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ORIGINAL ARTICLE

Analysis of vertical reference levels in the brazilian coast: comparing local and global approaches

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Abstract:

There is a historical search for the unification of different geodetic reference systems in order to better integrate geodetic investigations. In particular, coastal zones pose the challenge of connecting terrestrial and oceanic references when working with different vertical reference levels. This study aims to investigate the goodness-of-fit of ocean models to local observations, as well as to update and improve reference levels (RL) in two tide gauges (TGs) in Brazil (Imbituba and Fortaleza). Local RLs were connected to a global reference system (GRS80), which allowed absolute analyses using the mean sea surface (MSS) and lowest astronomical tide (LAT) models MSS_CNES_CLS15, DTU_15_MSS, DTU_18_MSS and DTU_15_LAT. In the selected TGs, the MSS models showed a difference of centimeters in regards to the local mean sea level (MSL) defined by the Directorate of Hydrography and Navigation (DHN). Sea Surface Topography (SSTop) values were estimated from Global Geopotential Models and MSL data. The results indicated possible inconsistencies in the global model of LAT when compared to local observations, likely due to the difficulty of modeling coastal zones.

Keywords: Vertical reference levels; Coastal zones; Unified ocean vertical reference system; Ocean models.

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1. Introduction

Although not yet widely understood within a governmental framework, Geodesy is fundamental for economic prosperity, security, and environmental management. Geodesy contributes to the understanding of the Earth System dynamics by providing reference systems that are used for the collection, integration, and application of geospatial data, while also supporting positioning activities that allow users to locate themselves in real time based on the Global Navigation Satellite System (GNSS) (UN-GGIM 2018).

In this context, in coastal zones, different spatial databases, sources, spatial resolutions and non-compatible geodetic and tidal references are a problem for the establishment of vertical reference levels at the local and global level (Da Silva and De Freitas 2019). Reference levels (RLs) are important for managing, monitoring, and enacting policies for the preservation of coastal zones. Thus, compatibility of different reference frames is essential to ensure data integration.

Advances in methodologies for computation of Global Geopotential Models (GGMs) and Ocean Models (OMs), the possibility of greater resolution for terrestrial information and the use of longer time series in the development of OMs lead the authors to believe that new estimates of the Sea Surface Topography (SSTop), also known as Mean Dynamic Topography (MDT), could be obtained with better quality, not only for the Brazilian Vertical Datum of Imbituba (DVB-I – *Datum Vertical Brasileiro de Imbituba*) but also for other tide gauge (TGs) on the coast. The determination of more accurate RLs and the analysis of available models are important contributions to the efforts for integrating vertical reference along the Brazilian coast. Santana and Dalazoana (2020) reviews the integration of land and sea vertical reference levels.

In this sense, this study aimed to define RLs in two Brazilian TGs (Imbituba and Fortaleza) by using strategies involving GGMs and OMs. In turn, these RLs will be used to compare and integrate local and global observations at both stations. We applied state-of-the-art models, such as GGMs with data weighting and residual terrain modeling and OMs derived from observations that cover a period longer than 18.6 years, with the goal of analyzing their goodness-of-fit to local observations. In addition, the primary benchmarks of the tide gauge (TGBMs) are located in places not accessible to GNSS. Therefore, it was necessary to develop a strategy to obtain the ellipsoidal heights of these benchmarks (BMs) and link them to a geodetic reference system. The present manuscript presents numerical results that are part of a master's study of the first author.

2. Material and methods

2.1 Material

National and international databases provided the data used in this study, which comprise the TGBMs, GGMs, and OMs. The data were spatialized in the open-source software QGIS 3.6 (QGIS Development Team 2019).

Tide gauge measurements are crucial for the integration of vertical references in coastal zones. Taking into account this fact, in addition to the recent advances in vertical datums, and the coming International Height Reference Frame (IHRF), we chose two TGs that will house future IHRF stations: one located in Fortaleza-CE and one in Imbituba-SC, which are part of Brazil's Permanent Maregraphic Network for Geodesy (RMPG – *Rede Maregráfica Permanente para a Geodésia*).

Documents prepared by the Brazilian Navy's Directorate of Hydrography and Navigation (DHN) with information from the selected stations were also consulted. These documents were obtained from the National Oceanographic Data Bank (BNDO – *Banco Nacional de Dados Oceanográficos*) of the Navy Hydrographic Center (CHM – *Centro de Hidrografia da Marinha*) in March 2019 (CHM 2019).

Two sets of stations of the Geodetic Control of Tide Gauge (CGEM – *Controle Geodésico de Estações Maregráficas*), maintained by the Brazilian Institute of Geography and Statistics (IBGE – *Instituto Brasileiro de Geografia e Estatística*), in Imbituba and Fortaleza, provided the geodetic observations used in this study. The CGEM aims to track vertical movements of non-oceanic origin in the region of the TGs, and contributes to determine the ellipsoidal coordinates of geodetic marks. Tide gauge observations can be transformed to the reference system of satellite altimetry by use of ellipsoidal heights, which enables the comparison and integration of geodetic observations (IBGE 2010).

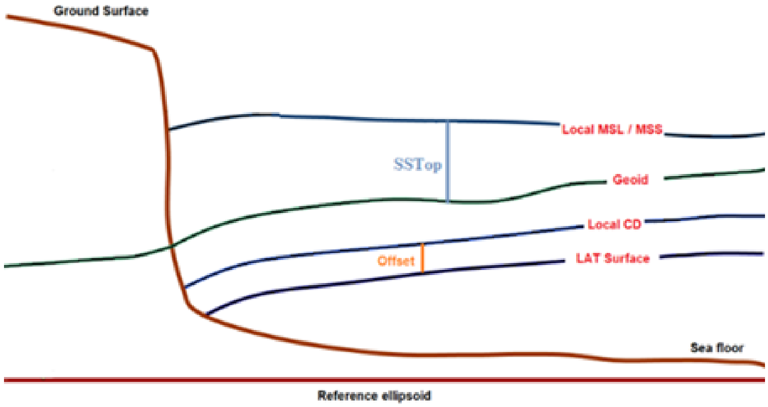
The GGMs XGM2016 (Pail et al. 2017) and XGM2019 (Gruber et al. 2019) were selected because they are precursors to the future EGM2020. These innovative models are based on data weighting and showed good results for Brazil (Pail et al. 2017; INCE et al. 2019). EGM2008 (Pavlis et al. 2012) and EIGEN-6C4 (Förste et al. 2014) were also included since they are the most suitable models for the chosen areas (Fortaleza-CE and Imbituba-SC) according to Nicácio, Dalazoana and De Freitas (2018).

For this study, two sets of global Mean Sea Surface (MSS) models and one Lowest Astronomical Tide (LAT) model were used. These models provide sea-level height values with respect to an ellipsoidal reference surface. The data comprise an area of 5°x5° around each TG with a spatial resolution of 1'.

The MSS models were developed by Collecte Localisation Satellites (CLS) and Centre National d'Etudes Spatiales (CNES) (MSS_CNES_CLS15) and DTU Space (DTU_15_MSS and DTU_18_MSS). The LAT model - DTU_15_LAT (Andersen et al., 2016) was provided by Dr. Ole Baltazar Andersen. The characteristics of the ocean models used in this study can be found in Cheng and Andersen (2011), Andersen et al. (2016), Andersen et al. (2018b), and AVISO (2019). The subsections are numbered starting with the main section number, followed by a dot and the corresponding number. Do not use automatic numbering. Subsections should be written in uppercase and low case, bold, Calibri Light font, size 14, centered. Skip two lines between the subsection title and the beginning of the text, and so on. Do not skip lines between paragraphs.

2.2 Methods

Figure 1 summarizes the main surfaces and RLs used in the study and highlights the relationships between them. Reference surfaces and planes include: MSL/MSS, that can be defined by local sea level observations at TGs (local approach) or by sea level observations from satellite altimetry (global approach); the geoid, which is the equipotential surface of the Earth's gravity field; the Chart Datum (CD), defined locally by tide gauge observations; and the LAT surface, generated by a model. In Brazil, CD is called Reduction Level (NR - *Nível de Redução*), which is defined as the zero of the vertical axis in nautical charts. It corresponds to the reference surface given by the mean of the low tides of syzygy (Santana and Dalazoana 2020). Furthermore, the offset between the local CD and the LAT surface represents a scaling between local and global approaches used to define the ocean vertical datum, while the SSTop corresponds to the discrepancy between geoid and MSL/MSS, whether global models or local observations determine the MSL/MSS.



Source: Adapted from Andersen (2018).

Figure 1: Summary of the main surfaces and reference levels.

2.2.1 Interpolation method

For the manipulation of MSS and LAT models, we chose to work with regular 1'x1' grids, which were converted to vector format (shapefile) using point as the graphic primitive. The interpolation of these grids was based on the Kriging interpolation method, which has already been used to interpolate regular grids of geoid heights of GGMs (Santana, Ribeiro and Guimarães 2017) and sea level values of MSS models (Montecino, Cuevas and De Freitas 2014). Ferreira et al. (2017) also pointed out the efficient performance of this method.

2.2.2 Data compatibility

Due to the use of data from different sources, it was necessary to make the data compatible regarding the permanent tide system and the reference frame used (Andersen et al. 2018a). We adopted the mean tide system, following the definitions of the International Height Reference System (IAG 2015). As a reference system, we chose the GRS80 ellipsoid, which is the base model of SIRGAS.

The non-compatibility of permanent tide systems can lead to incorrect analyses, because the global differences between the systems can reach 20 cm for defined height in mean and zero tide systems, 14 cm for those defined height between mean and free tide systems and 6 cm for zero and free tide systems (Tenzer et al. 2011).

The compatibility of permanent tide systems was a concern because the heights provided by the Brazilian Vertical Reference Frame are in the mean tide system, since no tidal corrections in terms of the permanent tide effect were applied (Ferreira, Zhang and De Freitas 2013). On the other hand, ellipsoidal heights obtained by GNSS are in the tide-free system (Mäkinen and Ihde 2006). Also, while the MSS models are based on the mean tide system, the LAT surface model is based on the tide-free system (Andersen et al. 2016). The International Centre for Global Earth Models calculation service allows the choice of tide system when calculating functionals of GGMs. Thus, the need for restricting data to the same permanent tide systems is evident, before any analysis or comparison can be carried out. The equation 1 expresses the conversion between free and mean tide systems (Tenzer et al. 2010).

$$h_{mt} = h_{tf} - (1 + k - j)[-0.198\text{m} \, (\frac{3}{2} \sin^2\Psi - \frac{1}{2})] \quad (1)$$

Where h_{mt} and h_{tf} are, respectively, ellipsoidal heights in the mean-tide and tide-free system, Ψ is the geocentric latitude, k and j are the Love numbers.

The same issue arises regarding the reference ellipsoids: the MSS models refer to the TOPEX/Poseidon (T/P) ellipsoid, the LAT surface model to WGS84, and the coordinates of geodetic stations to GRS80. In order to identify the discrepancies between the reference ellipsoids, IERS (2010), Rio (2009), and Dimarzio (2007) present the following parameters for the ellipsoids T/P, GRS80, and WGS84: major semi-axis (a), minor semi-axis (b), flattening (1/f), and eccentricity (e).

We followed the compatibility procedure described by Carrión (2017). The conversion was made according to the latitudes of the position of the TGs, using the formula described in Dimarzio (2007):

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

In equation (2), δ_h corresponds to the height difference (h_1 and h_2) between the two ellipsoids; a_1 and a_2 are the major semi-axis; b_1 and b_2 are the minor semi-axis; and Ψ is the geocentric latitude of the conversion's point of interest. This compatibility procedure changed the height values by approximately seventy centimeters.

2.2.3 Analysis of the global and local approaches regarding the oceanic reference

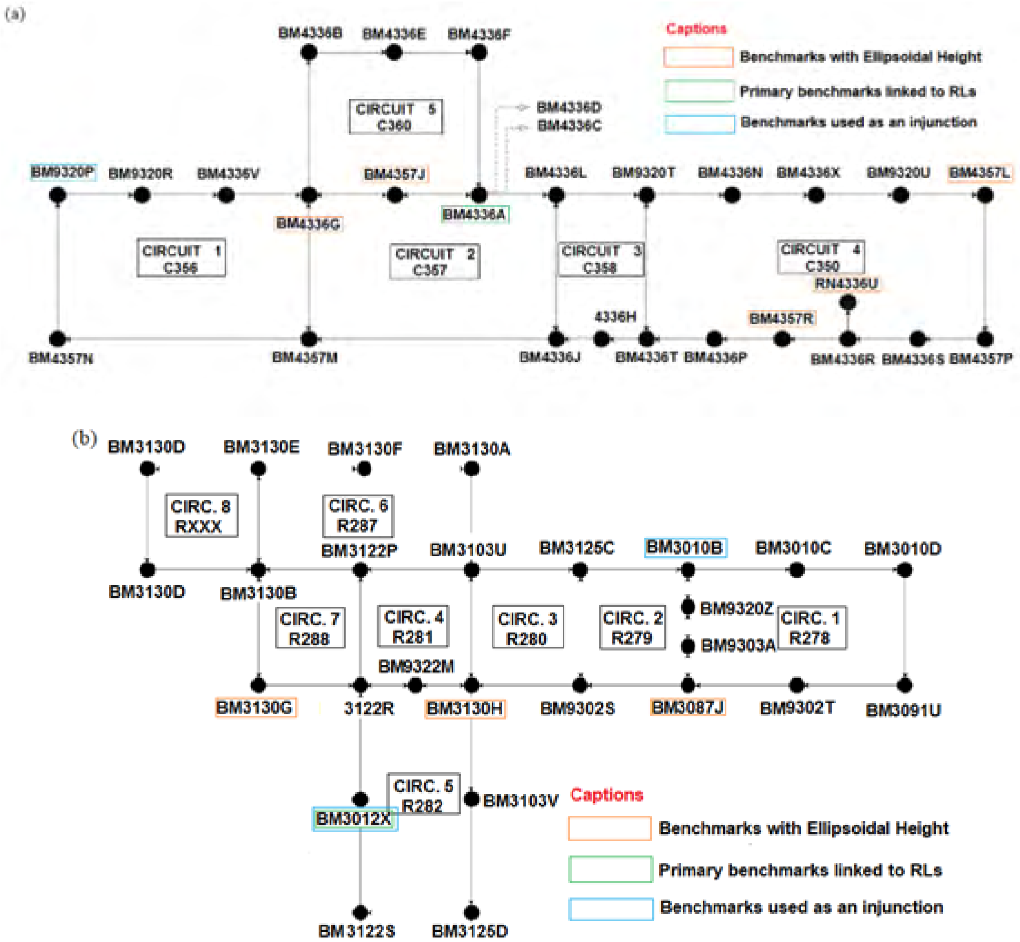
In the first step, we used data from TG files made available by the BNDO; the DTU_15_MSS, DTU_18_MSS and MSS_CNES_CLS15 models; and the LAT surface model, DTU_15_LAT. For the TGs whose data was collected from the BNDO, the analyses employed the reference planes defined by the DHN.

Determining the geocentric position of the TGs allowed us to perform absolute analyses. The LAT surface model and the MSS models led us to obtain a global solution, based on satellite altimetry. This approach was advantageous due to the spatial and temporal resolution of the models.

The discrepancies in results between the local approach, which employed CD and MSL values provided by the BNDO, and the global approach allowed us to estimate the impact of using global models and of defining the LAT surface as the CD. Results of a relative analysis of 8 TGs in the region of Fortaleza and 18 TGs in the region of Imbituba are reported in Santana and Dalazoana (2019). It should be noted these TGs belong to the Brazilian Navy and operate for a period of time, so they are not continuously monitoring TGs.

4336A and 3012X are primary BMs linked to the local RLs established by DHN for the TGs of Fortaleza and Imbituba, respectively. The geocentric positioning of the reference levels was obtained from these links and through the CGEM data. In addition to these primary BMs, there are also neighboring BMs. These neighboring BMs and their links to the primary BMs are described in the F-41 of each station. F-41 refers to the tidal BM sheet adopted in Brazil.

Since the ellipsoidal heights of the primary BMs are unknown, the ellipsoidal heights of neighboring BMs were used as a source of data for their definition. In area 1 - Fortaleza, 5 BMs have known ellipsoidal heights (Figure 2a). In contrast, only 3 BMs have known ellipsoidal heights in area 2 – Imbituba (Figure 2b).



Source: Adapted from IBGE (2019).

Figure 2: Schematic chart of the CGEM in the TGs in Fortaleza (a) and Imbituba (b).

As of August 2019, IBGE had not yet provided normal height values for the set of CGEM stations. That is why in this research normal-orthometric height were used. However, considering that geoid and quasi-geoid in coastal regions are almost coincident, we chose to assume that orthometric-normal height and orthometric height are equivalents in the study regions. To support the action, the authors investigated the values of geoidal height and height anomaly from MGGs and obtained equal results for both regions studied.

The equation for obtaining the ellipsoidal height of the BMs relates geoid height (*N*), ellipsoidal height (*h*), and orthometric height (*H*). The ellipsoidal height of the primary BMs is expressed by Equation (3), while the ellipsoidal height of neighboring BMs is expressed by Equation (4). These equations are adapted from Jekeli (2000) and Gemael (1999).

$$h_p = N_p + H_p \tag{3}$$

$$h_n = N_n + H_n \tag{4}$$

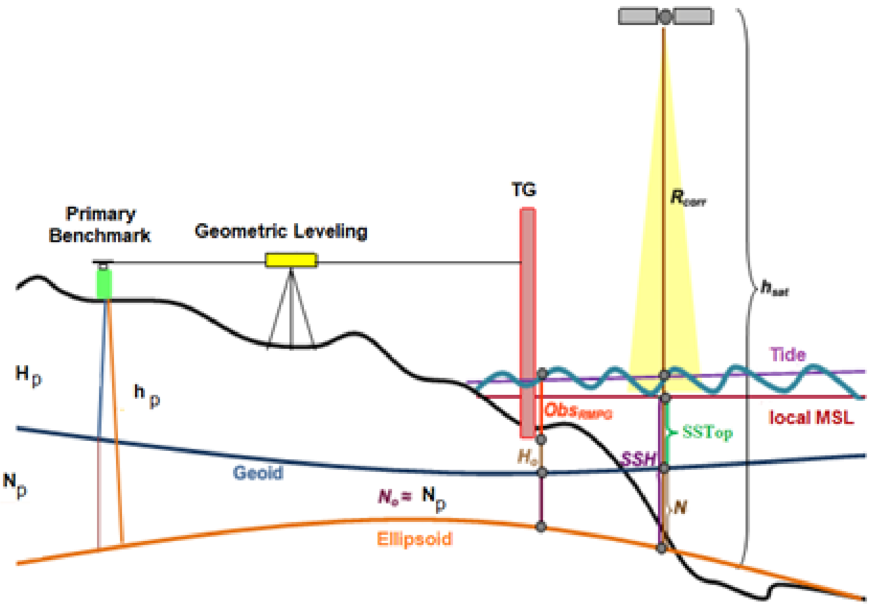
Where h_p, N_p and H_p are, respectively, the ellipsoidal height, the geoid height and the orthometric height of the primary BMs; h_n, N_n and H_n are, respectively, the ellipsoidal height, the geoid height and the orthometric height of the neighboring BMs.

By subtracting equations (3) and (4), we arrive at equation 5, by which the ellipsoidal height of the primary BMs is obtained: $N_p - N_n$ is the geoid height difference between RLs, and $H_p - H_n$, the altimetric difference.

$$h_p = (N_p - N_n) + (H_p - H_n) + h_n \tag{5}$$

As the N_p was unknown at the time of the first test, the geoid height difference was set to zero. Estimates of ellipsoidal heights were obtained for the primary BMs. In the second test, geoid heights of the primary BMs were based on GGM XGM2019 (model with a spectral resolution of degree and order (d/o) 2190), combined with the local geoid heights of neighboring BMs. Analysis of the standard deviations of both tests indicated the second test improved the quality of the estimation.

The primary BMs were connected to the RLs based on their ellipsoidal heights and the data from differential spirit leveling (available in the F-41 of each TG). It must be noted that geoid heights for both the primary BMs and the RLs (at the tide gauge position) were assumed to be equal (Figure 3).



Source: Adapted from Da Silva (2017).

Figure 3: Connection between RLs implied in the integration of models and observations (Variables: R_{corr} adjusted range; h_{sat}: ellipsoidal height from satellite altimetry; N: geoid heights; H: orthometric heights; h: ellipsoidal heights; SSH: Sea Surface Height).

2.2.4 Strategies for estimating SSTop

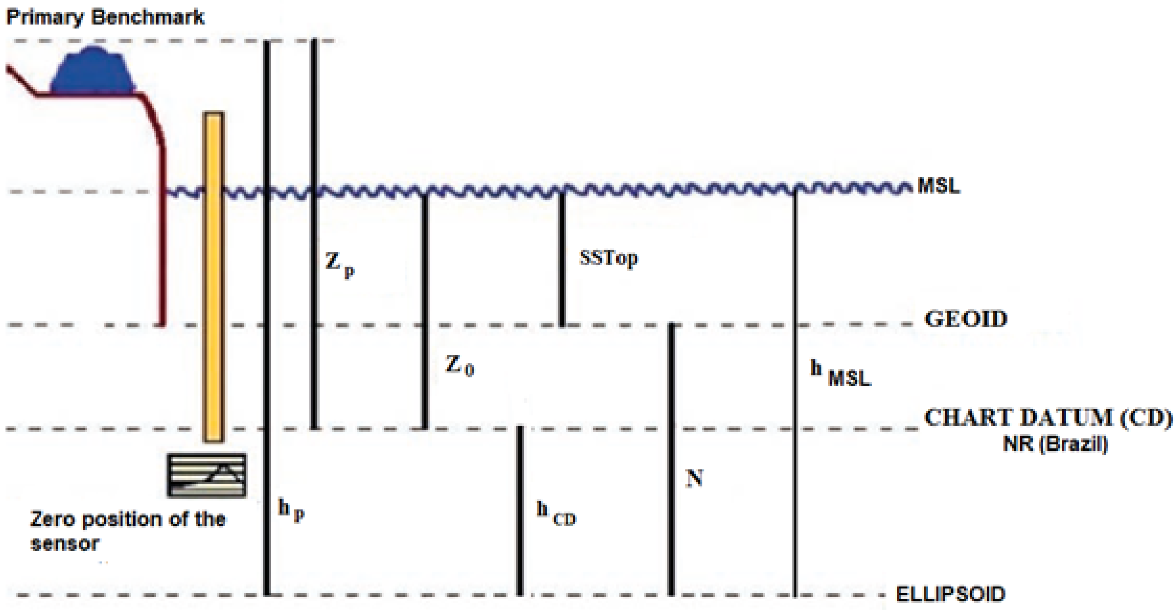
The SSTop was estimated according to geometric and oceanographic approaches (Filmer et al. 2018; Hayden et al. 2012; Silva and Guimarães 2018; Montecino, Cuevas and De Freitas 2014). The results from previous steps contributed to the estimation.

In the geometric approach, SSTop is estimated using: the ellipsoidal height (h_p) of the primary BM; the geoid height (N); the height of the primary benchmark above the CD (Z_p); and the value of Z_0 which is the height of MSL with respect to CD (Figure 4), as presented in equation 6:

$$SSTop = h_p - N - Z_p + Z_0 \tag{6}$$

However, this equation is only valid when the ellipsoidal height of MSL (h_{MSL}) is not available. h_{MSL} is known if the zero position of the sensor (TG) is linked to a geocentric reference system and in some cases this link does not exist. In this cases equation 6 can be applied because Z_p and Z_0 values have both been defined by the DHN and are presented in DHN's F-41 forms. As shown in Figure 4, $h_p - Z_p + Z_0$ is equal to the ellipsoidal height of MSL, than equation 6 can thus be rewritten as equation 7 (Andersen et al. 2018a; Filmer et al. 2018):

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



Source: Adapted from Silva and Guimarães (2018).

Figure 4: Geometric estimation of SSTop at the Tide Gauge.

In turn, the oceanographic approach is based on GGM and MSS models. The calculation was performed by using geoid heights (N) from GGMs and MSS heights (h_{MSS}) from models DTU_15_MSS, DTU_18_MSS, and MSS_CNES_CLS15, according to equation (8):

$$SSTop = h_{MSS} - N \tag{8}$$

This equation has already been applied in a study of Chile's vertical network (Montecino, Cuevas and De Freitas 2014). The values of *N* in both approaches will be calculated according to EGM2008, EIGEN-6C4, XGM2016, and XGM2019 models at their maximum degree.

3. Results

3.1 Defining the geocentric position of the RLs

In order to analyze the local and the GGM-based geoids, the local geoid heights and the geoid heights provided by the GGM were compared to a set of neighboring BMs whose ellipsoidal and normal-orthometric heights were known. The results are shown in Table 1. The root mean square error (RMSE) for Fortaleza (area 1) was 0.193 m and for Imbituba (area 2) it was 0.466 m.

Table 1: Comparison of geoid heights for each area.

	BM	Local Geoid Height (N=h-H) (m)	GGM Geoid Height XGM2019 (m)	Difference (m)
	BM4336G	-9.238	-9.429	-0.191
	BM4357J	-9.230	-9.429	-0.199
	BM4336U	-9.217	-9.424	-0.207
Fortaleza	BM4357R	-9.258	-9.425	-0.167
	BM4357L	-9.229	-9.426	-0.197
	Mean	-9.234	-9.427	-0.193
	RMSE	-	-	0.193
	BM3130G	1.277	0.811	-0.466
	BM3130H	1.269	0.804	-0.465
Imbituba	BM3087J	1.280	0.814	-0.466
	Mean	1.275	0.810	-0.465
	RMSE	-	-	0.466

The geoid heights provided by the XGM2019 model for the primary BMs 4336A and 3012X are -9.429 m and 0.813 m, respectively. Taking the RMSE into account (table 1), the geoid heights of primary BMs 4336A and 3012X were defined as -9.236 m and 1.279 m. This analysis is built on Gruber and Willber (2019), who observed that systematic errors between modeled and observed geoid heights were due to distinct height systems in each part of the globe. They argued these errors can be corrected by applying the RMSE to the geoid heights provided by the models.

The ellipsoidal heights of the primary BMs in Fortaleza and Imbituba according to the possible leveling lines are listed in Table 2. The addition of the geoid height difference between primary and neighboring BMs provides a remarkable improvement in the reliability of the ellipsoidal heights of the primary BMs, as evidenced by the standard deviation of each solution.

Table 2: Ellipsoidal heights of 4336A and 3012X BMs and their accuracy.

	Leveling line	Geoid Height - Primary BMs (m)	Estimated Ellipsoidal Height (m)	Geoid Height difference (m)	Updated estimation of Ellipsoidal Height (m)
	BM4336A/BM4336G	-9.238	-5.536	0.002	-5.534
	BM4336A/BM4357J	-9.230	-5.528	-0.006	-5.534
	BM4336A/BM4336U	-9.217	-5.514	-0.019	-5.533
Fortaleza	BM4336A/BM4357R	-9.258	-5.555	0.022	-5.533
	BM4336A/BM4357L	-9.229	-5.526	-0.007	-5.533
	Mean	-9.234	-5.532	-0.002	-5.534
	Standard Deviation	0.015	0.015	0.015	0.001
	BM3012X/BM3130G	1.277	3.322	0.002	3.324
	BM3012X/BM3130H	1.269	3.314	0.010	3.324
Imbituba	BM3012X/BM3087J	1.280	3.325	-0.001	3.324
	Mean	1.275	3.320	0.004	3.324
	Standard Deviation	0.006	0.006	0.006	0.000

Once the ellipsoidal heights of the primary BMs have been determined, we can represent the reference levels of the TGs with respect to the chosen global reference system, GRS80. The height of the primary BM with respect to CD (Z_p) and the height of the local MSL with respect to CD (Z_0) have both been defined by the DHN. These values were extracted from the F-41 of each TG: F41 “Standard - PORT OF MUCURIPE - 30340 - version 1/2018”, for the TG in Fortaleza; and F41 “Standard - PORT OF IMBITUBA - 60250 - version 1/2019”, for the TG in Imbituba. Table 3 presents the ellipsoidal heights of the CD (h_{CD}) and MSL ($h_{MSL(DHN)}$) with respect to the GRS80, as shown in Figure 4 these values are calculated by equations 9 and 10.

$$h_{CD} = h_p - Z_p \tag{9}$$

$$h_{MSL(DHN)} = h_p - Z_p + Z_0 \tag{10}$$

Table 3: Local levels set by DHN converted to the GRS80 ellipsoid.

Tide Gauge	h_{CD} (m)	$h_{MSL(DHN)}$ (m)	Time Interval
TG-Fortaleza	-10.322	-8.777	2008-04-18 to 2010-04-14
TG-Imbituba	0.873	1.282	1957-01-01 to 1957-12-31

Alternatively, tide gauge observations from the two stations that are part of the RMPG were used to determine the MSL at each location. For the TG in Fortaleza, the hourly tide gauge data refer to the time period from April 2008 to December 2015. 626 hours (≅1%) lacking data were identified. In total, 67533 hourly time instances were included for the calculation of MSL. In turn, for the TG in Imbituba, MSL was calculated based on hourly tide gauge data from August 2001 to December 2015 (125865 hours). 24352 hours (≅19%) lacked data.

The connection between the levels of the zero position of the sensor and the primary BMs was necessary in order to define the ellipsoidal height of the tide gauge observations, and it was defined based on correlations previously observed by IBGE (2015). The Table 4 presents the ellipsoidal heights of the MSL ($h_{MSL(RMPG)}$). Since the connection could be established from its relation to the CD or to the DVB-I, both strategies were tested. The results converged, with a 1-mm difference (Table 4).

Table 4: Local levels of the TG converted to the GRS80 ellipsoid.

Tide Gauge	$h_{MSL(RMPG)}$ (from CD) (m)	$h_{MSL(RMPG)}$ (from DVB-I) (m)	Time Interval
TG-Fortaleza	-8.756	-8.755	2008-04-18 to 2015-12-31
TG-Imbituba	1.352	1.353	2001-08-22 to 2015-12-31

3.2 Defining Absolute assessment of the goodness-of-fit of global models to local observations

In Table 5, the ellipsoidal height of the LAT model (h_{LAT}), the CD (h_{CD}), the MSS models (h_{MSS}) and the local MSL (h_{MSL}) are compared. These variables are explained in figures 3 and 4, and also in equations 9 and 10.

The of both TGs, Fortaleza and Imbituba, is lower than the h_{LAT} by 15.6 cm and 6 mm, respectively. This means that the CD surface is located below the LAT surface in both TGs. When h_{MSL} values obtained from DHN and from RMPG data are compared with the h_{MSS} from the three MSS models used, there is a difference of 13.1 cm to 16.7 cm for the TG in Fortaleza, and of 2.3 cm to 8.3 cm for the TG in Imbituba.

Although the h_{LAT} was expected to be slightly below h_{CD}, this was not observed. It is likely that the accuracy of the model is not yet sufficient to optimally develop the h_{LAT} at the TGs under study. The differences found in h_{MSL} values can be explained by the processing techniques applied by each model. In addition, differences between local levels may also be related to the time period when the observations took place. Furthermore, the $h_{MSL(DHN)}$ were calculated from harmonic analysis, while the $h_{MSL(RMPG)}$ was calculated directly from the raw data.

Table 5: Global Levels based on models and differences to Local Levels

TG	h_{LAT} (m)	Difference from h_{CD} (m)	h_{MSS} (m)	Difference from $h_{MSL(DHN)}$ (m)	Difference from $h_{MSL(RMPG)}$ (m)
Fortaleza	-10.166 (DTU_LAT_15)	-0.156	-8.610 (CNES/CLS15) -8.642 (DTU_15) -8.646 (DTU_18)	-0.167 -0.135 -0.131	-0.145 -0.113 -0.109
Imbituba	0.879 (DTU_ LAT_15)	0.006	1.305 (CNES_CLS15) 1.350 (DTU_15) 1.365 (DTU_18)	-0.023 -0.068 -0.083	-0.048 -0.003 -0.012

3.3 Estimation of SSTop

Since the SSTop may be calculated from the difference between the geoid and the MSL, we determined SSTop according to the ellipsoidal heights of the local MSL ($h_{MSL(DHN)}$ and $h_{MSL(RMPG)}$) (equation 7) and those provided by OMs (h_{MSS}) (equation 8). The mean found for the TG in Fortaleza was 77.2 cm, with a standard deviation of 7.3 cm. For this TG, the SSTop varied from 65.2 cm to 87.7 cm; estimations were based on five different MSL values and four GGMs (Table 6). At the TG in Imbituba, the mean was 51.9 cm, with a standard deviation of 4 cm; the SSTop varied from 44.1 cm to 58.5 cm (Table 6).

Table 6: Estimations of SSTop for the TGs in Fortaleza and Imbituba.

		SSTop estimated from $h_{MSL(DHN)}$ (m)	SSTop estimated from $h_{MSL(RMPG)}$ (m)	SSTop estimated from h_{MSS} CNES_CLS15 (m)	SSTop estimated from h_{MSS} DTU_15 (m)	SSTop estimated from h_{MSS} DTU_18 (m)	Mean (m)	Standard Deviation (m)
Fortaleza	EGM2008	0.662	0.684	0.829	0.797	0.793	0.753	0.075
	EIGEN-6C4	0.699	0.721	0.866	0.834	0.830	0.790	0.075
	XGM2016	0.710	0.732	0.877	0.845	0.841	0.801	0.075
	XGM2019	0.652	0.674	0.819	0.787	0.783	0.743	0.075
	Mean	0.681	0.703	0.848	0.816	0.812	0.772	-
	Standard Deviation	0.028	0.028	0.028	0.028	0.028	-	0.073
Imbituba	EGM2008	0.441	0.512	0.464	0.509	0.524	0.490	0.036
	EIGEN-6C4	0.502	0.573	0.525	0.570	0.585	0.551	0.036

Continue...

Table 6: Continuation.

		SSTop estimated from $h_{MSL(DHN)}$ (m)	SSTop estimated from $h_{MSL(RMPG)}$ (m)	SSTop estimated from h_{MSS} CNES_CLS15 (m)	SSTop estimated from h_{MSS} DTU_15 (m)	SSTop estimated from h_{MSS} DTU_18 (m)	Mean (m)	Standard Deviation (m)
Imbituba	XGM2016	0.469	0.540	0.492	0.537	0.552	0.518	0.036
	XGM2019	0.469	0.540	0.492	0.537	0.552	0.518	0.036
	Mean	0.470	0.541	0.493	0.538	0.553	0.519	-
	Standard Deviation	0.025	0.025	0.025	0.025	0.025	-	0.040

3.4 Improvement of RLs

Local reference levels in Brazil are determined by the IBGE and the DHN. The studies of Dalazoana, Luz and Freitas (2005), De Freitas et al. (2010), Palmeiro, De Freitas and Dalazoana (2013) and Da Silva and De Freitas (2019) were based on different solutions and defined RLs with respect to global reference systems for the TG in Imbituba. From the results obtained in this study, we can improve these RLs by making use of geodetic observations, models, and strategies that differ from those utilized by the aforementioned studies.

Figures 5 and 6 show the RLs for the TG in Fortaleza and Imbituba. These RLs are based on local observations, GGMs, and the MSS. The first levels refer to the CD and to the LAT surface, followed by the MSL values obtained by tide gauge observations and by OMs; lastly, the geoid heights provided by the GGMs are given.

We believe the differences found between model-based and local MSL values are due to potential crust movements and the temporal variation of the MSL, as well as errors in sea level measurements by satellite altimetry. The figures also show that DTU and MSS models were the closest to local MSL values for both TGs. As for the geoid heights provided by GGMs, EGM2008 and XGM2019 presented the closest results to one another; the same was observed for EIGEN-6C4 and XGM2016 in the TG in Fortaleza. In turn, for the TG in Imbituba, XGM2016 and XGM2019 had identical results. EGM2008 showed the largest discrepancy when compared to the others.

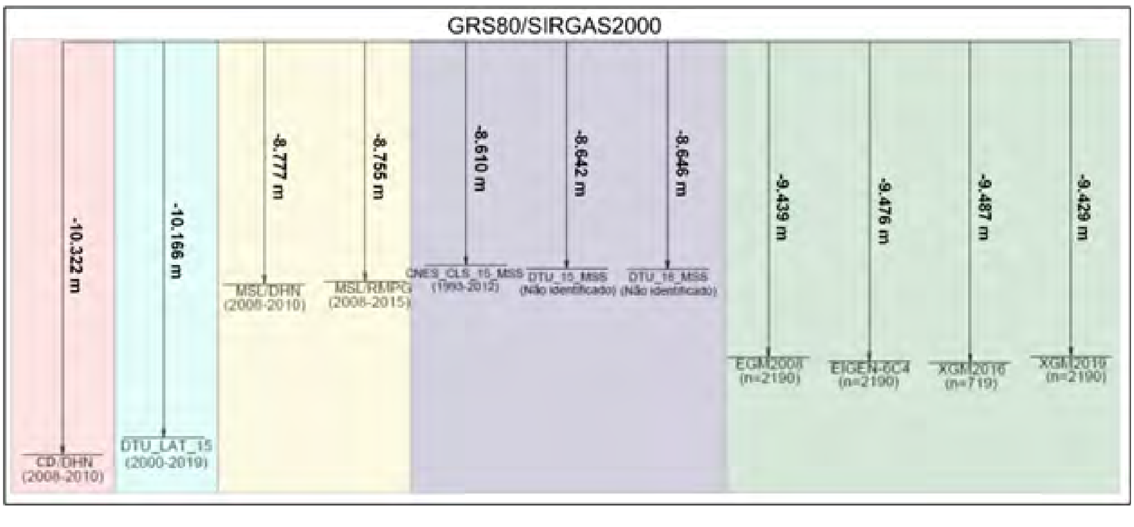


Figure 5: RLs with respect to GRS80/SIRGAS2000 for the TG in Fortaleza: from left to right: 1 CD (pink); 1 LAT (blue); 2 MSL (yellow); 3 MSS (purple); and 4 geoid models (green).

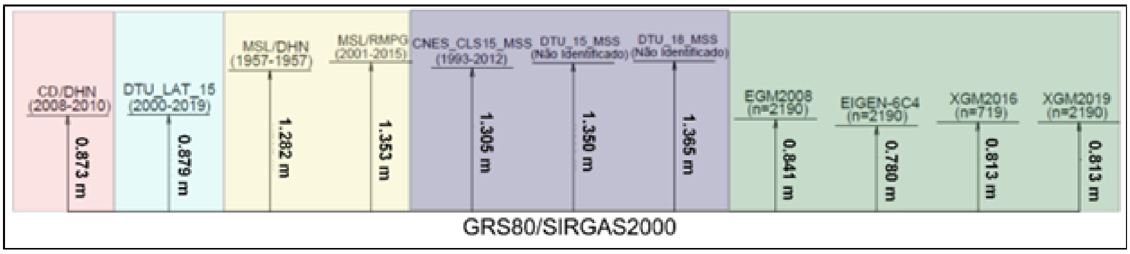


Figure 6: RLs with respect to GRS80/SIRGAS2000 for the TG in Imbituba: 1 CD (pink); 1 LAT (blue); 2 MSL (yellow); 3 MSS (purple); and 4 geoid models (green).

In conclusion, the absolute analysis of the RLs allows us to measure the offset between the CD and the DTU_15_LAT model. These results also indicate an estimated offset between the surface recommended by IHO (2018) and the local RLs.

4. Conclusions

This study confirmed the adequacy of the used methodology for determining ellipsoidal heights of primary BMs in places where GNSS surveys are not possible, such as those close to the TGs in this study. The inclusion of geoid height based on local geodetic observations and GGMs resulted in better accuracy (< 1 mm). Therefore, an analysis of local geoid height differences is recommended when estimating the ellipsoidal height. As of 2022, the CGEM stations have normal height values provided by IBGE, so the authors recommend carrying out new studies based on height anomalies and normal heights.

The results showed discrepancies that indicate the need for improvement in the modeling of altimetry data in shallow waters.

High-resolution GGMs also made it possible to obtain estimations of SSTop. We believe that the utilization of XGM2019 at a higher degree may provide more accurate solutions (Gruber et al. 2019). Other possible tool to acquire accurate solutions are the soon-to-be-released EGM2020 (Pail et al. 2017) and the geopotential space modeling strategy based on a solution to the Geodesy Boundary Value Problem (Carrion 2017).

In order to advance the integration of vertical reference levels in coastlines, standardization and systematization of geodetic survey methodologies are necessary. When connecting the TGs, the tolerance for the differential spirit leveling should not exceed 3 mm √k, as described in IBGE (2017), k is travelled distance (in km) in spirit leveling. Additionally, ellipsoidal heights for both primary and neighboring BMs should be calculated, making it possible to connect the RLs to an ellipsoid with a higher degree of precision.

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AUTHOR´S CONTRIBUTION

The first author performed the measurements, analyzed the data, and drafted the manuscript. The second author supervised the project and aided in writing and editing the article. Both authors conceived the idea and designed the methodology for the study.

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