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Estimates of Average Mean Dynamic Topography on the Brazilian coast using Satellite Altimetry

Estimativas da Topografia do Nível Médio do Mar na costa brasileira por meio da Altimetria por Satélites

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Abstract: The present study aims to obtain the Mean Dynamic Topography (MDT) values generated from satellite altimetry products, through the Sentinel-6A, CryoSat-2 missions and data from Global Ocean Gridded L4 Sea Surface Heights and Derived Variables. MDT variations were estimated for four tide gauge stations belonging to the Permanent Tidal Network for Geodesy (RMPG), maintained by the Brazilian Institute of Geography and Statistics (IBGE). These stations are located along the Brazilian coast in Fortaleza-CE, Salvador-BA, Macaé-RJ and Imbituba-SC. The BRAT version 4.2.1 software was used to extract the geophysical parameters of Sea Level Anomaly (SLA) and Absolute Dynamic Topography (ADT), and, from this, the MDT was estimated for the four tide stations. Finally, it was possible to obtain the monthly variations for the Sentinel-6A, CryoSat-2 missions and the multi-mission altimetry. These results were compared with each other by calculating the discrepancy and based on descriptive statistics criteria. The results demonstrate the contribution to the literature when exploring the multi-mission solution, highlighting the potential of the Sentinel-6A mission, since it obtained smaller discrepancies when compared with CryoSat-2 and the multi-mission solution.

Keywords: Synthetic Aperture Radar; Permanent Tideographic Network for Geodesy; Altimetry Missions.

Resumo: O presente estudo tem como objetivo a obtenção de valores de Topografia do Nível Médio do Mar (TNMM) gerados a partir de produtos de altimetria por satélites, por meio das missões Sentinel-6A, CryoSat-2 e dados globais oceânicos de Altitudes da Superfície do Mar e variáveis derivadas, do inglês, Global Ocean Gridded L4 Sea Surface Heights and Derived Variables, gerados a partir de uma solução multimissões. As variações da TNMM foram estimadas para quatro estações maregráficas pertencentes à Rede Maregráfica Permanente para Geodésia (RMPG), mantida pelo Instituto Brasileiro de Geografia e Estatística (IBGE). Estas estações estão localizadas ao longo da costa brasileira em Fortaleza-CE, Salvador-BA, Macaé-RJ e Imbituba-SC. Foi utilizado o software BRAT para extrair os parâmetros geofísicos de anomalia do nível do mar e topografia dinâmica absoluta, e a partir desses, estimou-se a TNMM e suas variações temporais para as quatro estações maregráficas. Esses resultados foram comparados entre si por meio do cálculo das discrepâncias e com base em critérios da estatística descritiva. Os resultados demonstram a contribuição para a literatura ao explorar a solução multimissões, destacando o potencial da missão Sentinel-6A, uma vez que, a mesma obteve menores discrepâncias ao serem comparadas com o CryoSat-2 e a solução multimissões.

Palavras-chave: Radar de Abertura Sintética; Rede Maregráfica Permanente para Geodesia; Missões Altimétricas.

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1. Introduction

The geoidal model refers to the physical representation that best describes the Earth's actual shape and closely approximates the Mean Sea Level (MSL) surface, extended beneath the continents, without fluctuations caused by currents, winds, water density, and other disturbances. Accurate knowledge of the geoid has been the subject of numerous studies in the field of Geodesy, with a range of practical implications in areas such as geosciences and engineering (DREWES, 2006; HOFMANN-WELLENHOF & MORITZ, 2006).

Its determination is particularly important for the implementation of height systems, which in turn require the definition and materialization of points on the Earth's surface relative to a physically meaningful vertical reference. Another context involves the study of the MSL surface and its relevance to research related to climate change and navigational safety (DA SILVA & DE FREITAS, 2019; SOUZA & FERREIRA, 2021).

With technological advances since the 1980s and the advent of modern space-based positioning techniques, a discrepancy has been observed between the geoid and the MSL, referred to as the Mean Dynamic Topography (MDT) (DA SILVA & DE FREITAS, 2019). MDT information is crucial in various studies, such as sea-level rise and climate change, and plays a key role in disciplines such as Oceanography and Climatology (LYU et al., 2016; WU et al., 2022).

MDT modeling, combined with MSL monitoring and other oceanographic components, contributes to human activities such as fishing, oil and gas exploration, economic development, and offshore engineering construction (XU, YUANRONG & WEI, 2016, p. 03). According to Smith and Kirwan (2021), MDT influences the coastal carbon cycle, the salinization of freshwater systems, and the marine ecological environment. MDT also affects shoreline change and coastal erosion, providing a scientific decision-making basis for environmental protection and coastal zone management (WEISSE et al., 2021, p. 872).

Due to its applications and the availability of both tide gauge data and Satellite Altimetry (ALTSAT) data, numerous studies have been developed. For instance, Kubryakov and Stanichny (2011) analyzed and compared MDT values in the Black Sea using altimetry data, velocity measurements from drifting buoys, and hydrological data. Their results showed good quantitative and qualitative agreement across the entire Black Sea basin when comparing all techniques.

Rio et al. (2014) estimated MDT values for the Mediterranean Sea region using ALTSAT and coastal tide gauge data. They concluded that the main currents and stationary structures in the Mediterranean Sea were well assessed by comparing MDT data from the SMDT07 model and tide gauge information. More recently, Soto-Mardones et al. (2023) investigated the combined use of MDT data with temperature and wind information to study the effect of the continental shelf and coastal shape on seasonal oceanographic patterns along the northern coast of the Eastern Tropical Pacific. Their results demonstrated the efficiency of ALTSAT in indicating sea surface temperature warming and the influence of resultant winds in the study area.

From a classical perspective, MDT determination in coastal regions is based on tide gauge data. According to Karimi, Andersen, and Deng (2020), despite the densification of spaceborne techniques using altimetric satellites, the use of tide gauge data located along the coast remains the main methodology for MDT estimation. However, the exclusive use of tide gauge data is inherently local, due to the geographical distribution of stations and the limited number of long-term observation series. Given the challenges of maintaining and recovering long-term tide gauge records, ALTSAT has become a viable alternative for obtaining oceanographic information, offering global availability, free access, and long time series through the combination of multiple altimetric missions (DALAZOANA, 2006).

From a modern perspective, ALTSAT data enables a global approach to MDT estimation, thanks to the coverage provided by altimetric satellites, particularly when data from different missions are jointly employed. The application of ALTSAT gained momentum with the launch of the Topex/Poseidon mission in 1992. More recently, advancements in Synthetic Aperture Radar (SAR) technology and its application in ALTSAT missions have enabled better spatial resolution in mapping sea surface heights at a global scale, surpassing the accuracy of conventional ALTSAT systems. Therefore, altimetric missions equipped with SAR technology represent a significant advancement in improving the accuracy of coastal MSL and MDT models when integrated with tide gauge observations (IDŽANOVIĆ, OPHAUG & ANDERSEN, 2017; SOUZA & FERREIRA, 2021).

Regarding the application of SAR-based ALTSAT data, Wu et al. (2022) analyzed MDT using SAR altimetry data along the coast of Japan and southeastern China. They found that the standard deviation of differences between the MDT modeled from the DTU21MSS (a model generated with Sentinel-3A/3B SAR altimetry data) and ocean data was 8 mm lower along the southeastern coast of China and 5 mm lower in Japan compared to the DTU15MSS model, which does not include SAR altimetry data.

A similar study in the context of the Brazilian coast was conducted by Souza and Ferreira (2021), who analyzed the spatiotemporal evolution of MDT at tide gauges of the Permanent Tide Gauge Network for Geodesy (RMPG) using data from the CryoSat-2 altimetric mission and tide gauge techniques. They observed that CryoSat-2 presented lower monthly variations compared to tide gauge data, and an annual discrepancy between the techniques, at all tide gauge stations, on the order of millimeters.

This study aims to estimate the MDT and its temporal variations at four RMPG tide gauge stations using SAR technology data from the CryoSat-2 and Sentinel-6A missions, in addition to global ocean Sea Surface Height (SSH) data and derived variables (Global Ocean Gridded L4 Sea Surface Heights and Derived Variables) from a multi-mission solution. The multi-mission approach, integrating different sources of altimetry—including conventional and SAR altimetry—is essential to improve the accuracy and robustness of the estimates, providing greater data availability and enabling more comprehensive analyses compared to using individual altimetric missions. This strategy contributes to a more detailed characterization of MDT variations and is fundamental for enhancing coastal models and better understanding sea-level dynamics.

2. Methodology

2.1. Study Area

The estimations of Mean Dynamic Topography (MDT) values and their temporal variations presented in this study were carried out considering the geographic location of a sample of four tide gauge stations belonging to the Brazilian Permanent Tide Gauge Network (RMPG): Fortaleza (EMFOR), Salvador (EMSAL), Macaé (EMMAC), and Imbituba (EMIMB) (Figure 1). Currently, the active tide gauge stations of the RMPG include: Santana (EMSAN), Belém (EMBEL), Fortaleza (EMFOR), Salvador (EMSAL), Arraial do Cabo (EMARC), and Imbituba (EMIMB).

The selected stations are located closer to open sea areas, which provides a better match with Satellite Altimetry (ALTSAT) data, since interpolation of these data is required—as will be further discussed in the methodology section. This condition does not apply to the Santana and Belém stations; therefore, they were excluded from the present study.

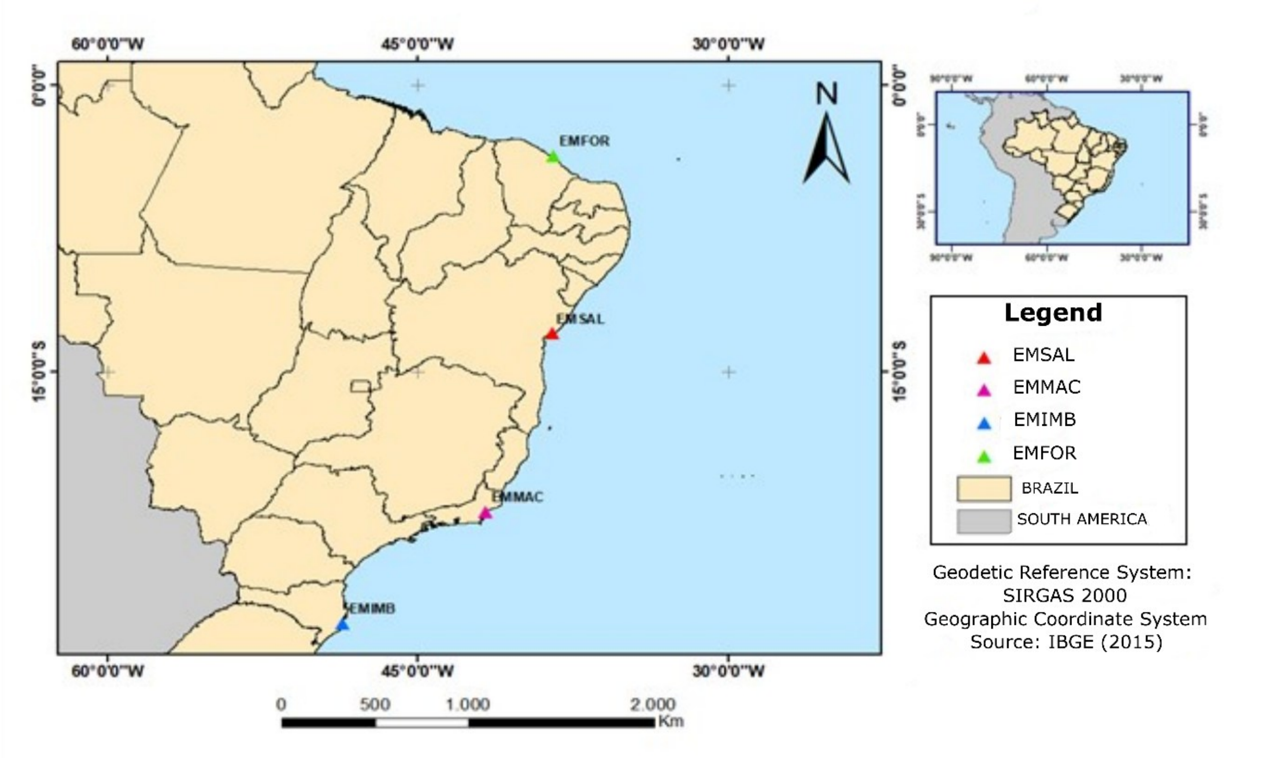

Figure 1 – Location map showing the tide gauge stations used in the study.
Source: Authors (2024).

2.2. Materials Used

For the development of this study, two SAR altimetry missions were selected: CryoSat-2 and Sentinel-6A, in addition to a multi-mission solution that combines both conventional and SAR altimetry. The time series of data spans from April 2022 to August 2023. From these missions, the following variables were used: Sea Level Anomaly (SLA) and Absolute Dynamic Topography (ADT), obtained from satellite tracks with a spatial resolution of 0.25° × 0.25°, approximately 27.8 km² in the equatorial region, and a data acquisition frequency of 1 Hz.

The data from the CryoSat-2 mission were obtained from the Open Altimeter Database (OpenADB) managed by the Deutsches Geodätisches Forschungsinstitut, Technische Universität München (DGFI-TUM)[1]. OpenADB is a satellite altimetry (ALTSAT) database that also provides related products, models, and algorithms (SCHWATKE et al., 2010). All information regarding the main products, altimetry missions, and access to the OpenADB database is available on the DGFI-TUM website.

The Sentinel-6A mission data were retrieved from the Copernicus Marine and Environment Monitoring Service (CMEMS). The CMEMS[2] data platform provides oceanographic products and services for maritime safety, coastal and marine environments, and weather and climate forecasting. It also offers free access to the academic community, combining ocean observations, remote sensing imagery, and ocean forecast models into a catalog of more than 150 products (CMEMS, 2023). Full information on the main products, altimetry missions, and data access is available on the Copernicus Marine Service website.

The third dataset used in this study comes from a multi-mission solution generated from the following satellites: Jason-3, Sentinel-3A, Sentinel-3B, Saral/AltiKa, and HY-2B. The data from all missions were corrected for orbital effects to ensure integration into the final solution. This multi-mission solution is also available through the Copernicus Marine Service.

[1] https://openadb.dgfi.tum.de/en/products/
[2] https://data.marine.copernicus.eu/products

In all cases, altimetry data are provided already corrected for atmospheric effects (ionosphere, dry and wet troposphere); geophysical effects (solid Earth tides, ocean tides, polar tides, ocean loading effects, and sea state bias); and signal propagation effects, among others.

It is worth noting that altimetry mission data are made available in encrypted format with the .nc (Network Common Data Form – NetCDF) extension. Therefore, it is necessary to use appropriate software for their visualization and processing. For this purpose, the Broadview Radar Altimeter Toolbox (BRAT GUI), version 4.2.1, was used. BRAT is a joint project of the European Space Agency (ESA) and the Centre National d'Études Spatiales (CNES). BRAT can be used in combination with routines (MATLAB/IDL) or via programming languages (C/C++/Python/Fortran), enabling users to extract desired data while avoiding formatting inconsistencies. BRAT also allows simple visualization or reading of data in formats such as ASCII, KML (Google Earth), and image formats (JPEG, PNG), among others (ROSMORDUK et al., 2016).

The International Centre for Global Earth Models (ICGEM)[3] calculation service was used to determine the values of geoid undulation (N) for each tide gauge station, considering the involved variables and the corresponding Global Geopotential Models (GGMs). N values were computed using the EGM2008 and EIGEN-6C4 models. EGM2008 was chosen because it is used in both the CryoSat-2 mission and the multi-mission solution, while EIGEN-6C4 is the reference model adopted in the context of the Sentinel-6A mission.

Additionally, ArcGIS software version 10.8 (Environmental Systems Research Institute – ESRI) was used to estimate and interpolate the values from satellite tracks at the RMPG tide gauge stations along the Brazilian coast, as well as to generate the cartographic products involved in the study. Microsoft Excel spreadsheets were used to compute MDT estimates, analyze discrepancies among the CryoSat-2, Sentinel-6A, and multi-mission solutions, and perform descriptive statistical analyses of the data.

2.3. Methodology

The flowchart presented in Figure 2 outlines the main methodological procedures used throughout this study, with the aim of determining the variations in Mean Dynamic Topography (MDT) at the four selected tide gauge stations belonging to the Brazilian Permanent Tide Gauge Network (RMPG).

[3] https://icgem.gfz-potsdam.de/calcpoints

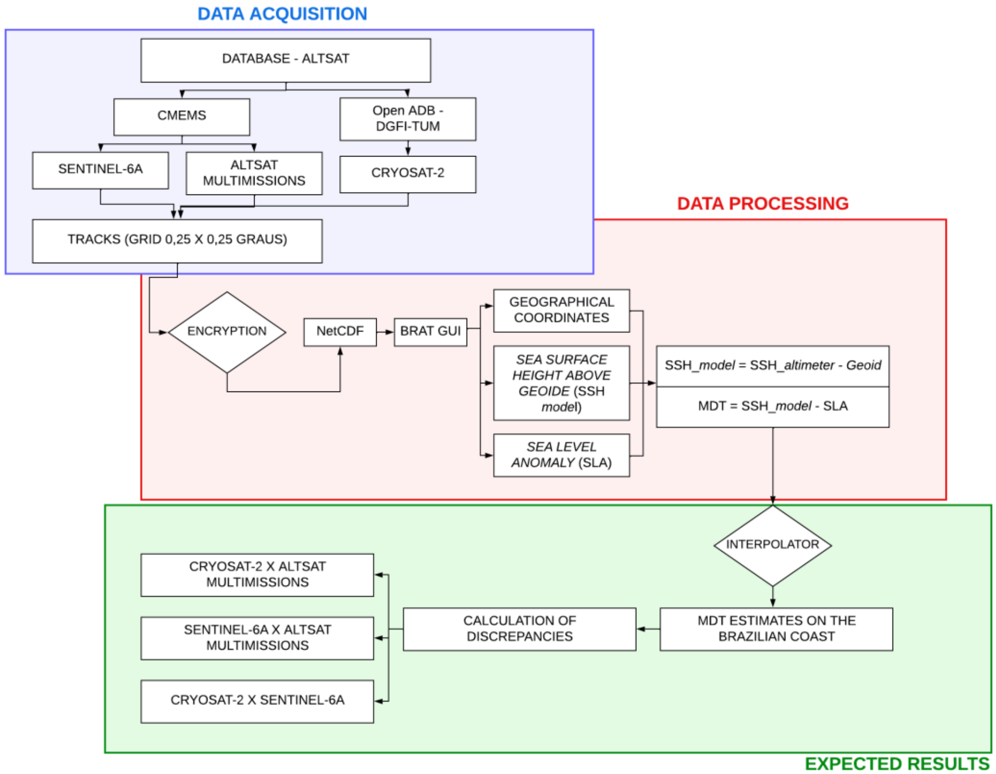

Figure 2 – Methodological flowchart of the study steps.
Source: Authors (2024).

Initially, the data acquisition was carried out through the CMEMS and Open ADB (DGFI-TUM) databases, where the satellite tracks from the Sentinel-6A and CryoSat-2 missions, as well as from the multi-mission solution, were downloaded.

Due to the fact that the data are encrypted and available in NetCDF format, the BRAT GUI software version 4.2.1 was used for the visualization and extraction of the ADT and SLA variables, whose values were necessary for the MDT estimations.

It is important to note that the ADT variable used in this study corresponds to the sea surface height above the geoid, obtained based on the geoidal height from the global geopotential model associated with each mission—namely, EGM2008 for the CryoSat-2 mission and the multi-mission solution, and EIGEN-6C4 for the Sentinel-6A mission. To provide a better understanding of the reference surfaces used in the context of satellite altimetry, Figure 3 illustrates the main variables that support MDT estimations.

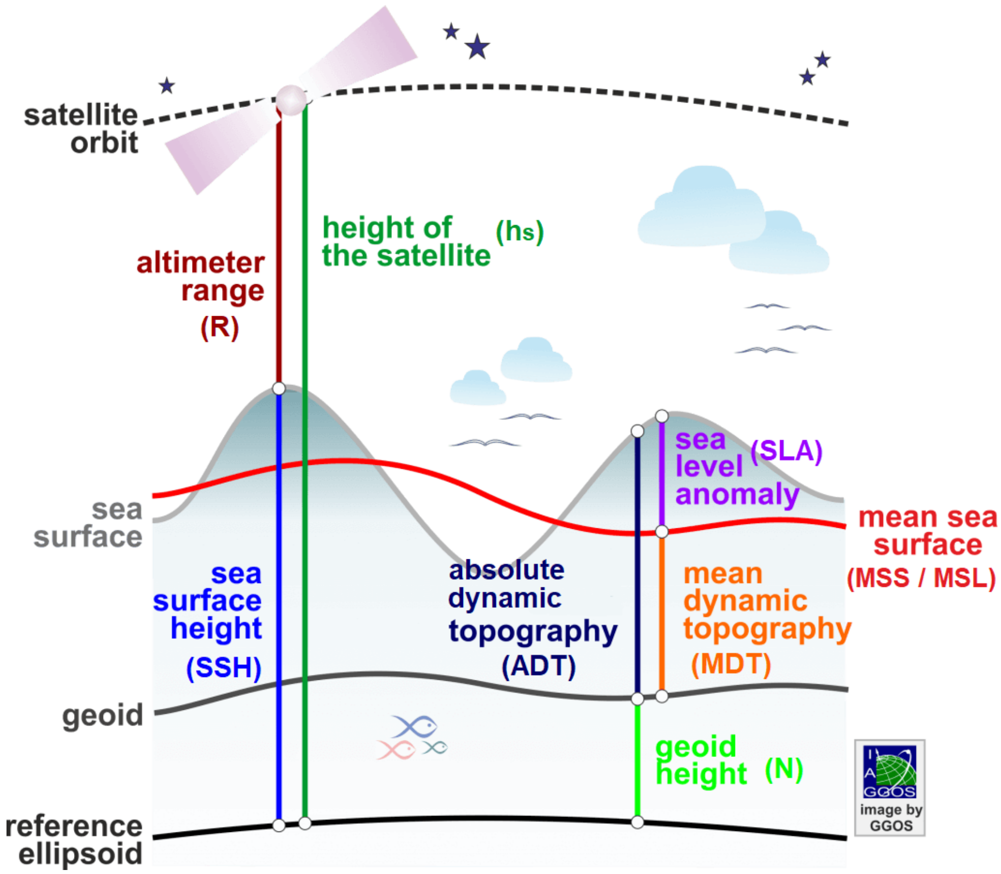

Figure 3 – Relationship between Reference Surfaces in the Context of Satellite Altimetry (ALTSAT).
Source: Adapted from GGOS (2024).

The distance between the satellite and the sea surface, known as the altimeter range (R), is the variable directly derived from satellite observations and must be corrected for a series of instrumental and atmospheric influences, as well as orbital corrections, among others. Once the satellite's orbit is known, its altitude relative to a reference ellipsoid is also known. From these variables, the sea surface height (SSH) is estimated, which corresponds to the distance between the instantaneous sea level (sea surface) and the reference ellipsoid. It is important to highlight that SSH is an instantaneous quantity, i.e., it is associated with the sea level at a given moment, obtained during a satellite altimeter pass.

Considering that the missions have a temporal resolution limited by the satellite revisit time, multiple altimeter passes allow the estimation of a mean sea surface (MSS), also known as mean sea level (MSL). The difference between the sea surface height and the mean sea level is called the sea level anomaly (SLA).

The absolute dynamic topography (ADT) refers to the separation between the instantaneous sea level (sea surface) and the geoid. In turn, the mean dynamic topography (MDT) corresponds to the difference between ADT and SLA, thus representing the difference between the mean sea level and the geoid.

Therefore, the variables presented are interrelated by Equations 1, 2, and 3. However, the application of these equations requires the variables to be properly standardized, taking into account the corrections applied, the reference ellipsoid used, and other relevant considerations.

$$ADT = SSH - N \quad (1)$$
$$SLA = SSH - MSS \quad (2)$$
$$MDT = ADT - SLA \quad (3)$$

Since the altimetric data have a spatial resolution of 0.25° x 0.25°, approximately 27.8 km², it was necessary to interpolate the data in order to obtain the variable values at the positions of the tide gauge stations used in this study. For this purpose, ArcGIS software version 10.8 (ESRI) was used to estimate the unsampled SLA and ADT values through Universal Kriging.

Kriging is a method with numerous examples demonstrating its efficient performance when applied in geosciences. Montecino, Cuevas, and de Freitas (2014) used kriging for the interpolation of mean sea level values derived from MSS models; Santana (2020) applied kriging to interpolate values in global ocean models and observed discrepancies of millimeter order when comparing with tide gauge data; Santana, Ribeiro, and Guimarães (2017) applied the method for interpolating regular grids of geoidal heights from Global Geopotential Models; Ferreira et al. (2017) highlighted the good performance of the method in generating bathymetric reference surfaces. Given these results, kriging was chosen as the interpolation method in this study.

Finally, after determining the MDT for each tide gauge station, the temporal variation and discrepancies between the CryoSat-2, Sentinel-6A, and multi-mission altimetry datasets were calculated.

3. Results and Discussion

When comparing the solutions, it is important to highlight two points: i) the time series for each altimetry mission have the same data sampling frequency to allow for comparison of the results; ii) some graphs were plotted using different scales in order to better illustrate the identified variations.

3.1. Estimates of MDT Variations

Tables 1, 2, and 3 present the descriptive statistical analyses of the MDT variations derived from the CryoSat-2 mission, Sentinel-6A mission, and the multi-mission solution at the tide gauge stations.

Table 1 – MDT variations from the CryoSat-2 altimetry mission.

Descriptive statistics				
Statistic	**EMFOR (cm)**	**EMSAL (cm)**	**EMMAC (cm)**	**EMIMB (cm)**
Mean	50,9	53,5	45,3	51,1
Median	50,9	53,4	45,3	51,1
Maximum	51,0	54,1	46,1	52,3
Minimum	50,8	53,2	44,7	50,1
Range	0,2	0,9	1,4	2,2
Standart Deviation	0,1	0,2	0,3	0,7

Source: Authors (2024).

Table 2 – MDT variations from the Sentinel-6A altimetry mission.

Descriptive statistics				
Statistic	**EMFOR (cm)**	**EMSAL (cm)**	**EMMAC (cm)**	**EMIMB (cm)**
Mean	51,1	53,7	45,8	49,7
Median	51,0	53,7	45,8	49,6
Maximum	51,2	54,2	45,8	50,1
Minimum	50,9	53,4	45,6	49,6
Range	0,3	0,9	0,2	0,5
Standart Deviation	0,1	0,2	0,1	0,2

Source: Authors (2024).

Table 3 – MDT variations from the multi-mission altimetry solution.

Descriptive statistics				
Statistic	**EMFOR (cm)**	**EMSAL (cm)**	**EMMAC (cm)**	**EMIMB (cm)**
Mean	50,9	54,0	46,1	53,0
Median	50,9	54,0	46,0	53,0

Maximum	50,9	55,5	52,2	59,9
Minimum	50,9	51,3	42,1	45,8
Range	0,0	4,3	10,0	14,1
Standart Deviation	0,0	1,1	2,2	3,4

Source: Authors (2024).

Figures 4, 5, and 6 depict the monthly local variations observed in the CryoSat-2, Sentinel-6A, and multi-mission solutions over the study period.

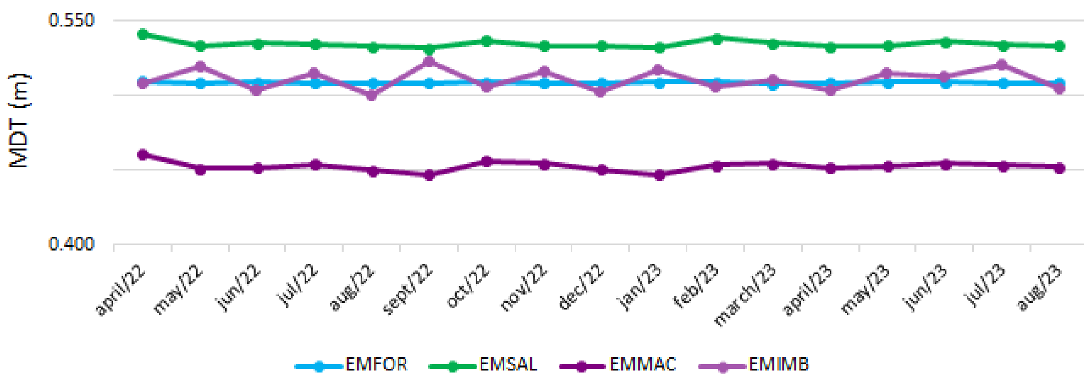

Figure 4 – Local variations in meters of the MDT estimated using the CryoSat-2 mission.
Source: Authors (2024).

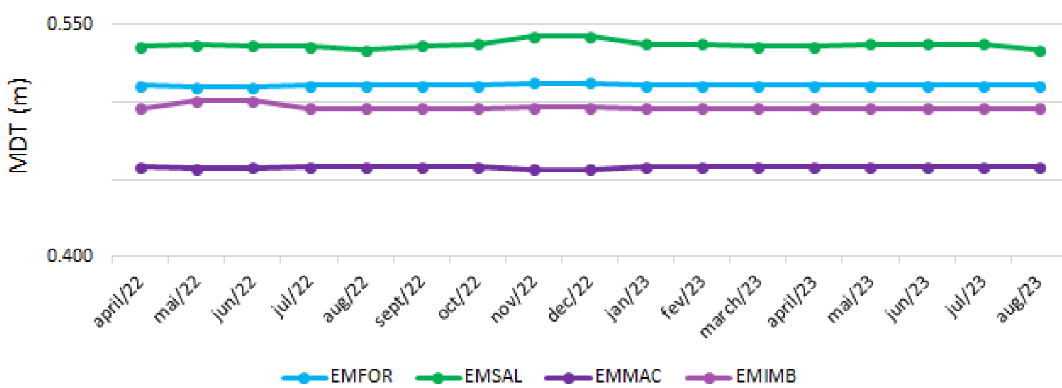

Figure 5 – Local variations in meters of the MDT estimated using the Sentinel-6A mission.
Source: Authors (2024).

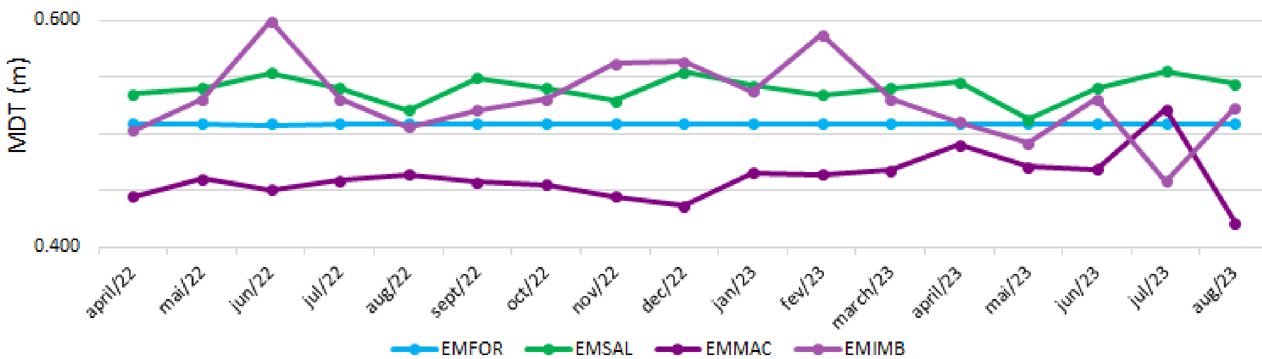

Figure 6 – Local variations in meters of the MDT estimated using the Sentinel-6A mission. Source: Authors (2024).

It can be observed that the MDT values vary along the Brazilian coast, with more similar values found at the Imbituba (EMIMB) and Fortaleza (EMFOR) tide gauge stations when data from the CryoSat-2 and Sentinel-6A missions are used. Regarding the results obtained from the CryoSat-2 mission (Table 1 and Figure 4), the average MDT values at EMFOR and EMIMB were 50.97 cm and 51.1 cm, respectively. For the Sentinel-6A mission, the average MDT values were 51.1 cm and 49.7 cm for EMFOR and EMIMB, respectively (Table 2 and Figure 5). The results found for EMIMB are consistent with the study by Reis, Barbosa, and Palmeiro (2018), who used observations from the Jason-1 altimetry mission and the global model MDT_CNES_CLS13, obtaining an average of 51.5 cm at this station.

Considering both missions and the analyzed time series, the spatial variability of the MDT values ranged from millimetric to centimetric. The highest variability was observed at EMIMB and EMMAC using CryoSat-2 data, with amplitudes of 2.2 cm and 1.4 cm, respectively. EMIMB showed greater dispersion compared to the other stations, with a standard deviation of 0.7 cm.

For the Sentinel-6A mission, the highest temporal variation in MDT was observed at EMSAL, with an amplitude of 0.9 cm and a standard deviation of 0.2 cm. EMMAC showed the lowest variation and dispersion, with a standard deviation of 0.1 cm and an amplitude of 0.2 cm.

As illustrated in Figure 6 and Table 3, the multi-mission solution exhibits the highest variability in MDT values throughout the analyzed period. An exception was found at the Fortaleza tide gauge station, where the values did not show significant differences compared to the other stations.

At EMIMB, MDT values peaked in June 2022 and February 2023, reaching 59.9 cm and 58.7 cm, respectively. In July 2023, the estimated MDT value dropped to 45.8 cm, representing the lowest value recorded in the analyzed time series.

The MDT estimates derived from the multi-mission solution for the Imbituba tide gauge station are consistent with the values reported by Santana and Dalazoana (2022), who found an average of 54.1 cm at this station using ellipsoidal heights derived from the RMPG and geoid heights from the EGM2008, EIGEN-6C4, XGM2016, and XGM2019 models.

3.2. Analysis of Discrepancies Between Solutions

This section presents the analyses based on discrepancies, i.e., the differences between the MDT values obtained from the CryoSat-2, Sentinel-6A missions and the multi-mission solution. The results are based on descriptive statistics and the behavior of the MDT at the tide gauge stations under study.

Table 4 shows the discrepancy analysis between the CryoSat-2 mission and the multi-mission altimetry. Table 5 presents the discrepancy analysis between the Sentinel-6A mission and the multi-mission solution. Finally, Table 6 shows the discrepancy analysis between the CryoSat-2 and Sentinel-6A missions.

Table 4 – Descriptive statistics of discrepancies between the CryoSat-2 mission and multi-mission altimetry.

Descriptive statistics				
Statistic	**EMFOR (cm)**	**EMSAL (cm)**	**EMMAC (cm)**	**EMIMB (cm)**

Mean	-0,05	-0,51	-0,87	-1,92
Median	-0,06	-0,58	-1,01	-1,74
Maximum	0,07	2,11	3,08	6,21
Minimum	-0,1	-2,12	-6,84	-9,49
Range	0,04	1,18	2,24	3,71

Source: Authors (2024).

Table 5 – Descriptive statistics of discrepancies between the Sentinel-6A mission and multi-mission altimetry.

Descriptive statistics				
Statistic	**EMFOR (cm)**	**EMSAL (cm)**	**EMMAC (cm)**	**EMIMB (cm)**
Mean	0,14	-0,28	-0,37	-3,36
Median	0,12	-0,44	-0,34	-3,42
Maximum	0,31	2,47	3,66	3,77
Minimum	0,02	-1,78	-6,36	-9,84
Range	0,07	1,13	2,17	3,35

Source: Authors (2024).

Table 6 – Descriptive statistics of discrepancies between the CryoSat-2 and Sentinel-6A missions.

Descriptive statistics				
Statistic	**EMFOR (cm)**	**EMSAL (cm)**	**EMMAC (cm)**	**EMIMB (cm)**
Mean	-0,18	-0,22	-0,50	1,44
Median	-0,17	-0,11	-0,49	1,51
Maximum	-0,05	0,55	0,31	2,68
Minimum	-0,40	-0,88	-1,10	0,35
Range	0,09	0,34	0,33	0,71

Source: Authors (2024).

Based on Table 4, it was found that the maximum (6.21 cm) and minimum (-9.49 cm) discrepancy values refer to EMIMB, corresponding to the MDT values in June 2022 and July 2023, respectively. Such discrepancies may be related to the fact that one solution is based on data from only one satellite mission — CryoSat-2, with a revisit period of 369 days — while the multi-mission solution is based on different satellites, providing data with better spatial and temporal resolution. The improved temporal and spatial resolution of the multi-mission solution allows for better representation of the temporal variability of the MDT, as observed, for example, in Figure 5. Generally, EMFOR was the station showing the smallest discrepancy among the solutions, exhibiting a standard deviation of 0.04 cm compared to the other stations.

Regarding the results in Table 5, the maximum (3.77 cm) and minimum (-9.84 cm) discrepancy values again correspond to June 2022 and July 2023 for EMIMB. Thus, the MDT values obtained for EMIMB from SAR altimetry showed the greatest discrepancy compared to those from the multi-mission solution.

According to Table 6, a pattern of reduced discrepancies in MDT values was observed for stations EMFOR, EMSAL, and EMMAC, which had means of -0.18 cm, -0.22 cm, and -0.50 cm, respectively. However, EMIMB was the only station to show a positive discrepancy of 1.44 cm for the period from April 2022 to August 2023. It is also noted that EMIMB was the tide gauge station with the largest discrepancy, quantified by a maximum of 2.68 cm.

3.3. Analysis of Different Global Geopotential Models (GGMs) in MDT Estimation

Before the evolution of satellite positioning techniques and the modernization of space technologies, it was assumed there was no discrepancy between MSL estimates and the geoid, i.e., from a classical viewpoint, these surfaces were considered coincident. Currently, it is known that there is indeed a distinction between the local MSL and the global geopotential model; this difference corresponds to the Mean Dynamic Topography (MDT) (TORGE, 2001; SEEBER, 2003). Thus, the influence of different GGMs on the determination of variables available for each altimetric mission or multi-mission solutions directly impacts the MDT determination.

Therefore, the differences in MDT values at tide gauge stations using CryoSat-2, Sentinel-6A missions and the multi-mission solution are also associated with the different GGMs employed. Table 7 presents the geoidal undulation (N) values derived from the EGM2008 GGM (used in the Absolute Dynamic Topography (ADT) variables of CryoSat-2) and EIGEN-6C4 (model used for the ADT variables of the Sentinel-6A mission) for each tide gauge station analyzed.

Table 7 – Geoid Undulation (N) Determination Based on the EGM2008 and EIGEN-6C4 Models.

Geoid Undulation (N) in Meters				
GGM	**EMFOR (m)**	**EMSAL (m)**	**EMMAC (m)**	**EMIMB (m)**
EGM2008	-8,603	-1,060	-6,429	1,740
EIGEN-6C4	-8,640	-1,067	-6,481	1,680
Difference	0,037	0,007	0,051	0,061

Source: ICGEM (2024).

For comparative purposes, the geoid undulation values (N) were estimated using the zero tide system, since the ALTSAT data are corrected for the influence of ocean tides. As shown in Table 7, the differences between the geoid models are on the order of centimeters, which contributes to the uncertainties in the determination of the Mean Sea Level Height Above the Geoid (MDT). Furthermore, it is evident that the EMIMB tide gauge station was the most affected by the differences between the Global Geopotential Models (GGMs), with a variation of 6.1 cm, thereby validating the centimeter-level discrepancies discussed previously.

4. Final Considerations

The results of this research highlight the strong potential of satellite altimetry missions based on SAR technology when compared to a multi-mission solution, which provides improved temporal and spatial resolution. The MDT discrepancies observed between the CryoSat-2 and Sentinel-6A missions, when compared to the multi-mission solution, were on average less than 3.5 cm at the analyzed stations. The direct comparison between the two missions resulted in average discrepancies of less than 1.5 cm, with standard deviations of 0.9 mm in Fortaleza (CE), 3.4 mm in Salvador (BA), 3.3 mm in Macaé (RJ), and 7.1 mm in Imbituba (SC).

The analyses demonstrated consistency in the mean values, corroborating previous studies carried out at the EMIMB station. However, a greater variability was observed at this station, suggesting the need for further investigation to understand the causes of this variability.

Another critical aspect to be evaluated is the use of different GGMs in the provision of variables associated with each altimetric mission or solution, as the differences in geoid undulation values derived from EGM2008 and EIGEN-6C4 are of the same order of magnitude as the observed discrepancies. This underscores the need to harmonize these models, as well as to standardize the corrections applied to satellite altimetry data. It reinforces the importance of carefully considering these factors in the interpretation of altimetric data.

Although multi-mission solutions exhibit greater variability, they provide a more comprehensive and detailed view of MDT variations over time and space, emphasizing the need to incorporate them into comparative analyses.

Based on the results obtained, it is recommended that future studies employ longer time series, which will allow for a deeper understanding of the temporal trends and spatial variations of MDT. Additionally, it is essential to conduct more detailed comparisons between MDT results and tide gauge measurements to validate and refine the methods used, particularly regarding the interpolation of altimetry data. Lastly, it is advisable to analyze MDT behavior using different Global Geopotential Models, prioritizing the most recent ones, in order to more accurately assess the implications of these choices on altimetric results.

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