto Brasileiro de Geografia e Estatística*), as well as the materialization of a Coastal Reference Geodetic Network (RGRC - *Rede Geodésica de Referência Costeira*), to fulfill the gap of data between the level references of tide stations on the coast between the cities of Macaé and Niterói, where it were installed 500 level references, representing an important begining for the SEP modelling of nautical charts (SOARES et al., 2019).

Another study was done by Nascimento (2019), that compared data from ALB (Airborne LASER Bathymetry Lidar) with multibeam bathymetry in Fernando de Noronha. Using data from ellipsoidal height of only one level reference, it was found a standard deviation of the differences of 0.289 m, with a confidence interval of 95%. One of the reasons for this uncertainty was attributed to SEP's modelling.

One year later, Santana (2020) used, in a pioneer way in Brazil, LAT global models in relation to the ellipsoid, derived from satellite altimetry. In a study carried in Fortaleza and Imbituba's tide stations, found a value of 15.6 cm and 6 mm above tide stations' CD. The author pointed that the reason for these inconsistencies in comparison to local observations was due to the modelling in cost areas. Besides that, highlighted the significance of a bigger densification of tide stations in the coast with known geocentric positions to unify terrestrial and ocean references.

## 4 PERSPECTIVES AND CHALLENGES FOR THE BRAZILIAN HYDROGRAPHY

In Brazil, the accomplishment of the Alt-Bat project will have as a consequence a SEP model to national level for hydrographic surveys with GPS-tide. In the global context, it is observed a trend in the growth in the use of artificial intelligence on hydrography and navigation. The Marine Autonomous Surface Ships (MASS) are already a reality in some countries like Norway. The first tests were accomplished in 2019, revealing a new horizon for navigation, safer and more sustainable, bringing innumerous benefits, such as the minimization of human errors and the reduction of emission of pollutant gases (LI; FUNG, 2019). Algorithms such as machine and deep learning allow to identify risk areas that should be avoided by MASS, although, as well as a mathematical model needs to be validated, the algorithms need to be trained from observations, making that the accurate bathymetry data are increasingly more necessary and valuable.

Besides that, the fact that these data are referenced to the GRS80 ellipsoid, oriented and fixed to a certain epoch of ITRF, eases the integration, both on time and space. (ADAMS, 2006; HAINS, 2019).

This may be a perspective for Brazilian's hydrography, although, a big national challenge must be surpassed: the lack of a infrastructure for constant tide, geodetic and gravimetric data to calibrate the models in critical areas, where are necessary the coast management and the navigation's security (SANTANA; DALAZOANA, 2020). Bosch (2016b) presents a diagnosis of Brazil's situation and the measures that could be taken to integrate vertical and ocean references in a long term, supporting the authors O'reilly, Parsons and Langelier (1996) when affirming that "*physical reference surfaces will always need revision and the inventory of hydrographic data will grow significantly in the future"*. Thus, with calibrated hydrodynamic models, accurate geoidal models and a dense monitored terrestrial surface, it is created the necessary base for the creation of SEP models with reduced level of uncertainty, whose benefits go beyond navigation and bathymetry. As affirmed by O'reilly, Parsons and Langelier (1996, p. 8):

> Although initial focus of the vertical separation models will be directed toward the main hydrographic client surfaces (i.e high and low water datums), aiming the surveys and navigation with electronic charts that inform the depth in real time, other client services (e.g. geodetic, engineering, dredging) will eventually require appropriate separation models.

For example, the Ministry of Environment launched PROCOSTA aiming "*the modelling of the process' involved in the coast morphodynamic, the correct evaluation of flood risks on the coast and the development of the respective strategies of adaptation and mitigation of these events"* (MMA, 2018). Although, the Alt-Bat project will need a big quantity of investments for data acquisition aiming this modelling. This way, it is worth to mention some institution's' initiatives that may subsidize these perspectives.

In 2018, COPPE/UFRJ presented the project Brazil's Bays (*Baías do Brasil*), which provides an online database of the SisBAHIA model for different locations, together with its descriptive reports, being already available for Baía de Guanabara (RJ), Baía de São Marcos (MA), Baía da Babitonga (SC), Baía de Ilha Grande e Sepetiba (RJ), Estuário do Rio Paraíba do Norte (PB), Sistema Lagunar Maricá-Guarapina (RJ), Lagoa dos Patos (RS) and Porto do Açu (RJ). (COPPE, 2020).

In the same year, at the initiative of UFPR's Center of Sea Studies (CEM - *Centro de Estudos do Mar*), was implemented the Brazilian Sea Observatory (BSO) for the regions of Paraná and Santa Catarina, with a resolution varying from 120 m to 1/12º. The system uses the MOHID hydrodynamic model, with open source and it has perspectives of being attached with other local hydrodynamic models, like in the Amazonas Estuary (FRANZ et al., 2018).

In 2019, the Navy Hydrography Center (CHM - *Centro de Hidrografia da Marinha*) started to use SWAN models to propagate waves in coast areas and the ADCIRC hydrodynamic models, with a resolution of 100 m to 4 km and transportation in two and three dimensions, being already generated the models in Guanabara Bay, Ilha Grande and Sepetiba Bays, São Sebastião Canal and Ilha Bela (Baía de Guanabara, Baías de Ilha Grande e Sepetiba, Canal de São Sebastião and Ilha Bela) (SILVA, 2019).

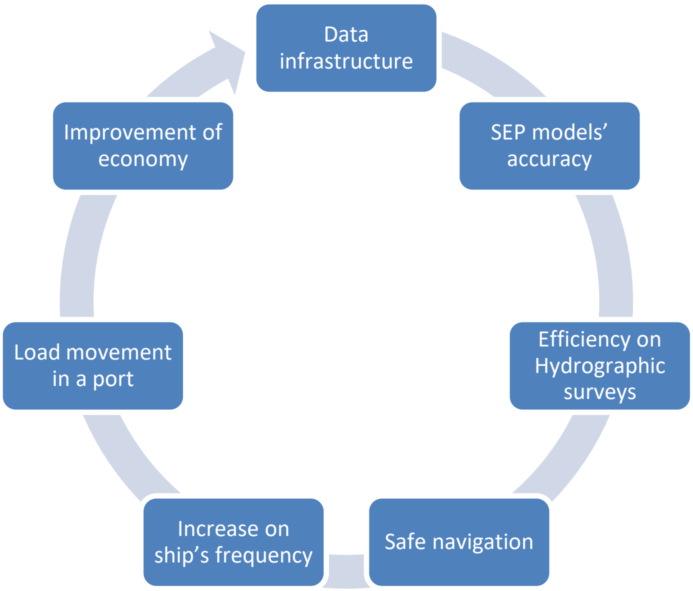
It is also mentioned the incorporation ofHydroceanographic Research Ship Vital de Oliveira (*Navio de Pesquisa Hidroceanográfico Vital de Oliveira*) to the Brazilian Navy, which had the gravimeter among its 28 scientific equipment's installed onboard, as well as the use of UAV's, announced by the Research Company of Mineral Resources (CPRM - *Companhia de Pesquisa de Recursos Minerais*), to support the projects aimed to the monitoring of all Brazilian's coast and shallow continental platform to define the coastline (CPRM, 2020).

In relation to the acquisition of data in a costal environment, it is incredibly important to evaluate the best method that can be through SAR Satellite, Lidar survey, single or multibeam bathymetry. In this sense, it is worth mentioning EMOdnet (2016) and Colin (2016), that presented the *Coastal Mapping Planner* (CMP) algorithm, that uses the Fuzzy logic to determine which survey is the most suitable according to the depth, water transparency and the equipment to be used.

On the planning step, it is also necessary to analyze the SEP modelling before colleting the data referenced to the ITRF, taking into consideration the spatial uncertainty of the geoidal model, the tide's interpolation, the SST determination and perform the corrections of the permanent tide's correction, depending on the order of the survey that it is aimed to achieve. For the SEP planning in national level, it is suggested to consult Wells, Kleusberg and Vaníček (1996), that propose the details that should be taken into consideration to its development, such as desired accuracy, model's resolution, coverage, available resources, tide station and GNSS network, storage and updating of the database, among others.

Thus, with an infrastructure of consistent data, the perspective is of a virtuous circle to the country's economy, with a bigger accuracy of SEP models and smaller uncertainties of the surveys (Figure 12). The steps of the cycle are essential in areas where the under keel clearance is measured in real time, increasing the movement of ships in port areas with more safety and efficiency, it is mentioned, for example, the ReDRAFT system, created by Argonáutica in a partnership with the Numerical Offshore Tank of University of São Paulo (TPN-USP - *Tanque de Provas Numéricos da Universidade de São Paulo*), and Santos Pilots. The system evaluates the environmental conditions in order that the maximum draft considered for the ships' maneuvers are not fixed but can vary according to the characteristics of the vessel, the type of the maneuver and the meteoceanographic conditions. In Santos, where it was implemented, the closing time of the port by the draft restrictions was of eight days in 2013, yet in 2017 it was reduced to only two days and it increased in 24% the number of maneuvers with the draft above 12 cm. A bigger draft represents bigger movement of load in the port, once the increase of 10 cm provides another thousand tons, or 65 containers for transportation (CONAPRA, 2020a; CONAPRA, 2020b; ARGONAUTICA, 2020)

Figure 12 – Virtuous circle about the importance of a data infrastructure for the port's modernization and the development of the country's economy.



Source: Based on Ziebart et al. (2007) and GERGS (2019).

To this point, it is noted that the start of the cycle is a solid infrastructure of environmental, terrestrial and ocean data. Therefore, it is worth making some inquires to orientate future works aiming the CD definition with an accuracy of 10 cm in relation to ITRF.

Challenges regarding tide data and modelling:

a) Iliffe (2013) presented the mathematical base to integrate data from satellite altimetry and tide stations, reaching an uncertainty of 10 cm around the coast. In a short term, could this methodology be applied to Brazil with this accuracy? If not, how much would be necessary to improve the data infrastructure?

b) El-Diasty (2019) used global tide models and global geopotential model to calculate the CD in relation to IRTF with an accuracy between 0.11 and 0.16 cm. In the short-term, could this methodology be applied to Brazil with this accuracy? If not, how much would be necessary to improve the data infrastructure to validate these models?

c) In the NEVREF project, Slobbe (2018) used the quasi-geoid as a vertical reference for the hydrodynamic model and the calculation of LAT, joining the vertical references between island with a sub centimetric accuracy. In the long-term, which data would be necessary to apply this methodology if Brazil were aiming to obtain this accuracy? For more details about a roadmap to follow, Slobbe (2013b) can be consulted.

d) In the VDatum project, Shi e Myers (2016) applied in the Chesapeake Bay the statistical interpolation of the uncertainty's spatial variation to determine the CD. A RMSE of 1.86 cm between the observed in tide stations and the predicted by the hydrodynamic model was obtained. How many new tide stations would be necessary to define SEP of all Brazil's estuaries with this accuracy?

e) Which financial and human resources would be necessary to install these stations, and maintain them permanently, realize the necessary maintenance according to IBGE (2019) and make the data available online for the community?

f) What would be the socioeconomic return of this investment in ten years? For the benefits' details, NOAA (2001) can be consulted.

g) In Canada a long-term planning to define SEP models was accomplished, dividing the country into specific hydrographic regions. In Brazil, which could be these regions? Which areas would be a priority to produce a database?

h) IHO recommends that the Lowest Astronomic Tide, or an equivalent level, to be adopted as CD in areas susceptible to tide effects. Slobbe et al. (2013a) found smaller depths than LAT and the LLWLT in the British canal and suggests being adopted as CD a percentual value below LAT, defined from tide stations observations for 18.6 years. If Brazil aims to change the type of CD, which should be this percentage to the Brazilian nautical charts?

i) According to Slobbe et al. (2018a), LAT in shallow waters is significantly changed by non-linear factor. How to accomplish a real time calibration of a hydrodynamic model and result in a spatial uncertainty grid of CD in relation to ITRF without using interpolation techniques?

Challenges regarding geodetic and gravimetric data:

a) The necessary data were raised in the NEVREF project to obtain a geoidal model with an accuracy of 5mm on land (FARHANI, 2017). Which should be the densification of the gravimetric data so that in Brazil the vertical reference, instead of the MSL, would be an equipotential surface with the same accuracy?

b) The tide stations are susceptible to vertical movements of Earth's crust. This way, it is asked: would the GNSS stations from RBMC be enough to model these movements with a sub centimetric accuracy? Having a negative answer, which would be the recommended places to install new stations of continuous monitoring?

c) Which financial and human resources would be necessary so that real time positioning in Brazil provides a centimetric accuracy for floating platforms, through Network-RTK or SBAS (*Sattelite Based Augmentation System*)?

d) Which areas would be a priority for gravimetric and geodetic surveys?

e) Which would be the socioeconomic return of these investments in 10 years? For the benefits' details, NGS (2001) and NGS (2013) can be consulted.

## 5 FINAL CONSIDERATIONS

Nautical charts with SEP contribute for the Decade of Ocean Science for Sustainable Development, so that the oceans can be safer, predictable, transparent and productive, in a way that sea level data allow an integrated bathymetry and topography; reduction of the hydrographic surveys' uncertainties; and navigation with a continuous surface of CD, easing the integration of hydrographic database both in time and space. Countries of continental dimensions such as the United States and Canada started locally until reaching a national coverage and the result was the calculation of the CD's surface in relation to ITRF with uncertainties close to 10 cm. Yet in Brazil, to define the CD, the technique of tidal zoning is used, that predicts an uncertainty up to 10 cm between adjacent zones, when referring to LMSL and adjusted only for small areas. Nonetheless, in 2010 initiatives to calculate the SEP of Guanabara's Bay (*Baía de Guanabara*) that may be used as subsidy for other surveys were accomplished. From Alt-Bat, there is a perspective of national coverage that, in turn, aimed to integrate terrestrial and maritime references, but its application is extended to hydrography and navigation safety.

When using the geoid as a vertical reference surface for hydrodynamic models, there is not the necessity to determine the SST, but it is necessary a bigger accuracy of the geoidal or quasi-geoidal model to be used in the country. This way, the Hydroceanographic Research Ship Vital de Oliveira may be an alternative to densify gravimetric data in the coast, being also necessary the investment on aerial, terrestrial and satellite gravimetry as a long-term project.

For the definition of the mean sea surface, MSS, the Canadian global tide model WebTideModel (section 3.1.2) were mentioned, or the global ocean model from Aviso+ (section 3.1.2), or DTU15MSS of DTU Space (section 2.3). These data are deteriorating when near the coast, but they can be adjusted by existent hydrodynamic models.

In relation to CD, it is suggested to divide Brazil in specific hydrographic regions and install a network of tide stations with known geocentric positions in areas where the navigations' safety and the coast management is critical. The definition of a National Tidal Datum Epoch of 18.6 years is also important. Besides the accomplishment of geometric levelling of tide stations during this period there is also the update of tide gauges, according to what was proposed by IBGE (2017). The use of statistical interpolation of tidal datums and computation of its associated spatially varying uncertainty on hydrodynamic models is still recommended. Finally, an interesting goal to be adopted would be the calculation of the spatial uncertainty of CD in relation of ITRF, whose uncertainties should be better than 10 cm when near the coast.

## Acknowledgments

The authors acknowledge the Brazilian Navy for granting the main author the possibility of pursuing the master's degree at at the Federal University of Paraná (UFPR), through the cooperation agreement number 87/2014 with the Navy Hydrography Center.

The Federal University of Paraná (UFPR) and the Graduate Program in Geodetic Sciences, in particular to the professor Regiane Dalazoana for the taught lessons of Basics Geodesy.

To the advices and references sent personally through e-mail: Catherine Robin and Shannon Nudds (Natural Resources Canada); Jonathan Illife (University College London); Cornellis Slobbe (Delft University of Technology); David Dodd (IIC Technologies); and Mohammed El-Diasty (King Abdulaziz University).

The revisions performed: Nikko Yumul (Ateneo of Manila University); Marcelo Benites (PPGCL/UENF); and Jorge Euriques (UFPR).

Besides the two anonymous revisors that contributed for the enhancement of this work.

## Author Contributions

Felipe Rodrigues Santana carried out the conceptualization, essay of the initial draft, essay of the final version, revision, and edition. Tulio Alves Santana: conceptualization, essay of the initial draft, assessment, edition, and bibliographic references. Cláudia Pereira Kreuger: conceptualization, assessment, revision and edition. Guilherme Antonio Gomes do Nascimento: assessment, revision and edition. Aluizio Oliveira Jr: assessment, revision and edition.

## Interests conflicts

The authors declare no conflicts of interest.

## References

ABDULLAH, M. A. B.; OMAR, A, H. Geoid Based Seamless Vertical Height Datum for Marine Cadastre Application. **Geoinformation Science Journal**, Malasya, 2011. Disponível em:< https://mafiadoc.com/queue/geoid-based-seamless-vertical-height-datum-for-_59e44c791723ddbdd515b761.html >. Acesso em: 24 jul. 2020.

ALTAMIMI, Z.; REBISCHUNG, P.; MÉTIVIER, L.; COLLILIEUX, X. **Analysis and results of ITRF2014**. 2017 (IERS Technical Note; 38) Frankfurt am Main: Verlag des Bundesamts für

Kartographie und Geodäsie, 76 pp., ISBN 978-3-86482-088-5 (print version), 2017.

ADAMS, R. The Development of a Vertical Reference Surface and Model for Hydrography – a Guide. In: XXIII INTERNATIONAL FIG CONFERENCE, 2006, Munich, Germany. **Proceedings...** Munich, Germany: UK Hydrographic Office, 2006. p. 1-13.

ALVAREZ MACHUCA, M. C. Á.; PULIDO NOSSA, D. A. P.; SOLANO TRULLO, L. J. S.; BARRERO OVIEDO, F. Construcción de la superficie hidrográfica de referencia vertical para las bahías de Buenaventura y Málaga, Pacífico colombiano. **Boletín Científico Cioh**, [s.l.], n. 36, p. 53-69, 12 dez. 2018. DOI.: 10.26640/22159045.438.

ARENTZ, M. F. R. **A Modelagem Hidrodinâmica Como Auxílio à Navegação no Canal Norte do Estuário do Amazonas**. 2009. 166 f. Dissertação (Mestrado em Engenharia Oceânica) – COPPE, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 2009.

ARGONÁUTICA. **Redraft**: Sistema de Calado Dinâmico. 2020. Disponível em:< https://argonautica.com.br/redraft/>. Acesso em: 25 jul. 2020.

BOSCH, W. Analytical Report for Integrating Hydrodynamic and Elevation Models. In: DIALOGOS SETORIAIS: UNIÃO EUROPEIA BRASIL. Rio de Janeiro, jun. 2016a. Disponível em:< https://www.concar.gov.br/temp/249@Analytical-Report_2016-07-18.pdf>. Acesso em: 25 jul. 2020.

BOSCH, W. European Experiences on Refinement, Connection, and Unification of Vertical Reference Surfaces in Coastal Zones. In: DIALOGOS SETORIAIS: UNIÃO EUROPEIA BRASIL. Rio de Janeiro, jun. 2016c. Disponível em:< https://www.concar.gov.br/temp/248@Report01final_Relat%c3%b3rio%20preliminar.pdf>. Acesso em: 25 jul. 2019.

BOSCH, W. Evaluating Technical Issues for Reconciling Continental Altimetry and Ocean Bathymetry. In: DIALOGOS SETORIAIS: UNIÃO EUROPEIA BRASIL. Rio de Janeiro, jun. 2016b. Disponível em:< https://www.concar.gov.br/temp/250@CLIM0009-EvaluationReport.pdf>. Acesso em: 25 jul. 2020.

CANADIAN HYDROGRAPHIC SERVICE (CHS). **Standards for Hydrographic Surveys**. Survey Management Guidelines. 2013. Disponível em:< https://ppa.gc.ca/sites/default/files/2018-09/CHS%20Standards%20for%20Hydrographic%20Surveys.pdf>. Acesso em: 13 jul. 2020.

COLIN, J. **Coastal Mapping Portal Demonstration**. 2020. Disponível em:< http://www.searica.eu/documents/category/26-2017-02-07?download=173:170207-joseph-colin-worldline.>. Acesso em: 30 jul. 2020.

COMISSÃO NACIONAL DE CARTOGRAFIA (CONCAR). **Comitê de Integração dos Componentes Verticais Terrestre e Marítima**. 2016. Disponível em:<https://www.concar.gov.br/detalheEntidades.aspx?cod=25>. Acesso em: 24 jul. 2020.

COMPANHIA DE PESQUISA DE RECURSOS MINERAIS (CPRM). **CPRM debate utilização de novas tecnologias nos projetos de Geologia Marinha**. 2019. Disponível em:< https://www.cprm.gov.br/publique/Noticias/CPRM-debate-utilizacao-de-novas-tecnologias-nos-projetos-de-Geologia-Marinha-5806.html>. Acesso em: 24 jul. 2020.

CONSELHO NACIONAL DE PRATICAGEM (CONAPRA). **Novo DPC, Almirante Roberto visita Praticagem do RJ e conhece o ReDRAFT**. 2020. Disponível em:< https://www.praticagemdobrasil.org.br/novo-dpc-almirante-roberto-visita-praticagem-do-rj-e-conhece-o-redraft/>. Acesso em: 24 jul. 2020.

CO-OPS. Center for Operational Oceanographic Products and Services. Tidal **Datums and their applications**. NOAA Special Publication NOS CO-OPS 1. NOAA: Silver Spring, MD, USA, 2001. Disponível em <https://tidesandcurrents.noaa.gov/publications/tidal_datums_and_their_applications.pdf>. Acesso em: 13 nov. 2020.

INSTITUTO ALBERTO LUIZ COIMBRA DE PÓS-GRAUDAÇÃO E PESQUISA EM ENHENHARIA (COPPE). **Pesquisadores da Coppe apresentam Big Data das Baías do Brasil.** 2018. Disponível em https://coppe.ufrj.br/pt-br/planeta-coppe-noticias/noticias/pesquisadores-da-coppe-apresentam-big-data-das-baias-do-brasilAcesso em: 03 nov. 2020

DANMARKS TEKNISKE UNIVERSITET (DTU). **DTU Space**. 2020. Disponível em: < https://www.space.dtu.dk/english/research/scientific_data_and_models >. Acesso em: 20 jul. 2020.

DE LANGE BOOM, B. Vertical Datum Separation Models for the British Columbia Coast. In: CHC 2012 CONFERENCE. Niagara Falls, Canada. 2012.

DIRETORIA DE HIDROGRAFIA E NAVEGAÇÃO (DHN). **Normas da autoridade marítima para levantamentos hidrográficos**. 2° Revisão. 2017. Disponível em: < https://www.marinha.mil.br/dhn/?q=pt-br/node/266 >. Acesso em: 13 jul. 2020.

DIRETORIA DE PORTOS E COSTAS (DPC). **Normas da autoridade marítima para implantação e operação de sistemas para determinação de folga dinâmica abaixo da quilha**. NORMAM-33/DPC. 2019. Disponível em: < https://www.marinha.mil.br/dpc/sites/www.marinha.mil.br.dpc/files/NORMAM-33_DPC_0.pdf >. Acesso em: 20 jul. 2020.

DODD e MILSS, 2012. Ellipsoidally Referenced Surveys Separation Models. In: FIG WORKING WEEK 2012 Rome, Italy, 6-10 May 2012.

EL-DIASTY, M.; AL-HARBI, S.; PAGIATAKIS, S. Development of Saudi continuous chart datum: arabian gulf case study. **Geomatics, Natural Hazards And Risk**, [s.l.], v. 10, n. 1, p. 1738-1749, 1 jan. 2019. DOI.: 10.1080/19475705.2019.1614682.

ELLMER, W.; GOFFINET, P. Tidal Correction Using GPS - Determination of the Chart Datum. In: XXIII FIG CONGRESS, 2006. Munich. **Proceedings...,** Munich: 2006, p. 1-14.

FARAHANI, H. H., Klees, R., & Slobbe, C. (2017). Data requirements for a 5-mm quasi-geoid in the Netherlands. **Studia Geophysica et Geodaetica**, *61*(4), p.675–702. DOI.:10.1007/s11200-016-0171-7

FÉDÉRATION INTERNATIONALE DES GÉOMÈTRES (FIG). **Ellipsoidally Referenced Surveying for Hydrography**. N. 62. Copenhagen, Denmark. 2014. Disponível em: < https://www.fig.net/resources/publications/figpub/pub62/Figpub62.pdf >. Acesso em: 20 jul. 2020.

FÉDÉRATION INTERNATIONALE DES GÉOMÈTRES (FIG). **FIG Guide on the Development of a Vertical Reference Surface for Hydrography**. N. 37. Copenhagen, Denmark. 2006. Disponível em: <https://www.fig.net/resources/publications/figpub/pub37/pub37.pdf>. Acesso em: 13 jul. 2020.

FENG, G.; JIN, S.; ZHANG, T. Coastal sea level changes in Europe from GPS, tide gauge, satellite altimetry and GRACE, 1993–2011. **Advances In Space Research**, [s.l.], v. 51, n. 6, p. 1019-1028, mar. 2013. DOI. 10.1016/j.asr.2012.09.011

FINALISING SURVEYS FOR THE BALTIC MOTORWAYS OF THE SEA (FAMOS). **Projeto FAMOS**. 2020. Disponível em:< http://www.famosproject.eu/>. Acesso em: 15 jul. 2020.

FLECHTNER, F.; SCHUH, W.-D.; SNEEUW, N. **Observation of the System Earth from Space - CHAMP, GRACE, GOCE and future missions**. Berlin: Springer, 2014. 190 p. (GEOTECHNOLOGIEN Science Report No. 20).

FRANZ, G.; LUERSEN, D.; BONATTO, B.; PALOSCHI, N.; ITALINI, D.; RODRIGO, P.; E NOERNBERG, M. Sistema Operacional de Modelagem Hidrodinâmica para a Plataforma Sudeste do Brasil Observatório do Mar. In: XIII SIMPÓSIO SOBRE ONDAS, MARÉS, ENGENHARIA OCEÂNICA E OCEANOGRAFIA POR SATÉLITE. Arraial do Cabo, Brazil. 2018.

GEORGAS, N.; WEN, B.; ZHAO, Y. **Calculation of vertical tidal datums for the tidal Hudson River north of Yonkers, New York**. Relatório Técnico Final. Stevens Institute of Technology. Disponível em: < https://web.stevens.edu/ses/documents/fileadmin/documents/pdf/Final_Report_20131220.pdf>. Acesso em: 30 jul. 2020.

GONZÁLEZ ACUÑA, J.; ARROYO SUAREZ, E. N. **Comparative methodologies for sounding reduction applied to a bathymetric survey referenced to the WGS84 ellipsoid , executed in Concepcion Bay and Gulf of Arauco, VIII region, Chile**. 2013. Disponível em:<

https://www.yumpu.com/en/document/view/15374601/comparative-methodologies-for-sounding-reduction-applied-to-a->. Acesso em: 24 jul. 2020.

GOVERNO DO ESTADO DO RIO GRANDE DO SUL. Plano de Desenvolvimento e zoneamento. Porto Alegre, 2019. Disponível em: <http://antigo.infraestrutura.gov.br/images/SNP/planejamento_portuario/pdz/pdz24.pdf>. Acesso em: 01 nov. 2020.

GRGIć, M.; NEREM, R. S.; BAŁIć, T. Absolute Sea Level Surface Modeling for the Mediterranean from Satellite Altimeter and Tide Gauge Measurements. **Marine Geodesy**, [s.l.], v. 40, n. 4, p. 239-258, 22 jun. 2017. DOI.: 10.1080/01490419.2017.1342726.

HAINS, D. Success Depends on the Quantity and Quality of All Available Data. Preparing for Hydrographic Artificial Intelligence Network and Systems. **Hydro international**. p. 16-17, july/august, 2019.

HESS, K. W. Spatial Interpolation of Tidal Data in Irregularly-shaped Coastal Regions by Numerical Solution of Laplace's Equation. **Estuarine, Coastal And Shelf Science**, [s.l.], v. 54, n. 2, p. 175-192, fev. 2002. DOI.: 10.1006/ecss.2001.0838.

HUGLES, C. W.; BINGHAM, R. J. An Oceanographer’s Guide to GOCE and the Geoid. **Ocean Science**, [s.l.], v. 4, n. 15, p.15-29, 2008.

ILIFFE, J. C.; ZIEBART, M. K.; TURNER, J. F.. A New Methodology for Incorporating Tide Gauge Data in Sea Surface Topography Models. **Marine Geodesy**, [s.l.], v. 30, n. 4, p.271-296, 7 nov. 2007. DOI. 10.1080/01490410701568384.

ILIFFE, J. C.; ZIEBART, M. K; TURNER, J. F.; TALBOT, A. J.; LESSNOFF, A. P. Accuracy of vertical datum surfaces in coastal and offshore zones. **Survey Review**, [s. l.], v. 45, n. 331, p. 254-262, jul. 2013. DOI.: 10.1179/1752270613y.0000000040.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE). **Especificações e Normas para Levantamentos Geodésicos associados ao Sistema Geodésico Brasileiro**. Rio de Janeiro. 2017. Disponível em: <ftp://geoftp.ibge.gov.br/metodos_e_outros_documentos_de_referencia/normas/normas_levantamentos_geodesicos.pdf>. Acesso em: 27 dez. 2019

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE). **Reajustamento da Rede Altimétrica com Números Geopotenciais 2018**. Rio de Janeiro: IBGE, 2018. Disponível em: <ftp://geoftp.ibge.gov.br/informacoes_sobre_posicionamento_geodesico/rede_altimetrica/relatorio/relatorio_REALT_2018.pdf>. Acesso em: 24 jul. 2020.

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION OF UNESCO (IOC/UNESCO); INTERNATIONAL MARITIME ORGANISATION (IMO); FOOD AND AGRICULTURE ORGANIZATION OF UNITED NATIONS (FAO); UNITED NATIONS DEVELOPMENT PROGRAMME (UNDP). **A Blueprint for Ocean and Coastal Sustainability**. Paris. 2011. Disponível em: < https://www.undp.org/content/dam/undp/library/Environment%20and%20Energy/Water%20and%20Ocean%20Governance/interagency_blue_paper_ocean_rioPlus20.pdf>. Acesso em: 20 jul. 2020.

INTERNATIONAL ASSOCIATION OF GEODESY (IAG). **Resolution (No. 1) for the definition and realization of an International Height Reference System (IHRS).** München, Alemanha, 2015. Disponível em: <https://iag.dgfi.tum.de/fileadmin/IAG-docs/IAG_Resolutions_2015.pdf>. Acesso em: 13 jul. 2020.

KE, H.; LI, F.; AI, S.; LEI, J.; WANG, Z.; ZHANG, S. Establishment of Chart Datum and Vertical Datum Transformation for Hydrography in the Chinese Great Wall Bay, Antarctic Peninsula. **Journal Of Surveying Engineering**, [s.l.], v. 146, n. 2, p. 1-12, maio 2020. DOI.: 10.1061/(asce)su.1943-5428.0000312.

KEYSERS, J.H.; QUADROS, N.D.; COLLIER, P.A. Vertical datum transformations across the Australian littoral zone**. Journal of Coastal Research**, Coconut Creek, v. 31, n. 1, p. 119-128, 2015.

KRUEGER, C. P. **Investigações sobre aplicações de alta precisão do GPS no âmbito marinho**. 1996. 288 f. Tese (Doutorado em Ciências Geodésicas) – Setor de Ciências da Terra, Universidade Federal do Paraná, Curitiba, 1996.

LEE, W.; CHOI, Y.; HAN, K.; PARK, H. Construction of Tidal Datums Based on Ellipsoid Using Spatial Interpolation. In: FIG WORKING WEEK 2017. Helsinki, Finland. 2017.

LEFAIVRE, D.; GODIN, A.; DODD, D.; HERRON, T. The Continuous Vertical Datum Canadian Waters Project (Beginnings, Vision, Methods and Progress). In: CHC 2010 CONFERENCE. Quebec, QC, Canada. 2010.

LI, S.; FUNG, K.S. Maritime autonomous surface ships (MASS): implementation and legal issues. **Maritime Business Review**, [S.l.], v. 4, n. 4, p. 330-339, 18 nov. 2019. DOI.: 10.1108/mabr-01-2019-0006.

LUZ, R. T. Cálculo de altitudes científicas e sua aplicação no reajustamento da Rede Altimétrica de Alta Precisão do Sistema Geodésico Brasileiro. **Revista Brasileira de Geografia**, Rio de Janeiro, v. 61, n. 1, p.79-97, jun. 2016.

LUZ, R. Vinculação entre os níveis de referência altimétricos e batimétricos para o posicionamento vertical onshore e offshore e o estudo dos impactos da elevação do NMM na zona costeira. In: VII SIMGEO. Recife, Brasil. 09 de Novembro de 2018.

MARINHA DO BRASIL. Centro de Hidrografia da Marinha. **Sondagem Batimétrica**. 2020. Disponível em: < https://www.marinha.mil.br/chm/dados-do-segnav-lev-hidro/sondagem-batimetrica>. Acesso em: 24 jul. 2020.

MARTIN, R. J.; BROADBENT, G. J. Chart Datum for Hydrography. **The Hydrographic Journal**, [s.l.], n. 112, p. 9-14, abril. 2004.

MATOS, A. C. O. C.; BLITZKOW, D.; GUIMARÃES, G. DO N.; LOBIANCO, M. C. B.; COSTA, S. M. A. Validação do MAPGEO2010 e comparação com modelos do geopotencial recentes. Boletim de Ciências Geodésicas, Curitiba, v. 18, n. 1, p. 101–122, 2012. DOI.: 10.1590/s1982-21702012000100006.

MINISTÉRIO DO MEIO AMBIENTE (MMA). **Programa Nacional para Conservação da Linha de Costa – PROCOSTA**. Brasília: MMA, 2018. Disponível em: < https://www.mma.gov.br/publicacoes/gestao-territorial/category/197-gest%C3%A3o-costeira-procosta.html?download=1443:programa-nacional-para-conserva%C3%A7%C3%A3o-da-linha-de-costa >. Acesso em: 24 jul. 2020.

MYERS, E. VDatum Development, Upgrades, and Future. In: ADCIRC USERS GROUP MEETING 2018. [s.l.]. Maio, 2018. Disponível em: < https://cdr.lib.unc.edu/concern/scholarly_works/x920g2067 >. Acesso em: 29 jul. 2020.

MYERS, E.; HESS, K.; YANG, Z.; XU, J.; WONG, A.; DOYLE, D.; WOOLARD, J.; WHITE, S.; LE, B.; GILL, S.; HOVIS, G. VDatum and strategies for national coverage. In: MARINE TECHNOLOGY SOCIETY/IEEE OCEANS CONFERENCE, 2007. Vancouver, British Columbia, Canada. **Proceedings...,** Vancouver, British Columbia, Canada, 2007, p. 1-8.

MYERS, E.P.; WONG, A.; HESS, K.; WHITE, S.; SPARGO, E.; FEYEN, J.; YANG, Z.; RICHARDSON, P.; AUER, C.; SELLARS, J. Development of a national VDatum, and its application to sea level rise in North Carolina. In: THE U. S. HYDROGRAPHIC CONFERENCE, 2005. San Diego, CA, USA. **Proceedings...,** San Diego, CA, USA, 2005, p. 29-31.

NASCIMENTO, G. A. G. **Verificação da Aplicabilidade de Dados Obtidos por Sistema Laser Batimétrico Aerotransportado à Cartografia Náutica**. 2019. 112 f. Dissertação (Mestrado em Ciências Cartográficas) – Faculdade de Ciências e Tecnologia, Universidade Estadual “Júlio de Mesquita Filho”, Presidente Prudente, 2019.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA). **Documentation for VDatum (and the Datum Tutorial)**. Vertical Datum Transformation Software Version 1.06. 2004. Disponível em: <https://vdatum.noaa.gov/download/publications/2002_milbert_VDatum106.pdf>.

Acesso em: 20 jul. 2020.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA). **Mapping and Charting**. 2020a. Disponível em:< https://tidesandcurrents.noaa.gov/mapping.html >. Acesso em: 25 fev. 2020.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA). **VDATUM**. 2020b. Disponível em:< https://vdatum.noaa.gov/ >. Acesso em: 15 jul. 2020.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA). **VDATUM: Webinar Séries**. 2018. Disponível em:< https://geodesy.noaa.gov/web/science_edu/webinar_series/vdatum_01-11-18.shtml>. Acesso em: 29 jul. 2020.

NUDDS, S.; ROBIN, C.; MACAULAY, P. Continuous vertical datum separations for Canadian Waters: Creating Canada's first hydrographic vertical separation surfaces. **Sea Technology**, v. 57, n. 9, p. 38–42, 2016.

NGS. National Geodetic Survey. **Socio-Economic Benefits Study: Scoping the Value of CORS and GRAV-D.** 2009. Disponível em <:https://www.ngs.noaa.gov/PUBS_LIB/Socio-EconomicBenefitsofCORSandGRAV-D>. Acesso em: 13 nov. 2020.

NGS. **Ten years strategic plan 2013 – 2023.** Positioning America For the Future. 2013. Disponível em<https://www.ngs.noaa.gov/web/news/Ten_Year_Plan_2013-2023.pdf. >. Acesso em: 13 nov. 2020.

O'REILLY, C.; PARSONS, S.; LANGELIER. A Seamless Vertical Reference Surface for Hydrographic Data Acquisition and Information Management. In: CANADIAN HYDROGRAPHIC CONFERENCE. Jun. 1996. p. 26-33.

ODAMAKI, M.; NAKAMURA, H. **Proposal on Integrated Database of Sounding Depth, Height and Mean Sea Level on Reference Ellipsoid, and A Trial of Time Variable Depth Display on ECDIS**. Relatório Técnico. Disponível em: < https://www.oceandocs.org/handle/1834/16587>. Acesso em: 20 jul. 2020.

OLIVEIRA JUNIOR, A. M.; ARROYO, E. N. S.; RAMOS, A. M.; ARENTZ, M. F. R. Seabed Mapping on an Earth Centered Earth Fixed (ECEF) Geocentric Reference Frame. Cooperative Validation with US Navy and Brazilian Navy in Guanabara Bay, Rio de Janeiro. In: ION GNSS 2010 CONFERENCE. Portland OR USA. September 21 - 24, 2010.

OREIRO, F.; D'ONOFRIO, E.; FIORE, M. Altimetric Reference Connection of Nautical Charts And WGS84 Ellipsoid For The Río de La Plata. **Geoacta**, Buenos Aires, v. 40, n. 2, p. 109--120, 2016.

ORGANIZAÇÃO HIDROGRÁFICA INTERNACIONAL (OHI). **IHO Guidelines for Creating S-100 Product Specifications**. Principauté de Monaco. 2020b. Disponível em:< https://iho.int/en/s-100-based-product-specifications >. Acesso em: 20 jul. 2020.

ORGANIZAÇÃO HIDROGRÁFICA INTERNACIONAL (OHI). **IHO Standards for Hydrographic Surveys**. Principauté de Monaco. 2020a. Disponível em:< https://iho.int/uploads/user/pubs/Drafts/S-44_Edition_6.0.0-Final.pdf >. Acesso em: 29 jul. 2020.

ORGANIZAÇÃO HIDROGRÁFICA INTERNACIONAL (OHI). **S-32 IHO Hydrographic Dictionary**. Principauté de Monaco. 2020c. Disponível em:< http://iho-ohi.net/S32/engView.php?quick_filter=tide+heights&quick_filter_operator=Contains>. Acesso em: 06 ago. 2020.

OSILIERI, P. R. G.; SEOANE, J. C. S.; DIAS, F. F. Coastal Vulnerability Index revisited: a case study from maricá, rj, brazil. **Revista Brasileira de Cartografia**, Uberlândia, v. 72, n. 1, p. 81-99, 30 mar. 2020. DOI.: 10.14393/rbcv72n1-47025.

PARKER, B. The Integration of Bathymetry, Topography and Shoreline and the Vertical Datum Transformations behind It. **International Hydrographic Review**, v. 3, n. 3. p. 14-26. 2002.

PARKER, B.; MILBERT, D.; HESS, K.; GILL, S. **National Vdatum - The Implementation of a National Vertical Datum Transformation Database**. National Ocean Service. 2003. Disponível em:< https://vdatum.noaa.gov/download/publications/2003_parker_USHydro_nationalvdatum.pdf>. Acesso em: 20 jul. 2020.

PINEAU-GUILLOU, L. **Set-up of CD using spatial altimetry and GPS**. 2009. Disponível em:< https://legacy.iho.int/mtg_docs/com_wg/IHOTC/TWLWG%201/France.pdf >. Acesso em: 24 jul. 2020.

PINEAU-GUILLOU, L.; DORST, L. Creation of Vertical Reference Surfaces at Sea Using Altimetry and GPS. In: ALTAMIMI, Z.; COLLILIEUX, X. **Reference Frames for Applications in Geosciences**. v. 138, 2012. p.229-235. DOI. 10.1007/978-3-642-32998-2.

PLAG, H-P.; BEUTHER, G.; GROSS, R.; HERRING, T. A.; RIZOS, C.; RUMMER, R.; SAHAGIAN, D.; ZUMBERGE, J. Introduction. In: Plag, H-P. Pearlman, M. **The Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020**. New York: Springer, 2009. p. 1-13. DOI: 10.1007/978-3-642-02687-4.

RAMOS, A. M. **Aplicação, Investigação e Análise da Metodologia de Reduções Batimétricas Através do Método GPS Diferencial Preciso**. 2007. 227 f. Dissertação (Mestrado em Ciências Geodésicas) – Setor de Ciências da Terra, Universidade Federal do Paraná, Curitiba, 2007.

REIS, V. P.; BARBOSA, L. G.; PALMEIRO, A. S. Determinação da topografia do nível médio do mar com altimetria por satélites. **Revista Brasileira de Geomática**, Curitiba, v. 6, n. 2, p. 77, 21 maio 2018. DOI.: 10.3895/rbgeo.v6n2.5517.

RICE, G.; RILEY, J. Measuring the Water Level Datum Relative to the Ellipsoid During Hydrographic Survey. In: U. S. HYDROGRAPHIC CONFERENCE, 2011. **Proceedings...** Tampa, Florida, 2011, p. 1-11.

ROBIN, C.; GODIN, A.; MACAULAY, P.; DE LANGE BOOM, B.; LEFAIVRE, D.; HERRON, T.; SINNOTT, D.; BALLANTYNE, A.; MALTAIS, L.; VÉRONNEAU, M. The Canadian Hydrographic Continuous Vertical Datum: Methodology and Accuracy. In: CHC 2012 CONFERENCE. Niagara Falls, Canada. 2012.

ROBIN, C.; MACAULAY, P.; NUDDS, S.; GODIN, A.; DE LANGE BOOM, B.; BARTLETT, J.; MALTAIS, L.; HERRON, T.; CRAYMER, M.; VÉRONNEAU, M.; FADAIE, K. Modeling tidal water levels for Canadian coastal and offshore waters: implications for coastal change and adaptation. In: AGU FALL MEETING SAN FRANCISCO, December 15-19, 2014. Paper NH53A-3876.

ROBIN, C.; NUDDS, S.; MACAULAY, P.; GODIN, A.; DE LANGE BOOM, B; BARTLETT, J. Hydrographic Vertical Separation Surfaces (HyVSEPs) for the Tidal Waters of Canada. **Marine Geodesy**, [s.l.], v. 39, n. 2, p. 195-222, 3 mar. 2016. DOI.: 10.1080/01490419.2016.1160011.

SÁNCHEZ, L.; CUNDERLÍK, R.; DAYOUB, N.; MIKULA, K.; MINARECHOVÁ, Z.; SÍMA, Z.; VATRT, V. VOJTÍSKOVÁ, M. A conventional value for the geoid reference potential $W_0$. **Journal of Geodesy**, [s.l.], v. 90, n. 9, p.815-835, 23 maio 2016. DOI.10.1007/s00190-016-0913-x.

SÁNCHEZ, L.; SIDERIS, M. G. Vertical *datum* unification for the International Height Reference System (IHRS). **Geophysical Journal International**, [s.l.], p.570-586, 21 jan. 2017. DOI. 10.1093/gji/ggx025.

SANTANA, T. A. **Contribuições para os Estudos de Integração das Componentes Verticais Terrestre e Marinha ao Longo da Costa Brasileira**. 2020. 140 f. Dissertação (Mestrado em Ciências Geodésicas) – Setor de Ciências da Terra, Universidade Federal do Paraná, Curitiba, 2020.

SANTANA, T. A.; DALAZOANA, R.. Integração dos Referenciais Verticais Terrestre e Oceânico: conceitos relacionados, projetos desenvolvidos e desafios. **Revista Brasileira de Cartografia**, Uberlândia, v. 72, n. 2, p. 345-364, 22 jun. 2020. DOI.: 10.14393/rbcv72n2-52611.

SHI, L.; HESS, K. W.; MYERS, E. P. Spatial Interpolation of Tidal Data Using a Multiple-Order Harmonic Equation for Unstructured Grids. **International Journal Of Geosciences**, [s.l.], v. 04, n. 10, p. 1425-1437, 2013. DOI.: 10.4236/ijg.2013.410140.

SHI, L.; MYERS, E. Statistical Interpolation of Tidal Datums and Computation of Its Associated Spatially Varying Uncertainty. **Journal Of Marine Science And Engineering**, [s.l.], v. 4, n. 4, p. 64, 22 set. 2016. DOI.: 10.3390/jmse4040064.

SILVA, D. Condições Metereológicas e Ambientais. In: 7°ENCONTRO SOBRE NORMAS DA AUTORIDADE MARÍTIMA PARA LEVANTAMENTOS HIDROGRÁFICOS. Rio de Janeiro. 21 e 22 de Novembro de 2019. Disponível em:< https://www.marinha.mil.br/chm/sites/www.marinha.mil.br.chm/files/u2009/condicoes_meteorologicas_e_ambientais.pdf >. Acesso em: 25 jul. 2020.

SIMON, B. **Coastal Tides**. Prince de Monaco: Institut océanographique, 2013. 413 p.

SLOBBE, D. C. **Roadmap to a mutually consistent set of offshore vertical reference frames**. Netherlands: Ncg, Nederlandse Commissie Voor Geodesie, Netherlands Geodetic Commission, Delft, The Netherlands, 2013. 263 p. Disponível em: https://ncgeo.nl/downloads/82Slobbe.pdf. Acesso em: 06 dez. 2020.

SLOBBE, D. C.; KLEES, R. **Establishing a consistent vertical reference frame for the North Sea area**. Relatório. ago. 2012. Disponível em:< http://blast-project.eu/media.php?file=623 >. Acesso em: 20 jul. 2020.

SLOBBE, D. C.; KLEES, R. **Establishing a consistent vertical reference frame for the North Sea area**. Relatório. ago. 2012. Disponível em:< http://blast-project.eu/media.php?file=623 >. Acesso em: 25 jul. 2019.

SLOBBE, D. C.; KLEES, R.; GUNTER, B. C.. Realization of a consistent set of vertical reference surfaces in coastal areas. **Journal Of Geodesy**, [s.l.], v. 88, n. 6, p. 601-615, 26 mar. 2014. DOI.: 10.1007/s00190-014-0709-9.

SLOBBE, D. C.; KLEES, R.; VERLAAN, M.; ZIJL, F.; ALBERTS, B.; FARAHANI, H. H.. 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,** [s.l.], v. 92, n. 12, p. 1439-1456, 9 mar. 2018. DOI.: 10.1007/s00190-018-1133-3.

SLOBBE, D. C.; SUMIHAR, J.; FREDERIKSE, T.; VERLAAN, M.; KLEES, R.; ZIJL, F.; FARAHANI, H. H.; BROEKMAN, R. A Kalman Filter Approach to Realize the Lowest Astronomical Tide Surface. **Marine Geodesy**, v. 41, n. 1, p. 44–67. 2018. DOI. 10.1080/01490419.2017.1391900.

SLOBBE, D. C.; SUMIHAR, J.; FREDERIKSE, T.; VERLAAN, M.; KLEES, R.; ZIJL, F.; FARAHANI, H. H.; BROEKMAN, R. A Kalman Filter Approach to Realize the Lowest Astronomical Tide Surface. **Marine Geodesy**, [s.l.], v. 41, n. 1, p. 44-67, 12 out. 2017. DOI.: 10.1080/01490419.2017.1391900.

SLOBBE, D. C.; KLEES, R.; VERLAAN, M.; DORST, L. L.; GERRITSEN, H. Lowest Astronomical Tide in the North Sea Derived from a Vertically Referenced Shallow Water Model, and an Assessment of its Suggested Sense of Safety. Marine Geodesy, v. 36, n. 1, p.31–71, 2013. DOI.: 10.1080/01490419.2012.743493

SOARES, S.; SANTOS, E. G.; SIQUEIRA, J. C. S.; LIMA, M. K.; LUZ, R. T. Rede Geodésica de Referência Costeira: Ações preliminares para integração de altitudes e profundidades. In: XIII SIMPÓSIO SOBRE ONDAS, MARÉS, ENGENHARIA OCEÂNICA E OCEANOGRAFIA POR SATÉLITE, 2009. **Anais...** Instituto de Estudos do Mar Almirante Paulo Moreira: Arraial do Cabo, RJ, 2009, p. 1-5.

GOVERNO DO ESTADO DO RIO GRANDE DO SUL (GERGS). Plano de Desenvolvimento e zoneamento. Porto Alegre, 2019. Disponível em: < http://antigo.infraestrutura.gov.br/images/SNP/planejamento_portuario/pdz/pdz24.pdf>. Acesso em: 01 nov. 2020.

TURNER, J. F.; ILIFFE, J. C.; ZIEBART, M. K. WILSON, C.; HORSBURGH, J. Interpolation of Tidal Levels in the Coastal Zone for the Creation of a Hydrographic Datum**. Journal of Atmospheric and Oceanic Technology**, [s.l.], v. 27, n. 3, p.605-613, mar. 2010. DOI. 10.1175/2009jtecho645.1.

TURNER, J. F.; ILIFFE, J. C.; ZIEBART, M. K.; JONES, C. Global Ocean Tide Models: Assessment and Use within a Surface Model of Lowest Astronomical Tide. **Marine Geodesy**, [s.l.], v. 36, n. 2, p.123-137, jan. 2013. DOI. 10.1080/01490419.2013.771717.

UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANISATION (UNESCO). **A ciência que precisamos para o oceano que queremos**. Década das Nações Unidas da Ciência Oceânica para o Desenvolvimento Sustentável (2021-2030). 2019. Disponível em: < http://ciencianomar.mctic.gov.br/wp-content/uploads/2020/06/265198por.pdf>. Acesso em: 13 jul. 2020.

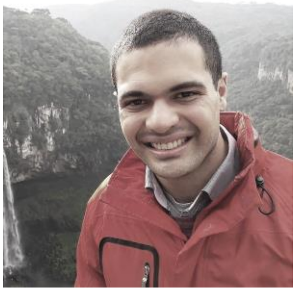
VALE. **Navio de pesquisa patrocinado pela Vale é entregue no Rio de Janeiro**. 2015. Disponível em: < http://www.vale.com/brasil/pt/aboutvale/news/paginas/navio-pesquisa-patrocinado-vale-entregue-rio-janeiro.aspx>. Acesso em: 30 jul. 2020.

WELLS, D. E.; KLEUSBERG, A.; VANÍČEK , P. **A Seamless Vertical-Reference Surface for Acquisition, Management and ECDIS Display of Hydrographic Data**. Canadá: University of New Brunswick, 1996. 74p. Relatório técnico.

WIŚNIEWSKI1, B.; WOLSKI, T.; GIZA, A. Adjustment of the European Vertical Reference System for the representation of the Baltic Sea water surface topography. **Scientific Journals Maritime University of Szczecin**, [s.l.], v. 38, n. 110, p. 106-117, 2014.

ZIEBART, M.; ILIFFE, J.; TURNER, J.; OLIVEIRA, J.; ADAMS, R. VORF - The UK Vertical Offshore Reference Frame: Enabling Real-time Hydrographic Surveying. THE 20TH INTERNATIONAL TECHNICAL MEETING OF THE SATELLITE DIVISION OF THE INSTITUTE OF NAVIGATION (ION GNSS 2007). **Proceedings…** Fort Worth, TX, September 2007, pp. 1943-1949.

## Authors' biography



Lieutenant Captain of the Brazilian Navy, holds a bachelor’s degree in Naval Sciences from the Navy Academy (2008-2011), with a postgraduate course in Hydrography from the Directorate of Hydrography and Navigation (*Diretoria de Hidrografia e Navegação*, DHN - 2015). Has carried out the Course for the development of international skills and social leadership (2017 - Italy and 2018 - Switzerland). Has already accomplished several bathymetric surveys through the brazilian coast and in inland waters. Currently, is a master’s student of the Geodetic Sciences of the Federal University of Paraná (*Universidade Federal do Paraná*, UFPR).

Claudia Pereira Krueger, from Curitiba, Paraná, graduated in Civil Engineering at Federal University of Parana (UFPR), Curitiba, Paraná, Brazil. MsC in Geodetic Sciences at UFPR (1994); Ph.D. in Geodetic Science, UFPR, with research period at Institut für Erdmessung, Hannover University (UH), Germany (1996) and Honorary Hydrographer by the Brazilian Navy (2009). Currently, she is a professor Department of Geomatic and permanent member of the Post-Graduation Program in Geodetic Sciences (PPGCG) and in Water and Environmental Engineering (PPGERHA) at UFPR. She coordinates the Laboratory of Space Geodesy and Hydrography (LAGEH) and developing researches related to Satellite Geodesy, Hydropraphy and GNSS positioning.

Tulio Alves Santana was born in Paracatu, northwest of Minas Gerais, in 1995. Attended Cartographic and Surveying Engineering (*Engenharia de Agrimensura e Cartográfica*) in the Federal University of Uberlandia (*Universidade Federal de Uberlândia*), Monte Carmelo campus (UFU/MC) (2013-2017). Holds a master’s degree in Geodetic Sciences from Federal University of Paraná (*Universidade Federal do Paraná*, UFPR, 2018-2020). Currently is a Cartographer and Surveyor Engineer in UFU/MC (since 2019) and is pursuing a doctorate in Geodetic Sciences in UFPR. Has an interest in the following topics: integration of vertical references in coastal zones; monitoring systems of the Earth; integration of data from satellite altimetry with tidal data; monitoring of the sea level; modelling of the geopotential; connection of vertical data; and International Height Reference System.

Guilherme A. G. do Nascimento was born in Niterói-RJ. Corvette Captain of the Brazilian Navy, holds a bachelor's degree in Naval Sciences from the Navy Academy (Escola Naval), is advanced in Hydrography from the Directorate of Hydrography and Navigation (DNH - *Diretoria de Hidrografia e Navegação*) and has a master's degree in Cartographic Sciences from the Paulista State University (*Universidade Estadual Paulista* – Unesp). Has accomplished several hydrographic surveys through the brazilian coast and in the Amazon region. Currently, is in charge of the Topogeodetic Information Section (*Seção de Informações Topogeodésicas*) of the Navy's Hydrography Center, (*Centro de Hidrografia da Marinha*), in Niterói-RJ.

Aluizio Oliveira Jr., Captain retired from Brazilian Navy, also PhD in marine geology. He has been working in hydrography since 1998, especially with multibeam echosounders, onboard ships and as the head of bathymetry division in the Brazilian Navy Hydrographic Center. Awarded with "Prince Albert I" medal from the International Hydrographic Organization in 2012. Now is the Technical Director at Delfos survey company.