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Absolute Comparison between Sentinel-3A Satellite and Tide Gauges Observations of RMPG in Imbituba, Arraial do Cabo, Salvador, Fortaleza and Santana

Comparação Absoluta entre Observações do Satélite Sentinel-3A e dos Marégrafos da RMPG em Imbituba, Arraial do Cabo, Salvador, Fortaleza e Santana

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Abstract: Coastal regions are of great interest for geodetic and geophysical studies, since in them resides a significant portion of the population. The improvement of satellite altimetry over the years has enabled better observations in these regions, mainly using Synthetic Aperture Radar (SAR) technology. The present study aims to analyze, absolutely, the tide gauges data (SSH_{TG}) of the RMPG in Imbituba-SC, Arraial do Cabo-RJ, Salvador-BA, Fortaleza-CE and Santana-AP and of altimetric observations (SSH_{SA}) from the Sentinel-3A satellite arranged in cells within a radius of up to 100 km over the ocean from the location of the tide gauges stations, for the period between November 2017 and April 2020. In each tide gauge station was chosen the closest altimetry cell and that obtained the best correlation with the tide gauge data, and then this cell was extrapolated to the coast (SSH_{SA-TG}) using a Global Geopotential Model (GGM) and a Mean Dynamic Topography (MDT). The results indicated correlations equal and above 0.90 in all tide gauges and highlights the small distances between the altimetry cells and the tide gauges in Arraial do Cabo, Salvador and Fortaleza, presenting values of 5.37 km, 4.51 km and 4.62 km, respectively. The averages of SSH_{TG} and SSH_{SA-TG} did not show significant differences in all analyzed tide gauges, as they were within the standard deviation range. The main contribution of this work was to verify the quality of SAR altimetry in the Brazilian coast.
Keywords: Tide Gauge. Satellite Altimetry. GGM. MDT.

Resumo: As regiões costeiras são de grande interesse para estudos geodésicos e geofísicos, uma vez que nelas reside uma parcela significativa da população. O aperfeiçoamento da altimetria por satélite ao longo dos anos tem possibilitado melhores observações nestas regiões, principalmente, a partir da tecnologia de Radar de Abertura Sintética (SAR). O presente estudo visa analisar, absolutamente, os dados maregráficos (SSH_{TG}) da RMPG em Imbituba-SC, Arraial do Cabo-RJ, Salvador-BA, Fortaleza-CE e Santana-AP e de observações altimétricas (SSH_{SA}) provenientes do satélite Sentinel-3A dispostas em células num raio de até 100 km sobre o oceano a partir da localização das estações maregráficas, para o período entre novembro de 2017 e abril de 2020. Em cada estação maregráfica foi escolhida a célula altimétrica mais próxima e que obteve a melhor correlação com os dados maregráficos, e na sequência está célula foi extrapolada até costa (SSH_{SA-TG}) com o uso de um Modelo Global do Geopotencial (MGG) e de um *Mean Dynamic Topography* (MDT). Os resultados indicaram correlações iguais e acima de 0,90 em todos os marégrafos e destaca-se as pequenas distâncias entre as células de altimetria escolhidas e os marégrafos em Arraial do Cabo, Salvador e Fortaleza, apresentando os valores de 5,37 km, 4,51 km e 4,62 km, respectivamente. As médias de SSH_{TG} e SSH_{SA-TG} não apresentaram diferenças significativas em todos os marégrafos analisados, pois se encontraram dentro do intervalo do desvio-padrão. A principal contribuição deste trabalho foi verificar a qualidade da altimetria SAR na costa brasileira.
Palavras Chave: Marégrafo. Altimetria por satélite. MGG. MDT.

1 INTRODUCTION

Sea level monitoring has become a relevant practice within Geodesy, which is a science that allows measurement and analysis of phenomena and effects related to the Earth's physical processes and, in this way, contributes significantly to studies related to a series of geodynamic processes and global climate change (DREWES, 2006).

According to Arias et al. (2021), the global mean sea level increased by 0.20 m between 1901 and 2018 with the mean trend in sea level rise being 1.3 mm/yr between 1901 and 1971, increasing to 1.9 mm/yr between 1971 and 2006, and increasing further to 3.7 mm/yr between 2006 and 2018. These values indicate an acceleration of global sea level rise over the years and which is expected to continue throughout the 21st century. The same authors indicate that among the main causes of this increase is global warming that causes loss of continental ice sheets and thermal expansion of the oceans.

The estimated global population living in regions no higher than 5 meters above sea level was 290 million in 1900, 380 million in 2010, 460 million in 2030 and 495 million in 2050 (KUMMU et al., 2016). Brazil still lacks estimates of the population living in coastal regions exposed to sea level rise, however the special report of the Brazilian climate change panel about the impact, vulnerability and adaptation of Brazilian coastal cities to climate change indicates that more than 60% of the Brazilian population lives in coastal cities (PBMC, 2016).

In addition to tide gauge data, sea level monitoring can be performed through satellite altimetry data, which has been improved over the years, thus enabling better observations in coastal regions, mainly through Synthetic Aperture Radar (SAR) technology. The basic working principle of the satellites known in the literature as conventional altimetry or Low Resolution Mode (LRM) satellites, such as the Jason 1, 2 and 3 missions, consists in transmitting a pulse of electromagnetic radiation (microwaves) in a nadiral direction to the sea surface. This pulse interacts with the sea surface and is reflected back to the altimeter's receiver. The travel time between transmission and reception of the signal multiplied by speed of light propagation in vacuum, makes it possible to determine the distance between the satellite and the sea surface (SEEBER, 2003; CHELTON et al., 2001). However, these satellites lose resolution near the coast due to the roughness of the sea surface resulting from disturbances caused by shallow sea depth and interference of the terrain in the return signal (DALAZOANA, 2006).

A significant improvement in the quality of altimetric observations in coastal oceanic regions has come from satellites operating in SAR mode, also called delay/Doppler altimeter (DDA), where the footprint area is smaller, enabling an increase in the number of observations and, consequently, providing better estimates of geophysical parameters than conventional altimetry (RANEY, 1998). The CryoSat-2, Sentinel-3A and Sentinel-3B missions were the first to explore the SAR mode (ESCUDIER et al., 2017).

According to Liebsch et al. (2002), the problems in comparing tide gauge and satellite altimetry data are that they do not refer to the same vertical reference system and do not overlap, i.e., they are observed at different locations, thus requiring application of an extrapolation method.

Therefore, comparison of tide gauge data and satellite altimetry data can be done in either a relative or an absolute manner. When using relative comparison, the analysis aims to verify that both data are observing the same ocean signal and, therefore, the data do not need to be converted to a common vertical reference (GIEHL, 2020; MONTECINO et al., 2017). The relative form enables comparison of data coming from satellites and tide gauge stations that do not have, in their proximity, a Global Navigation Satellite System (GNSS) continuous monitoring station. On the other hand, when using the absolute form, both data sets are referenced to the Earth's geocenter (LIEBSCH et al., 2002; ACUÑA; BOSCH, 2003; DALAZOANA, 2006; DA SILVA; DE FREITAS, 2014). The absolute form enables, for instance, analysis of altimetric satellite stability by means of tide gauge data (MITCHUM, 1998). As such, it is essential that tide gauge stations have, in their vicinity, continuous GNSS monitoring stations to reference tide gauge data in the absolute form. In Brazil, stations forming part of the Brazilian Network for Continuous Monitoring of GNSS Systems (Rede Brasileira de Monitoramento Contínuo dos Sistemas GNSS - RBMC) have been installed close to each tide gauge of the Geodetic Permanent Tide Gauge Network (*Rede Maregráfica Permanente para Geodésia* - RMPG).

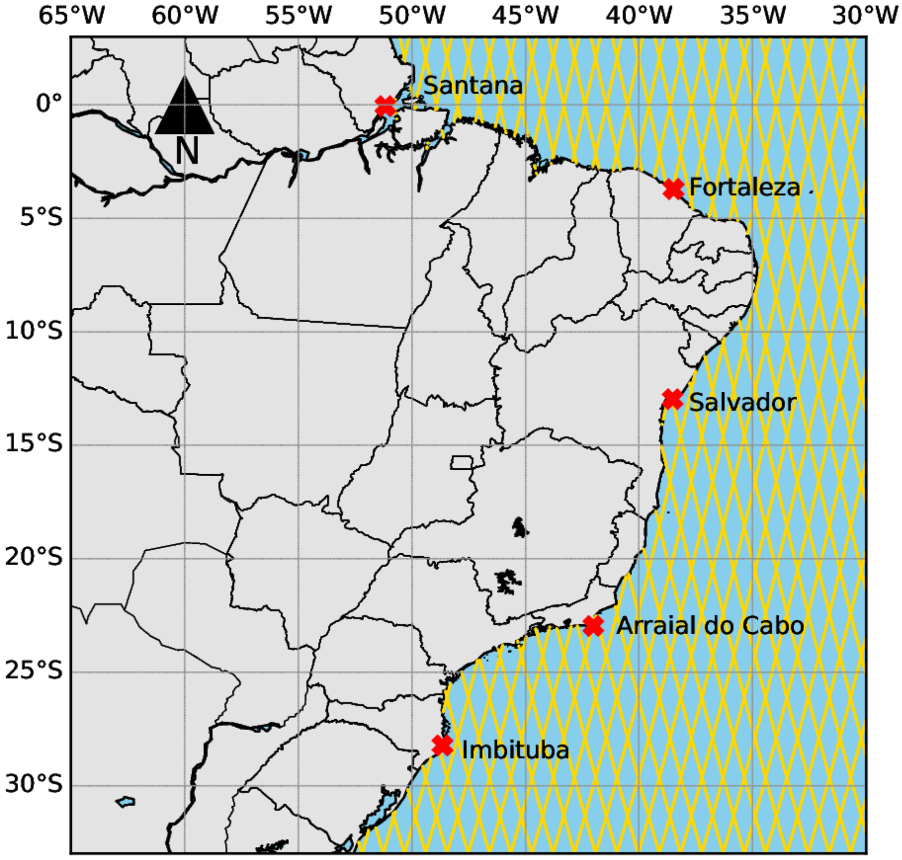
Studies related to the integration of tide gauge and altimetry data in Brazil are concentrated in Imbituba-SC and are based on conventional altimetry, such as the Topex/Poseidon, Jason 1, 2 and 3 missions (DALAZOANA, 2006; DA SILVA, 2017; GIEHL, 2020). As such, the objective of the present study is to perform absolute analysis between the data observed by the Sentinel-3A satellite (SSH_{SA}) and data from RMPG tide gauges in Imbituba (Santa Catarina), Arraial do Cabo (Rio de Janeiro), Salvador (Bahia), Fortaleza (Ceará) and Santana (Amapá) (SSH_{SA}). The satellite altimetry data were split into cells and extrapolated to the location of the tide gauge stations (SSH_{SA-TG}) based on the XGM2019e_2159 Global Geopotential Model (GGM) and the global Mean Dynamic Topography (MDT) model, referred to as CNES-CLS18. The nearest cell with the best correlation within a radius of 100 km over the ocean from each tide gauge location was used to analyze the absolute comparison between SSH_{SA-TG} e SSH_{TG}.

2 METHODS

2.1 Study area

In this study we used tide gauge data from the RMPG stations. The location of the tide gauges and Sentinel-3A satellite tracks along the Brazilian coast (in yellow) are shown in Figure 1. SSH_{SA} observations can be seen very close to the Brazilian coast and also within the Amazon River and some bays. The SSH_{SA} values were obtained from cells made along the Sentinel-3A satellite tracks within a 100 km radius over the ocean from the location of each tide gauge.

Figure 1 – Location of the tide gauges and Sentinel-3A satellite tracks along the Brazilian coast.



Source: The Authors (2022).

2.2 Tide gauge data

The tide gauge data used in this study were obtained from the RMPG, comprising the period between November 2017 and April 2020. This time period was delimited according to the range of the Sentinel-3A satellite data, provided by the *Deutsches Geodätisches Forschungsinstitut Technische Universität München* (DGFI). The Belém tide gauge was not used due to the amount of missing data for the period analyzed. The time series are sampled in hourly time intervals and are referenced to a local vertical reference (established by IBGE). In this way, these data were linked to the Brazilian Geodetic System (ellipsoid GRS80/SIRGAS2000) as shown in Eq. (1) and (2) (IBGE, 2021).

$$SSH_{TG} = NM_{TG} - S \tag{1}$$

$$S = A + B + C + J - T \tag{2}$$

where SSH_{TG} is the observed Sea Surface Height in relation to the reference ellipsoid (Figure 2), NM_{TG} is the observed sea level height in relation to the sensor "zero", A is the difference between the tide gauge "zeros" and those of the tide staff, resulting from sensor readings (Van de Casteele Test), B is the nominal reading from the pin/top of the tide staff, C is the height difference between the pin/top of the tide staff and the prime benchmark (BM) (obtained through spirit leveling of the tide staff), T is the ellipsoidal height of the neighboring benchmark and J is the monitored stability of the benchmarks arounding the tide gauge station by spirit leveling. Table 1 shows the reference levels at the RMPG stations in Imbituba, Arraial do Cabo, Salvador, Fortaleza and Santana using the mean tide system.

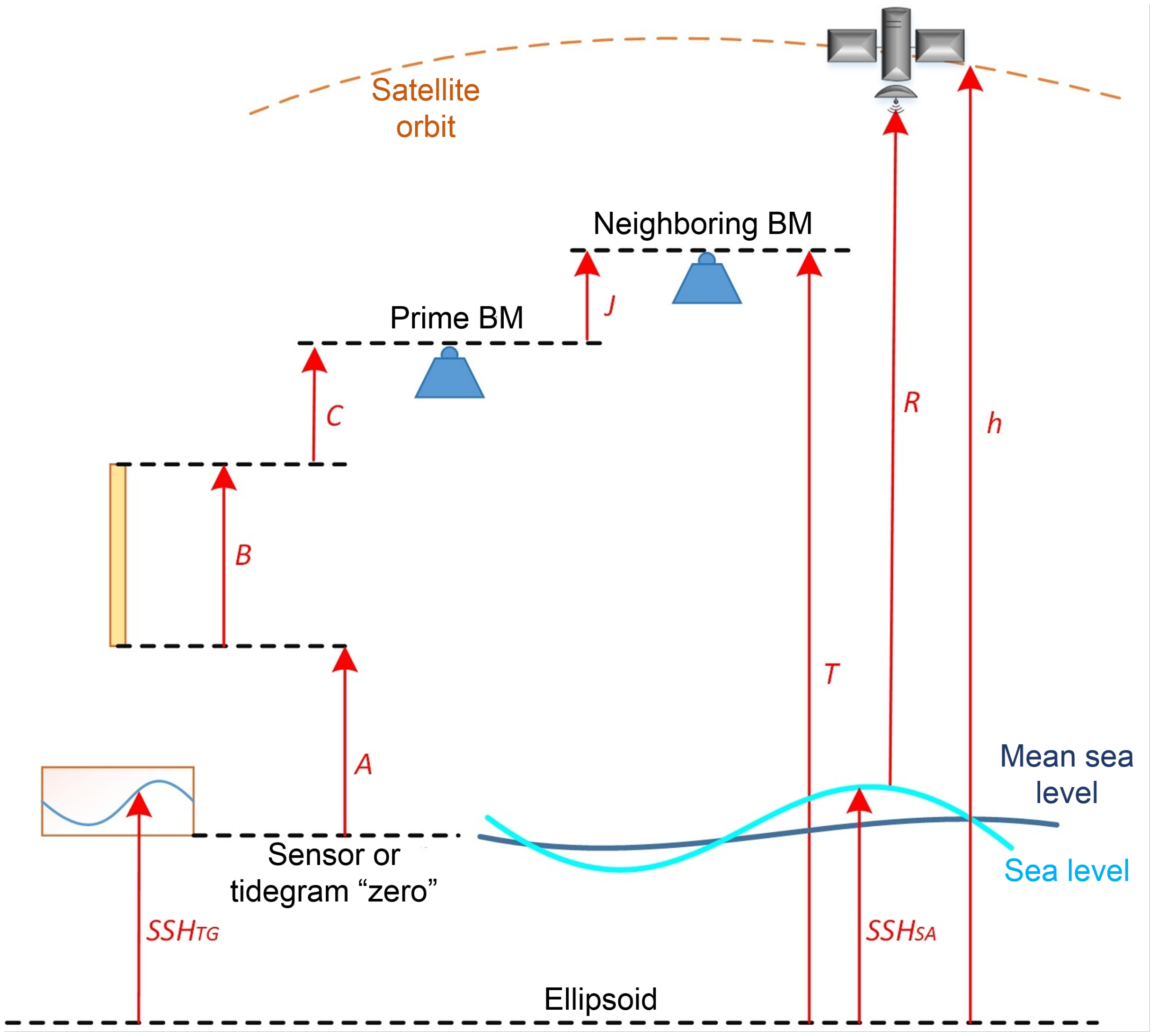
Table 1 – Reference Levels at the RMPG stations in Imbituba, Arraial do Cabo, Salvador, Fortaleza and Santana.

Magnitude	**Imbituba**	**Arraial do Cabo**	**Salvador**	**Fortaleza**	**Santana**
A (m)	0.983 ± 0.023	-0.002 ± 0.035	5.043 ± 0.066	3.257 ± 0.036	0.051 ± 0.017
B (m)	2.016 ± 0.001	3.013 ± 0.001	4.015 ± 0.001	6.030 ± 0.001	6.010 ± 0.001
C (m)	0.4874 ± 0.0001	1.4630 ± 0.0001	0.2325 ± 0.0000	0.2637 ± 0.0002	1.4049 ± 0.0002
J (m)	4.4580 ± 0.0001	0.0214 ± 0.0001	0.2703 ± 0.0001	0.057 ± 0.0001	0.0628 ± 0.0001
T (m)	7.788 ± 0.003	-2.945 ± 0.001	-8.449 ± 0.002	-5.480 ± 0.001	-17.751 ± 0.001
S (m)	0.157 ± 0.023	7.440 ± 0.035	18.010 ± 0.066	15.088 ± 0.036	25.280 ± 0.017

Source: IBGE (2022a, 2022b, 2022c, 2022d, 2022e).

The relationship between the tide gauge reference levels shown in Table 1 and some magnitudes associated with satellite altimetry are presented in Figure 2.

Figure 2 – Relationship between tide gauge reference level and some satellite altimetry magnitudes.



Source: Adapted from IBGE (2021) and Lu, Qu e Qiao (2014).

2.3 Satellite altimetry data

In this study we used SSHSA data produced by the Sentinel-3A altimetric satellite between 11/23/2017 and 04/05/2020. This satellite was launched by the European Space Agency in February 2016, has a temporal resolution of 27 days and operates at an altitude of 814.5 km in a polar orbit synchronous with the Sun (AVISO, 2022a). The Sentinel-3A satellite together with its twin, Sentinel-3B, are part of the Sentinel-3 mission under the Copernicus program that aims to provide services mainly applied to the ocean such as numerical ocean prediction, maritime safety and security, coastal zone monitoring, ocean and ice monitoring (COPERNICUS PROGRAMME, 2022).

The SSH_{SA} values are processed by the *Deutsches Geodätisches Forschungsinstitut Technische Universität München* (DGFI) and made available through the Open Altimeter Database (OpenADB) at a sampling rate of 1 Hz which corresponds to a measurement being taken at approximately 7 km intervals along the track (SCHWATKE et al., 2010). Therefore, cells 7 km long and 3 km wide were created along the Sentinel-3A satellite tracks, considering a radius of up to 100 km over the ocean from the location of the Imbituba, Arraial do Cabo, Salvador, Fortaleza and Santana tide gauges. According to DGFI (2022), the satellite altimetry data used in this study are processed by an Adaptive Leading Edge Subwaveform Retracker (ALES) which improves sea level estimates in coastal regions and offshore in terms of noise content. More details about processing can be found in Passaro et al. (2014),Passaro, Fenoglio-Marc e Cipollini (2015) and Passaro et al. (2017). In addition, orbit, tidal and atmospheric corrections are applied, among others. Thus, in order to assume that the data from the altimetric satellites and the tide gauges were observing the same ocean signal, we removed the ocean tide and ocean load corrections from the SSHSA values by means of the Empirical Ocean Tide Model from Multi-Mission Satellite Altimetry (EOT11a) (SAVCENKO; BOSCH, 2012) as well as the high and low frequency atmospheric corrections, using the Dynamic Atmospheric Correction (DAC) model, available from the Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) facility.

The SSH_{SA} values are observed in relation to the Topex/Poseidon (T/P) ellipsoid, while the SSH_{TG} values were referenced to the GRS80 ellipsoid, as described in Section 2.2. As such, in order to make the reference system compatible, the SSH_{SA} values were converted to the GRS80 ellipsoid using the formula described in Renganathan (2010):

$$\delta_h = h_1 - h_2 = -((a_2 - a_1)(cos\Psi)^2 + (b_2 - b_1)(sin\Psi)^2) \tag{3}$$

where δ_h corresponds to the difference between heights h_1 and h_2 referenced to the two ellipsoids, a_1 and a_2 are the semi-major axes and b_1 and b_2 are the semi-minor axes of the T/P and GRS80 ellipsoids, as shown in Table 2, and Ψ is the geocentric latitude of the point of interest for the conversion that is wanted. The δ_h values are in the order of 70 centimeters (RENGANATHAN, 2010).

Table 2 – Ellipsoidal parameters used in the study.

Ellipsoid	**T/P**	**GRS80**
a (m)	6378136.3	6378137.0
b (m)	6356751.600563	6356752.31414

Source: Renganathan (2010) and Moritz (2000).

The cells containing the SSH_{SA} values were correlated with the SSH_{TG} values for the Imbituba, Arraial do Cabo, Salvador, Fortaleza and Santana tide gauges. Temporal integration was done by taking the hourly SSH_{TG} value that most closely matched the SSH_{SA} observations. After determining the correlation coefficients, we chose the altimetry cell to be used in the absolute comparison with the tide gauge data, according to two conditions:

a) Choosing the cells contained in the range comprising the “Very Strong Correlation” classification for each tide gauge, as shown in Table 3; and

b) Choosing each tide gauge’s closest cell from among the cells defined in item a.

Table 3 – Interpretation of the Pearson correlation.

Correlation coefficient (+ or -)	**Interpretation**
0.00 a 0.19	Very weak correlation
0.20 a 0.39	Weak correlation
0.40 a 0.69	Moderate correlation
0.70 a 0.89	Strong correlation
0.90 a 1.00	Very strong correlation

Fonte: Shimakura (2006).

Following this, in order to facilitate the written description, the cells that met the conditions set forth above, in each tide gauge, were called “chosen cells”.

Finally, the SSH_{SA} data were extrapolated to the position of the Imbituba, Arraial do Cabo, Salvador, Fortaleza and Santana tide gauges using a GGM model and an MDT model, as will be seen in greater detail in the next Section.

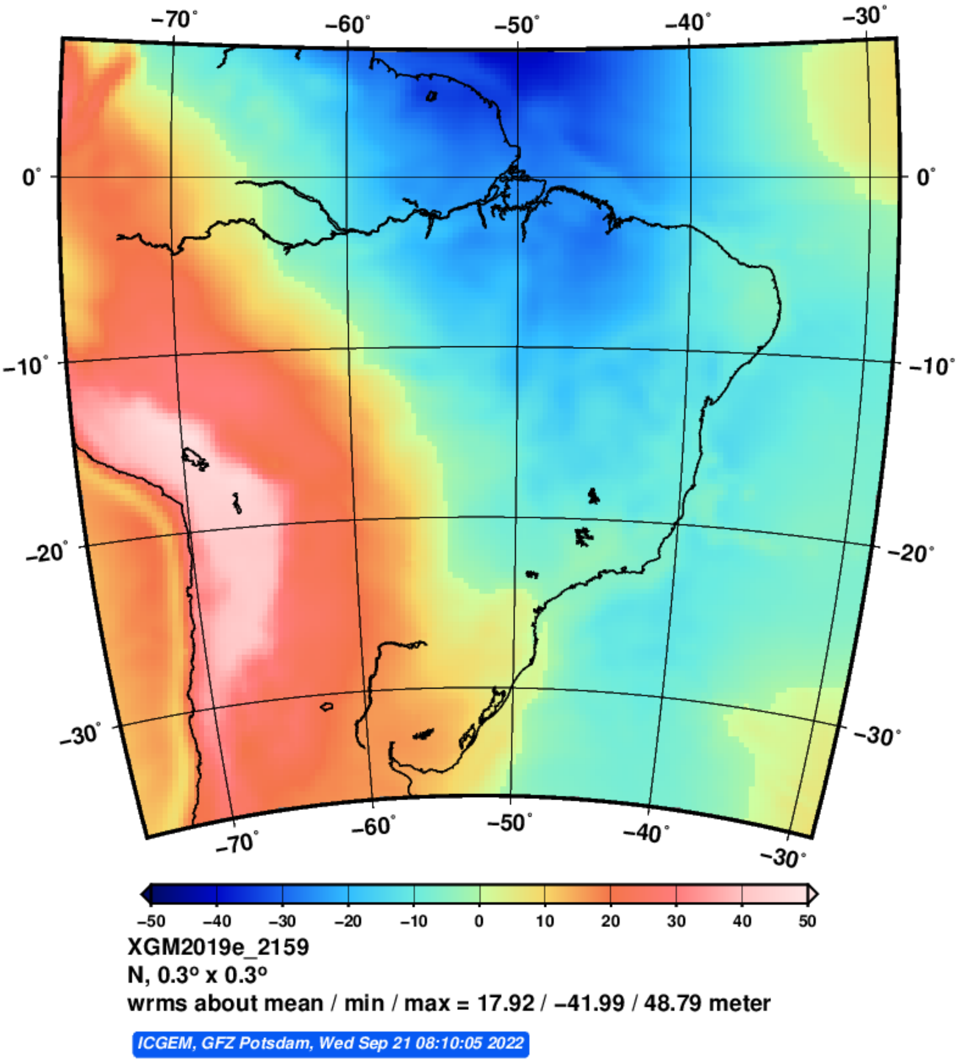
2.4 Extrapolation of the altimetric data to the coast

According to Acuña e Bosch (2003), the main critical factor between tide gauge and satellite altimetry data comparison is the fact that satellite altimetry observations cannot be obtained at the tide gauge location, because the altimeter radar signal is generally corrupted when the footprint includes the land surface in coastal regions.

As the satellite tracks do not pass over the tide gauge locations, the SSH_{SA} data need to be extrapolated to the coast. According to Liebsch et al. (2002), it would be recommendable to use accurate regional geoids, however, due to the unavailability of these models in the study area, in this work we used the XGM2019e_2159 GGM, according to the mean tide system, to extrapolate the altimetric data to the location of each tide gauge. The XGM2019e_2159 GGM was developed from the expansion of gravitational potential into spherical harmonics to degree and order 2159. It is classified as a combined data model that includes the GOCO06s satellite-only global gravity field model in the longer wavelength range and Earth gravity data which covers the shorter wavelengths (ZINGERLE et al., 2020).

The GGM data were obtained from the International Center for Global Gravity Field Models (ICGEM) via its calculation service, using the user-defined points option, taking as input data the coordinates of the tide gauges and the mean coordinates referring to the cell that correlated best in each tide gauge (ICGEM, 2022). Figure 3 shows the XGM2019e_2159 model in the study area, in which a geoidal height variation of approximately 5 m to -25 m along the Brazilian coast can be seen.

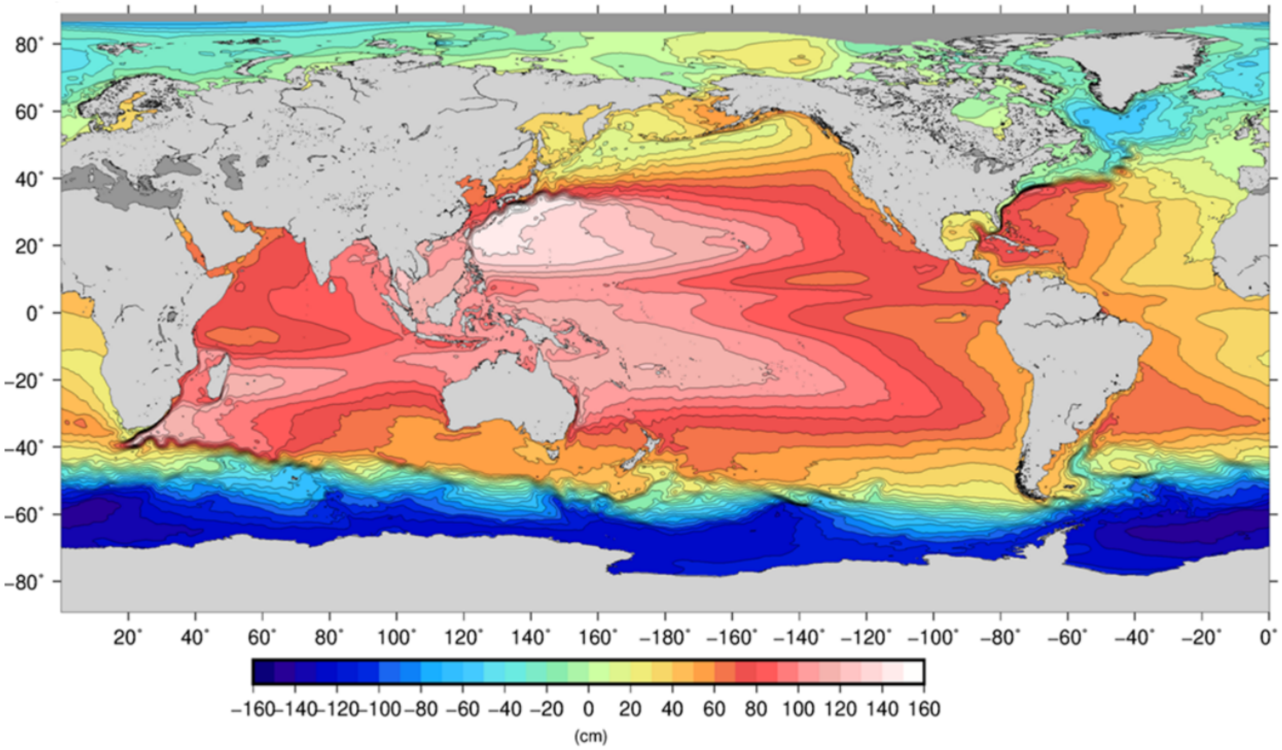
Figure 3 – XGM2019e_2159 Model.



Source: ICGEM (2022) and Zingerle et al. (2020).

In addition to the GGM model, we also applied a global MDT model, named CNES-CLS18, which provides the distance between mean sea level and the geoid. This model was developed using satellite altimetry data, gravity field provided by the GRACE and GOCE missions, and in situ oceanographic measurements (MULET et al., 2021). This model was obtained from AVISO (AVISO, 2022b). Figure 4 shows the CNES-CLS18 MDT global values.

Figure 4 – CNES-CLS18 Global Model.



Source: Mulet et al. (2021).

The chosen altimetric cell was extrapolated to the location of its respective tide gauge (SSH_{SA-TG}) by subtracting SSH_{SA} with both the geoidal height difference (dN) and the mean dynamic topography difference (dh_{MDT}) obtained for the locations of the Imbituba, Arraial do Cabo, Salvador, Fortaleza and Santana tide gauges and cells, respectively, as shown in Eq. (4) (LIEBSCH et al., 2002):

$$SSH_{SA-TG} = SSH_{SA} - dN - dh_{MDT} \tag{4}$$

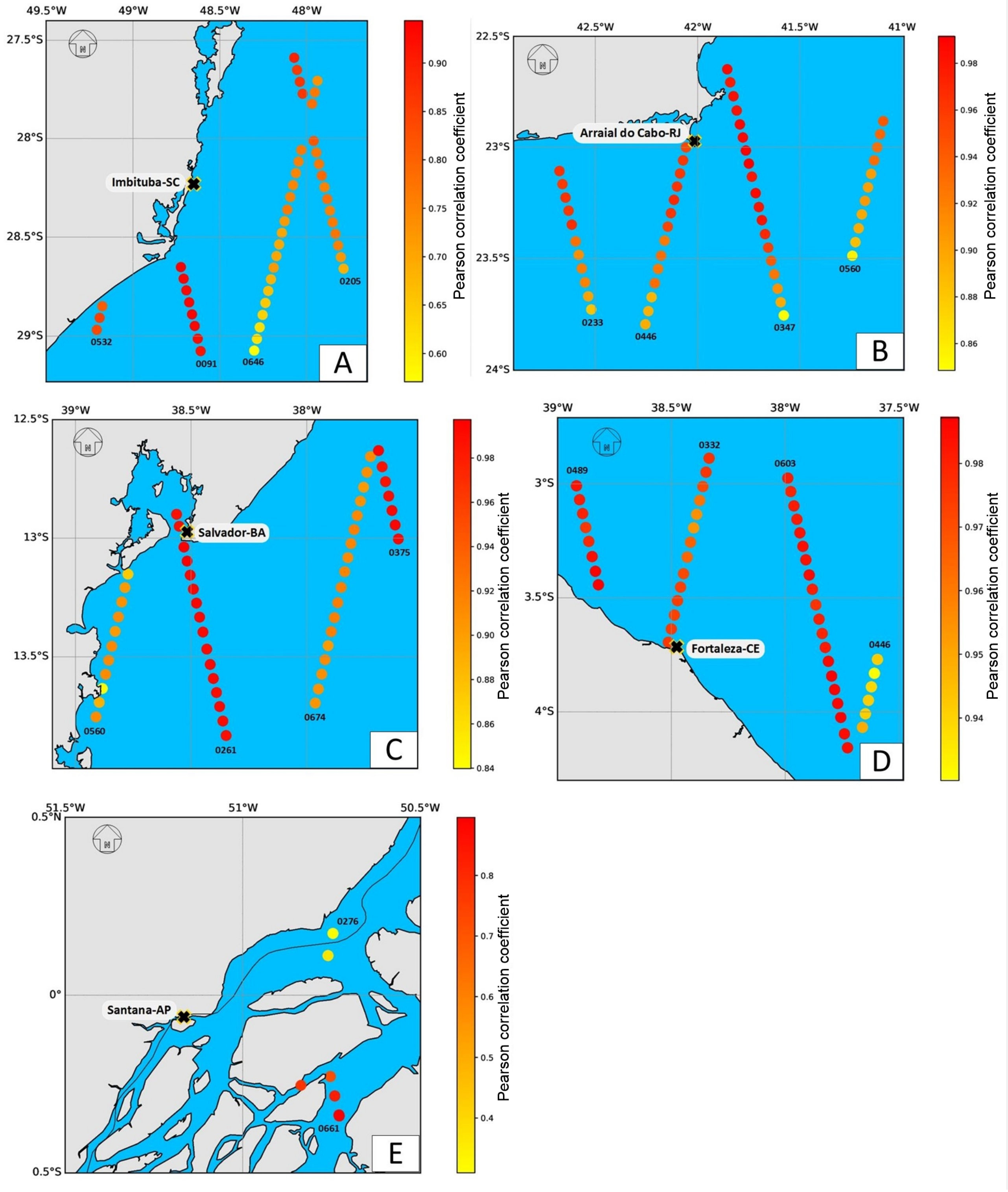
Finally, in order to attest the quality of the Sentinel-3A satellite observations of the Brazilian coast, we analyzed the correlations and mean values along with the respective deviations between SSH_{SA-TG} and SSH_{TG}. Furthermore, the distances between the cells and the tide gauges were also discussed, since, in Geodesy, it is desirable that this distance be as short as possible without affecting the quality of the altimetric observations.

3 RESULTS AND DISCUSSION

Integration between the tide gauge data from the Imbituba, Arraial do Cabo, Salvador, Fortaleza and Santana stations and the altimetry cells located along the Sentinel-3A satellite tracks, created at a distance of 100 km from the tide gauges, predominantly showed strong and very strong correlations according to Shimakura (2006) classification, as can be seen in Figure 5.

Creating altimetry cells within the area delimited by a 100 km radius over the ocean from each tide gauge led to the creation of 48 cells along tracks 0532, 0091, 0646 and 0205 at Imbituba (Figure 5A), 55 cells along tracks 0233, 0446, 0347 and 0560 at Arraial do Cabo (Figure 5B), 52 cells along tracks 0560, 0261, 0674 and 0375 at Salvador (Figure 5C), 48 cells along tracks 0489, 0332, 0603 and 0446 at Fortaleza (Figure 5D) and 6 cells along tracks 0276 and 0661 at Santana (Figure 5E). In Santana the cells were located inside the Amazon River and Vieira Grande Bay, where the land-water interface can corrupt the satellite signal, but even so, very strong correlations were obtained in 4 of the 6 cells (Figure 5E). These altimetric cells can contribute to future research, since Santana together with Imbituba define the Official Brazilian Vertical Datum.

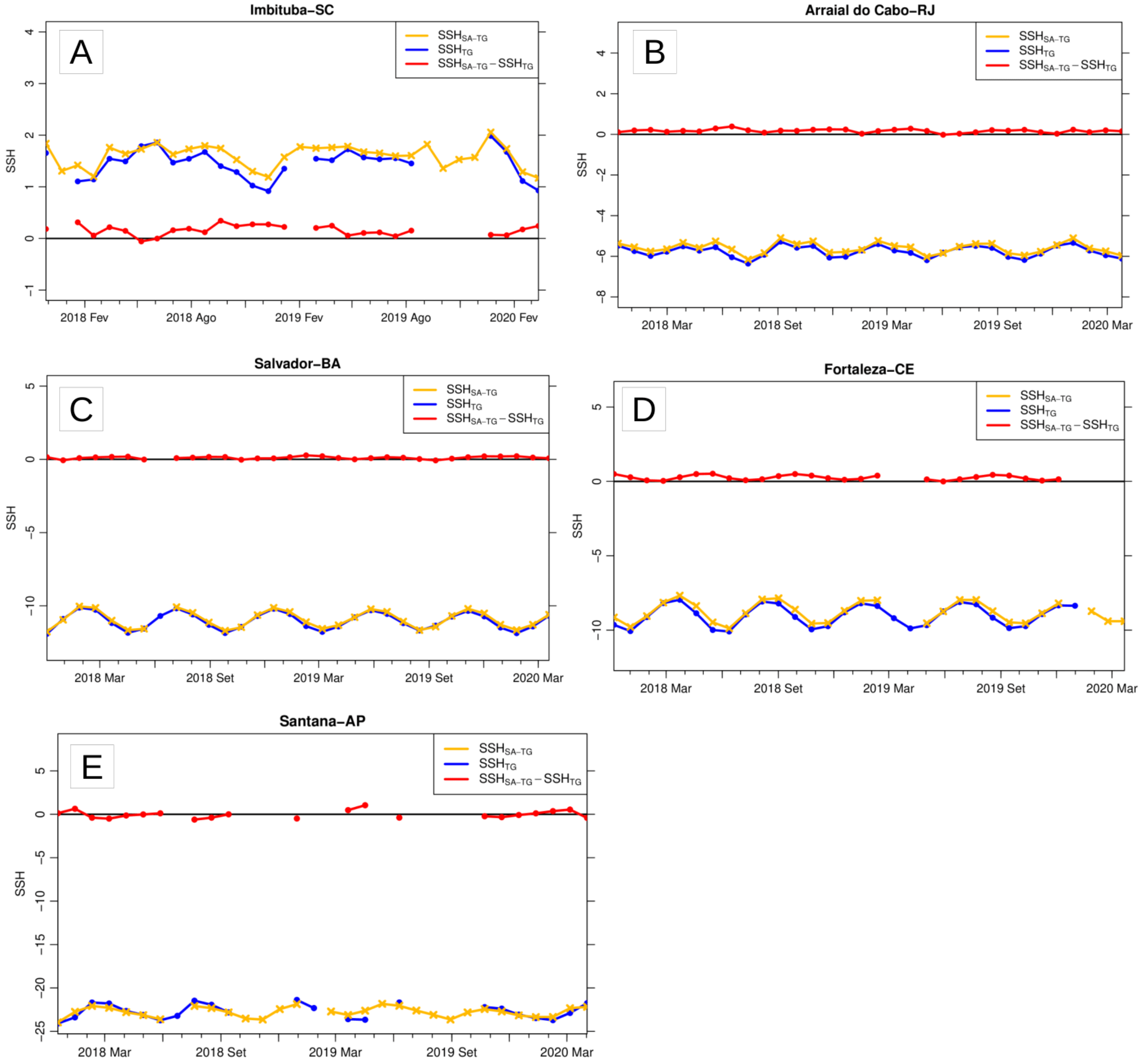
Figure 5 – Correlation between SSH_{TG} and SSH_{SA} along the Sentinel-3A satellite tracks at Imbituba, Arraial do Cabo, Salvador, Fortaleza and Santana.



Source: The Authors (2022).

Figure 6 presents graphs for the SSH_{TG} values (blue line) from the tide gauges at Imbituba (Figure 6A), Arraial do Cabo (Figure 6B), Salvador (Figure 6C), Fortaleza (Figure 6D) and Santana (Figure 6E) and graphs for the SSH_{SA-TG} values (yellow line) from the altimetry cells obtained via the Sentinel-3A altimetry satellite that correlated best and closest to the tide gauges. The data period is from 11/23/2017 to 04/05/2020. Figure 6 also shows the residuals generated by the difference between SSH_{SA-TG} and SSH_{TG} (red line).

Figure 6 – Comparison between SSH_{SA-TG} and SSH_{TG} at Imbituba, Arraial do Cabo, Salvador, Fortaleza and Santana.



Source: The Authors (2022).

Table 4 shows the geodetic coordinates of the tide gauges and the chosen cells and their respective distances, while Table 5 shows the correlation coefficient, mean and standard deviations for SSH_{SA-TG} and SSH_{TG} values and their respective differences. Noteworthy are the small distances found between the chosen cells and the tide gauges in Arraial do Cabo, Salvador and Fortaleza, namely 5.37 km, 4.51 km and 4.62 km, together with the high correlations (0.95, 0.99 and 0.98), respectively. This fact demonstrates the potential of the Sentinel-3A mission in coastal regions and integration with these tide gauges for future research. At Imbituba and Santana, larger distances of 47.39 km and 57.67 km were found, and correlations of 0.94 and 0.90, respectively. Based on Shimakura (2006), the correlations between the altimetry data and the data from all the tide gauges were classified as very strong (0.90 - 1.00).

Table 4 – Geodetic coordinates of the tide gauges and chosen cells and their respective distances.

Tide gauge	**Tide gauge latitude (degrees)**	**Tide gauge longitude (degrees)**	**Cell latitude (degrees)**	**Cell longitude (degrees)**	**Distance between tide gauge-cell (km)**
Imbituba	-28.23119444	-48.65057222	-28.6519254688	-48.72458075	47.39
Arraial do Cabo	-22.97250000	-42.01361111	-23.0002515313	-42.0564230937	5.37
Salvador	-12.97396944	-38.51720833	-12.9504174839	-38.5510247097	4.51
Fortaleza	-3.714597222	-38.47681667	-3.6944926897	-38.513249931	4.62
Santana	-0.3397755667	-50.7289276333	-0.06138888889	-51.16583333	57.67

Source: The Authors (2022).

According to Table 5, the mean SSH_{SA-TG} and SSH_{TG} values were, respectively, 1.61 m ± 0.22 m and 1.46 m ± 0.28 m at Imbituba, -5.59 m ± 0.27 m and -5.77 m ± 0, 28 m at Arraial do Cabo, -10.93 m ± 0.57 m and -11.03 m ± 0.57 m at Salvador, -8.80 m ± 0.67 m and -9.02 m ± 0.72 m at Fortaleza and -22.78 m ± 0.58 m and -22.69 m ± 0.84 m at Santana. As such, the SSH_{SA-TG} and SSH_{TG} values do not present significant differences, since their means are within the standard deviation range.

Table 5 – Correlation coefficients, means and standard deviations for the SSH_{SA-TG} and SSH_{TG} values and their respective differences.

Tide gauges	**Correlation coefficient**	**Mean** SSH_{SA-TG} **(m)**	**Mean** SSH_{TG} **(m)**	**Mean residual** SSH_{SA-TG}-SSH_{TG} **(m)**
Imbituba	0.94	1.61 ± 0.22	1.46 ± 0.28	0.16 ± 0.10
Arraial do Cabo	0.95	-5.59 ± 0.27	-5.77 ± 0.28	0.17 ± 0.09
Salvador	0.99	-10.93 ± 0.57	-11.03 ± 0.57	0.11 ± 0.08
Fortaleza	0.98	-8.80 ± 0.67	-9.02 ± 0.72	0.25 ± 0.16
Santana	0.90	-22.78 ± 0.58	-22.69 ± 0.84	-0.03 ± 0.44

Source: The Authors (2022).

Regarding the mean values of the residuals generated by the difference between SSH_{SA-TG} and SSH_{TG} shown in Table 5, we found values with variation in the first and second decimal place, being 0.16 ± 0.10 in Imbituba, 0.17 m ± 0.09 m in Arraial do Cabo, 0.11 m ± 0.08 m in Salvador, 0.25 m ± 0.16 m in Fortaleza and -0.03 m ± 0.44 m in Santana. Analyzing the standard deviation of the residuals, it can be seen that the greatest dispersion, in descending order, was in Santana (0.44 m), Fortaleza (0.16 m), Imbituba (0.10 m), Arraial do Cabo (0.09 m) and Salvador (0.08 m). In Santana, the missing values found in the tide gauge data and the complexity of the region for satellite altimetry observations may have contributed to this greater dispersion.

Table 6 shows the *N* (XGM2019e_2159) values and the h_{MDT} (CNES-CLS18) values used to extrapolate the chosen altimetry cells to the Imbituba, Arraial do Cabo, Salvador, Fortaleza and Santana tide gauges, as shown in Eq. (4). At Imbituba and Santana the *dN* values were the most expressive, 0.504 m and -0.513 m, while at Arraial do Cabo, Salvador and Fortaleza, the *dN* values were 0.021 m, -0.086 m and -0.067 m, respectively. This is largely due to the fact that the distances between the tide gauges at Imbituba and Santana and the chosen cells are greater, as shown in Table 4. Regarding the dh_{MDT} values, we found the highest value (-0.026 m) at Imbituba, while at Arraial do Cabo and Fortaleza there were only variations in the millimetric range of 0.006 m and -0.001 m, respectively, at Salvador the result was null and in the vicinity of the Santana tide gauge there are no CNES-CLS18 MDT data available.

Table 6 – N (XGM2019e_2159) values and h_{MDT} (CNES-CLS18) values at the tide gauges and chosen cells.

Tide gauges	N **Cell (m)**	N **Tide gauge (m)**	dN **(m)**	h_{MDT} **Cell (m)**	h_{MDT} **Tide gauge (m)**	dh_{MDT} **(m)**
Imbituba	1.316	0.813	0.504	0.497	0.523	-0.026
Arraial do Cabo	-6.209	-6.230	0.021	0.456	0.450	0.006
Salvador	-11.641	-11.556	-0.086	0.540	0.540	0.000
Fortaleza	-9.496	-9.429	-0.067	0.508	0.509	-0.001
Santana	-25.112	-24.599	-0.513	-	-	-

Source: The Authors (2022).

4 CONCLUSION

The correlations found between Sentinel-3A satellite data and the Imbituba, Arraial do Cabo, Salvador, Fortaleza and Santana tide gauge data were equal and above 0.90, which according to Shimakura (2006), characterizes a "very strong correlation".

The distances between the chosen cells and the tide gauges were small for the Arraial do Cabo, Salvador and Fortaleza tide gauges, i.e. 5.37 km, 4.51 km and 4.62 km, coupled with high correlations (0.95, 0.99 and 0.98), respectively. This fact demonstrates the potential of the Sentinel-3A mission in coastal regions and in integration with these tide gauges for future research.

The SSH_{SA-TG} and SSH_{TG} mean values showed no significant differences in any of the tide gauges analyzed, because they were within the standard deviation range, whereby their values were 1.61 m ± 0.22 m and 1.46 m ± 0.28 m at Imbituba, -5.59 m ± 0.27 m and -5.77 m ± 0.28 m at Arraial do Cabo, -10.93 m ± 0.57 m and -11.03 m ± 0.57 m at Salvador, -8.80 m ± 0.67 m and -9.02 m ± 0.72 m at Fortaleza and -22.78 m ± 0.58 m and -22.69 m ± 0.84 m at Santana.

The standard deviation of the residuals indicates how well the tide gauge and altimetry data "fitted" each other, with dispersion, in descending order, of 0.44 m at Santana, 0.16 m at Fortaleza, 0.10 m at Imbituba, 0.09 m at Arraial do Cabo and 0.08 m at Salvador.

The dN values used to extrapolate the chosen cells to the location of the tide gauges were higher at Imbituba (0.504 m) and Santana (-0.513 m) and lower at Arraial do Cabo (0.021 m), Salvador (-0.086 m) and Fortaleza (-0.067 m). This fact is largely due to the distances between the tide gauges at Imbituba and Santana and the chosen cells being much larger than the distances found at Arraial do Cabo, Salvador and Fortaleza.

The main contribution of this study was that it verified the quality of the absolute integration between altimetric observations operating in SAR mode, as is the case of Sentinel-3A satellite, and data from RMPG tide gauges at Imbituba, Arraial do Cabo, Salvador, Fortaleza and Santana, for the period between November 2017 and April 2020. Regarding recommendations for future research, we suggest including missions based on conventional altimetry, such as the Topex/Poseidon mission and the Jason 1, 2 and 3 missions, given the possibility they provide of working with a larger time series.

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Authors' contribution

The author S. G. was responsible for conceptualization, research investigation, curation and data visualization, wrote the initial draft and carried out revisions and editing. The author R. D. assisted in defining the idea and in revisions and supervision of this article. Author T. A. S. assisted in revisions and supervision of this article.

Conflict of interes

The authors declare no conflict of interest.

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