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Estimation Test of the Topography of the Local Mean Sea Level in tide gauges on the Brazilian coast

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RESUMO: O objetivo deste trabalho, é indicar um procedimento para determinação da estimativa da Topografia do Nível Médio do Mar (TNMM) como insumo à definição moderna de um sistema vertical. A modelagem empregada foi baseada nas abordagens geométrica e oceanográfica, na qual são utilizadas observações do Nível Médio do Mar (NMM) provenientes de marégrafos. As principais etapas da modelagem foram: a determinação da posição geocêntrica dos marégrafos; o cálculo do NMM local; e o cálculo da altura geoidal. Os valores obtidos para os sítios de Niterói-RJ, Arraial do Cabo-RJ e Macaé-RJ apontam que a região não apresenta variações muito significativas. Os sítios de Imbituba-SC e Salvador-BA apresentam valores próximos entre si, apesar de possuírem peculiaridades importantes. O sítio de Fortaleza-CE não difere significativamente dos valores obtidos em outras pesquisas. A estratégia empregada apontou que os valores de TNMM para parte da costa brasileira são coerentes com outras abordagens. Esses resultados podem ser subsídios ao aprimoramento de referenciais verticais.

PALAVRAS-CHAVE: Sistema vertical. Geóide. Nível médio do mar. Modelo Global do Geopotencial.

ABSTRACT: The objective of this work is to indicate a procedure for determining the estimate of the Sea Surface Topography (SSTop) as an input to the modern definition of a vertical system. The modeling used was based on geometric oceanographic and approaches, in which observations of Mean Sea Level (MSL) from tide gauges are used. The main steps of the modeling were: the determination of the geocentric position of the tide gauges; calculating the local MSL; and the calculation of the geoid height. The values obtained for the sites of Niterói-RJ, Arraial do Cabo-RJ and Macaé-RJ indicate that the region does not present very significant variations. The Imbituba-SC and Salvador-BA sites have similar values despite having important peculiarities. The Fortaleza-CE site does not differ significantly from values obtained in other researches. The strategy employed indicated that the SSTop values for part of the Brazilian coast are consistent with other approaches. These results can be subsidies for the improvement of vertical references.

KEYWORDS: Height system. Geoid. Mean Sea Level. Global Geopotential Model.

1. Introduction

The classic definition of the geoid was first explained by Gauss, in 1828, as the reference for the geometric representation (or a model) of the terrestrial surface. Later, in 1973, Listing called such a model a geoid (or geoid surface of the Earth). The geoid consists of an equipotential surface that most closely approximates the undisturbed mean sea level. The modern definition recognizes that the average surface of the oceans does not coincide with the level surface of the earth's gravity field [1]. This non-coincidence is because the Mean Sea Level (MSL) is not static. This is caused by the movement of ocean currents and other quasi-stationary effects [2], that is, it is not a surface in equilibrium with the Earth's gravity field. Therefore, there is a difference (or separation) between the MSL and the geoid known as Sea Surface Topography – SSTop (Sea Surface Topography – SSTop) [3].

This difference is due to the interaction of several physical phenomena, such as meteorological and oceanographic ones, and may also vary according to time [4]. When compared to the geoid, such a separation is of the order of ± 2 m [5]. That said, it leads to the conclusion that each point on the coast, that is, each tide gauge, is related to a different value of SSTop [6].

The classic geodetic networks of many countries, including Brazil, used, and still use, as a reference vertical data defined and realized based on one, or more, value (s) of MSL obtained in a certain period and linked to a time [7] assuming a coincidence between the MSL and the geoid.

In Brazil, the two vertical data (systems), that is, the Datum of Imbituba - SC, defined by observations of sea level in the period from 1949 to 1957, and the Datum of Santana - AP, defined by observations of sea level in the period from 1957 to 1958, were based on tidal observations disregarding temporal and spatial variations in mean sea level and vertical movement of the crust [6].

The modern conception understands that the determination of a vertical system must be as homogeneous as possible. To do so, it requires a complex geodetic infrastructure, where it is necessary to reconcile information and methodologies that have global standardization. This issue, within the ambit of the American continent, has been discussed by the Working Group III of SIRGAS (Vertical Datum) established in 1997 [8]. It is worth noting that other groups in the scientific community have coordinated efforts regarding the development of knowledge aimed at improving the vertical component [9]. However, the infrastructure depends on the advancement of technology in some areas of knowledge, in addition to applied studies, in order to make possible the objective of building a unified vertical system at a global level.

In this sense, the International Association of Geodesy (IAG), through its resolution Nº. July 1, 2015 [9], recommends the adoption of an equipotential surface of the gravity field with geopotential 0= 62 636 853,4 m2s-2 as a reference surface that will enable the unification of the different existing altimetric systems. Evidently, SSTop must be considered in the realization of such systems.

A fundamental subsidy to the unification of different local data is the combination of observations from the MSL, collected through tide gauges, to the SSTop, obtained through altimetric satellites or approaches associated with Global Geopotential Models – GGMs.

The objective of this work is to indicate a modeling based on the geometric and oceanographic approaches to determine the SSTop estimate, in tide gauge stations on the Brazilian coast, as input to the discussions on the modern definition of a vertical datum.

2. Modeling to determine the SSTop estimate

The geometric approach is the method that combines mean sea level records with geopotential models, as proposed by [10] and revisited by [11]. The solution for estimating the SSTop is given by Eq. (1), based on variables that make up the tidal reference system. The presented modeling will be applied to part of the tide gauges of the Rede Maregráfica Permanente para Geodésia - RMPG.

$$SSTop = h_{BM} - N - H_{CD} + Z_0 \quad (1)$$

In Eq. (1) there h_{BM} is the ellipsoidal altitude of the primary Banchmark (BM of a tide gauge, N is the geoid height provided by geopotential models or geoid models, H_{BM} is the height of the BM above the Chart Datum (CD) – informed by the Hydrography and Navigation Board in form F 41 [12] – and Z_0 the height of sea level above the BM. If the height of the MSL referred to an ellipsoid is available (h_{MSL}) the Eq. (1) can be rewritten in the form of the oceanographic approach [13]:

$$SSTop = h_{MSL} - N \quad (2)$$

Figure 1 schematizes the terms of Eq. (1) and the surfaces related to it. It is worth mentioning, among these surfaces and elements, respectively, the Chart Datum (CD), a reference which corresponds to the average of the smallest spring tides [14], and the “zero” of the tide sensor, a reference point to which the observation maregrafica is linked

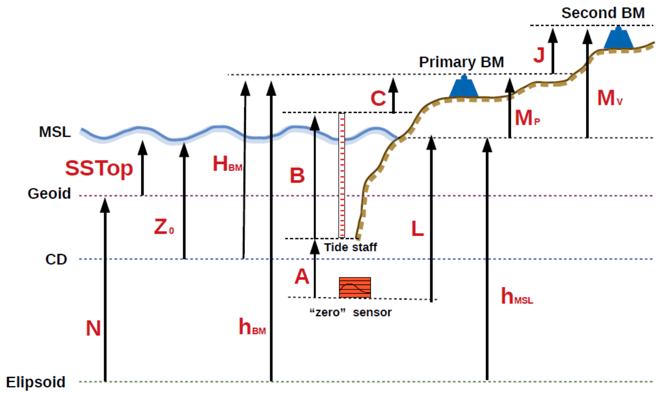

Fig. 1 – Components of the system for calculating the SSTop estimate. Fonte: Adapted from [10] and [16]

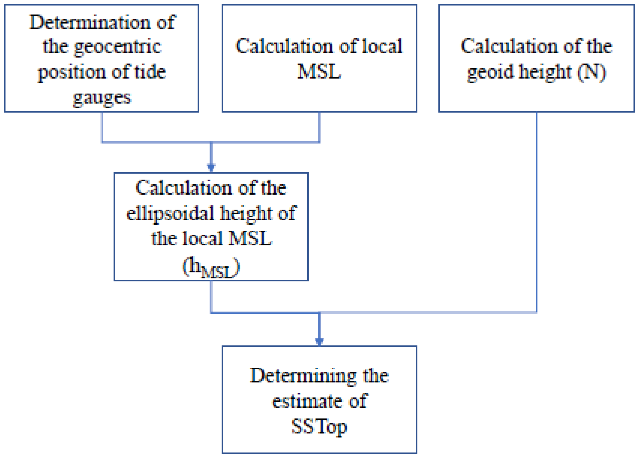

Fig. 2 – Flowchart for determining the SSTop value

For the proper reading and understanding of **figure 1**, which also presents the other magnitudes for linking the SSTop to the primary BM, it is necessary to:

- A - unevenness between the "zeros" of the tide gauges and the ruler, resulting from the measurement of the sensors obtained through the Van de Casteele Test [15];
- B - nominal reading of the pin/top of the ruler;
- C - unevenness of the pin/top of the ruler to the primary RN (geometric leveling of the ruler);
- J - unevenness between the primary and neighboring Level References (RRNN) (obtained through the scientific geometric leveling of the Geodetic Control of Tide Stations – CGEM [16];
- L - Average local sea level obtained from the tide sensor readings;
- Mp and Mv - height of the primary and neighboring BM above the local mean sea level [16].

Figure 2 shows the flowchart of the strategy used to determine the SSTop estimate, which will be detailed in the next sections.

Six sites distributed along the Brazilian coast were selected in order to have a better spatial representation of the Brazilian coast. Important points were also considered for studies aimed at monitoring the temporal and spatial evolution of Brazilian vertical data and their relationships with the other reference levels used in the coastal region. Are they: Imbituba-SC, as it is the Datum that covers most of the High Precision Altimetric Network; Niterói-RJ; Arraial do Cabo-RJ and Macaé-RJ, as they are part of the Coastal Reference Geodetic Network [17]; Salvador-BA and Fortaleza-CE, as they are located in the Northeast Region, complementing the spatial layout. In addition to the reasons explained, the sites of Imbituba-SC and Fortaleza-CE are stations chosen for studies on the International Height Reference System/Frame – IHRS/IHRF (see [3]).

2.1 Determination of the geocentric position of tide gauges

The strategy for determining the geocentric position of the tide gauges, materialized by the primary RRNN to which the sensors and tide rulers are linked, was based on the methodology presented by [18]. Three RRNN belonging to the sub-networks of each tide gauge with a Forced Centering Device (DCF) structure were selected, except for the Macaé site, which does not have the aforementioned device installed. **Figure 3** shows an BM model composed of DCF and carrying out the GNSS tracking with a 10 cm metallic support (in this case, the height of the antenna does not vary; in the case of Macaé, it does).

Fig. 3 – DCF deployed in a geodesic landmark.

A fundamental aspect of leveling within the CGEM, both for the DCFs and for the other geodetic control stations, is that better closure errors have been achieved than $1mm\sqrt{D}_{Km}$, where D is the length of a leveling section in kilometers. Given the above, the estimated ellipsoidal altitude (h_A), of the primary CD of the tide gauge, is given by Eq. (3):

$$h_A = h_B - \Delta J_{BA} \tag{3}$$

The data used came from the Global Navigation Satellite System (GNSS) surveys, referring to 4 sessions lasting 6 hours of tracking at an interval of 15 seconds (see [19]), and differences resulting from the CGEM of the year 2019, carried out by IBGE in the RMPG tide gauges. In the case of Macaé, the corresponding data from the CGEM for the year 2015 were used, since after the activities of this tide gauge ceased, no further controls were carried out.

The processing of the GNSS observations was performed using the Leica Infinity 3.1 software using the relative method for the SIRGAS week at the time of the survey. The reference ellipsoid was the GRS80.

Regarding the differences in levels used in the calculation, it should be noted that they were adjusted using the least squares method, in the Geodetic adjustment program using Helmert blocking Of Space and Terrestrial data (GHOST), with a standard deviation equal to $1mm\sqrt{D}_{Km}$. The mean permanent tide concept was used, therefore, it was also necessary to convert the ellipsoidal altitudes to the mean tide concept, as presented by [20]. **Table 1** presents the values of the estimated ellipsoidal altitude for each tide gauge according to Eq. (3), as well as its standard deviation.

Tab. 1 – Estimated ellipsoidal height for each site.

Tide gauge	Unevenness leveling geometric ΔJ_{BA} (m)	Calculated ellipsoidal height h_B (m)	Estimated ellipsoidal altitude h_A (m)	Standard deviation (m)
Niterói	0,450	-3,807	-4,257	0,006
Arraial do Cabo	-0,017	-2,973	-2,956	0,002
Macaé	0,257	-3,265	-3,522	0,001
Imbituba	5,950	9,253	3,0303	0,006
Salvador	0,676	-8,039	-8,716	0,002
Fortaleza	2,943	-2,582	-5,525	0,008

Complementarily, the height of the primary BM above the local mean sea level (MP) was calculated. For that, Eq. (4), which lists the components shown in **figure 1**. The results of MP values for each site studied are shown in **table 2**.

$$M_P = A + B + C - L \tag{4}$$

Tab. 2 – Ellipsoidal height of the primary BM

Tide gauge	A (m)	B (m)	C (m)	L (m)	Mp (m)
Niterói	0.001	3.800	-0.224	1.908	1.669
Arraial do Cabo	-0.002	3.013	1.463	1.739	2.735
Macaé	0.161	0.313	1.498	1.341	3.331
Imbituba	0.998	2.016	0.487	1.984	1.607
Salvador	5.015	4.015	0.233	7.283	1.980
Fortaleza	3.257	6.030	0.264	6.339	3.212

2.2 Calculation of the geoid height

According to [21], for the determination of the TNMM, the combined type models are more suitable, that is, models that, in addition to satellite data, have terrestrial gravimetry data, among other information, in their constitution. The XGM2019e is a combined type MGG that brought important innovations in its realization [22] and [23]. Brazil, through IBGE, contributed a dataset of 1.970 GNSS observations/leveling points to XGM2019e. This measure provided a significant improvement in standard deviation values, especially in the states of Rio de Janeiro and Santa Catarina, as reported by [24].

Another way to calculate the geoidal height for the Brazilian territory is through MAPGEO2015, available on the IBGE website (https://www.ibge.gov.br/geociencias/informacoes-sobre-posicionamento-geodesico/servicos-para-posicionamento -geodesico/10855-geoidal-wave-model.html?=&t=access-to-product). However, the model does not show data compatibility with the GGGs, as these are based on a series of parameters that consistently involve gravimetry by satellites and terrestrial observations of the entire globe, in addition to gravimetric information from the ocean. This information is fundamental to the consistency of data in coastal regions, the focus of this research. Additional information about MAPGGEO2015 can be found in [25].

In possession of the geocentric position of the reference of each tide gauge constant in this research, through the ICGEM website (http://icgem.gfz-potsdam.de/home) it was possible to calculate the geoid height for each of them. The reference ellipsoid was the GRS80, as was done in section 2.1. The tide concept was the average. The adoption of this concept for this research was based on the recommendation of the IAG in Resolution No. 1 of 2015, which is in line with what was established for the IHRS. The degree zero term was not considered. The function for the calculation was the geoid. Regarding the degree and order, it was used up to 2.190, the maximum development available up to the calculation date. Finally, the Gaussian filter was not used in order not to insert smoothing of the calculated surface. The calculation of the geoid height, to determine the SSTop, was performed using the MGG XGM2019e [22]. **Table 3** presents the values found for the geoid heights, referring to each site in this research, linked to the primary RRNN of each tide gauge.

Tab. 3 – Geoidal height for each site.

Tide gauge	Primary BM	Geoid height (m)
Niterói	2994L	-5.57
Arraial do Cabo	2987P	-5.30
Macaé	3086U	-6.31
Imbituba	3012X	1.75
Salvador	3640A	-10.62
Fortaleza	4336A	-8.49

2.3 Calculation of the local Sea Surface Topography

The determination of local mean sea levels was performed as described in [16]. Therefore, the computational tools applied to each calculation step came from the SLP 64 software package [26].

The observation period for determining the MSL in each surveyed site varies according to the date of installation of the tide gauge or the possibility of recovering the data. In this way, the limit period for most of the series is 2019, except for the Macaé tide gauge, which had an interruption in data collection in May 2015. Another relevant aspect is that the calculation of the local MSL did not take into account the correction of geodynamic effects. Faced with this question, the determined variations of MSL used here are relative. Additional information on this issue can be found in.

Once obtained the MSL values, these need to be referenced to the ellipsoid in order to satisfy the calculation of Eq. (2). In view of this need, through Eq. (5), the values of h_{MSL}.

$$h_{MSL}=h_A+M_P \quad (5)$$

Table 4 presents the MML values for each location contemplated in the survey and the observation period, as well as the MML height values referenced to the GRS80 ellipsoid.

Tab. 4–Sea Surface Topography for each site.

Tide gauge	MSL (m)	h_{MSL} (m)	Period of observation
Niterói	1.908	-5.926	2009-2019
Arraial do Cabo	1.739	-5.692	2009-2019
Macaé	1.341	-6.853	2001-2015
Imbituba	1.984	1.696	2001-2019
Salvador	7.283	-10.696	2004-2019
Fortaleza	6.339	-8.737	2008-2019

2.4 Determination of the local SSTop estimate

The Sea Surface Topography (SSTop) is the separation between the MSL and the geoid, so its determination can be obtained by the difference between the MSL referred to an ellipsoid (h_{MSL}) and the geoid height (N) from a MGG, Eq. (2) (shown in **table 3**). For that, it is necessary that the MSL be referenced to the same ellipsoid as the geoid heights.

The calculated SSTop was referenced to the primary RRNN of each tide gauge. Given that such RRNN are very close to the sensors, less than 3 m, it is assumed, therefore, that the variation of the geoidal gradient does not present significant differences. **Table 5** presents the estimated SSTop values referring to the tide gauges in this research calculated using Eq. (2).

Tab. 5 – Estimated Sea Surface Topography for each site.

Tide gauge	SSTop (m)
Niterói	-0.356
Arraial do Cabo	-0.395
Macaé	-0.538
Imbituba	-0.050
Salvador	-0.074
Fortaleza	-0.242

3. Analysis of results

The sites of Niterói, Arraial do Cabo and Macaé present SSTop values compatible with each other, thus indicating that the SSTop in the region does not present very significant variations. It is observed that as one moves from south to north such values gradually decrease, indicating how the geoid gradient behaves in relation to the MSL in the region. However, it is worth mentioning that the heterogeneity of sea level time series, GNSS observations and leveling can also introduce important deviations to the calculations.

The sites of Imbituba and Salvador have values close to SSTop, respectively 0.050 m and 0.074 m, despite having important peculiarities related to the nature of each site. As examples, the continental shelf, the meteorological regime, the temporality of the MSL series, among other aspects. In the research of [28] this similarity of values is pointed out. It is worth noting that the research used a different methodology from that addressed in this article: based on SSTop ocean models and referenced to the ellipsoid.

The SSTop value obtained for the Fortaleza site was -0.242 m (using the GRS80). The same station presented the value of -0.260 m in the investigation carried out by [29] when this author used the WGS84. The observed discrepancy translates, among other possible factors, the difference in ellipsoid, time and methodology of the GNSS survey. On the other hand, using the same ellipsoid (GRS80), the difference becomes 0.916 m, given that in [29] the value of the estimated SSTop is 0.674 m. It is essential to point out that the methodology employed by [29], despite having considered the same ellipsoid and the same MGG used here, have significant differences from this work.

On the other hand, the adoption of the same MGG makes it possible to make more adequate comparisons, mainly because the geoid height is one of the main factors in the calculation of the SSTop estimate (see Eq. (2). The adoption of the type of MGG for the solution is very important, as such a model may or may not be suitable for the study region. A comparison on this issue applied to Brazil can be seen in [23], in which five different GGMs are analyzed, including

XGM2019e, and their improvements in terms of standard deviation are presented.

Another fundamental aspect addressed in this research was the estimation analysis of the potential of the geoidal model (or quasi-geoidal). Ferreira *et al* [30] sustaining that it is possible to carry out such an analysis by comparing the values of geoidal height/height anomaly from GNSS observation/ Leveling with GGM derivatives. The same authors add that the standard deviation is the most suitable statistical resource for analyzing the results. When applying the aforementioned verification to the studied sites, values of standard deviations ranging from 0.004 m to 0.007 m were obtained, which indicates that the XGM2019e model is suitable for the researched regions. It should be noted that the smallest discrepancies were presented in the sites of Niterói-RJ and Arraial do Cabo-RJ and the largest in Salvador-BA and Fortaleza-CE, agreeing with the results found by [23].

The series used in the calculation of the MSL are factors that directly imply the determination of the SSTop. It is recommended that series of 18.6 years be used (complete cycle of nutation of the Moon) [1]. However, the sites adopted in this research do not have that number of observations.

The decision to use the periods in their entirety, instead of a common period of observations, lies in the fact that the shorter the period observed, the more favorable the risk of punctual variations affecting the values of the series, consequently causing fictitious trends. In this sense, simulations were carried out, which showed that the MSL estimates resulted in less homogeneous values as the observation time was reduced; in some cases, there was a significant increase in these values. This question points to the occurrence of seasonal factors in certain periods that may present negative or positive trends in the tide series.

Another relevant aspect, as mentioned in section 2.3, is that the calculation of the MSL did not take into account the correction of geodynamic effects, since the tide gauge stations in Niterói-RJ, Arraial do Cabo-RJ and Macaé-RJ do not have a Continuous GNSS that makes it possible to monitor the phenomenon of local crustal movement. As for the case of Imbituba-SC, Salvador-BA and Fortaleza-CE, which have continuous monitoring stations, there are issues related to the change of reference of the International GNSS Service [31] that require more rigorous corrections, but that are beyond the scope of this research.

The detection and quantification of vertical movements of non-oceanic origin are fundamental for the refinement of MSL values. They are also used to carry out a truly compatible comparison of SSTop values from global SSTop models, since these models do not suffer from possible deviations caused by vertical crustal movement, unlike sensors installed on the Earth's surface.

4. Conclusions

The essay for determining the SSTop estimate presented by this work brings contributions to the discussion about the current precepts of the determination of modern vertical references.

The calculation of the local MSL proved to be consistent with that carried out in 2016 by the IBGE [16]. Improvements in the analysis and insertion of data from the period 2016 to 2019 made it possible to better represent and understand the behavior of sea level rise trends, in addition to providing more refined series for geodetic studies, especially in series with periods of approximately 15 years, such as Macaé-RJ, Imbituba-SC and Salvador-BA.

The MGG used to determine the SSTop, the XGM2019e, was adequate for the study region in the degree and order used, that is, 2,190. It is expected that when this MGG reaches its maximum development of 5.540, it will be able to contribute with even more accurate solutions.

The strategy employed in this work indicated that the SSTop values for part of the Brazilian coast are consistent with the approaches that have been developed in other studies. These results can be used as subsidies for research that discusses the use and improvement of vertical references.

Despite the results allowing us to point out the behavior of the relationship between the geoid and the MSL along the Brazilian coast, it is still necessary to extend this study to other locations in order to better understand the SSTop panorama for Brazil. There are other places that have tidal and geodesic infrastructure that allow to improve this research, as an example, the tide gauge of Cananéia-SP.

It is also necessary to consider the need for further improvements in order to have the best possible refinement for the determination of the TNMM estimate. In this sense, it is essential to analyze the impacts of applying crustal movement rates to MSL values on tide gauges that have this information, especially those with a time series close to 18 years. Another relevant factor is to verify the use of global oceanic models for the calculation of the TNMM, with the purpose of evaluating the influence of the crustal movement in the determination of the variation of the MML.

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