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Evaluation of the Consistency between In Situ and Satellite Data for Sea Surface Monitoring at Continuous Tide Gauge Stations

Avaliação da Consistência entre Dados in Situ e Satelitais para o Monitoramento da Superfície do Mar em Estações Maregráficas de Monitoramento Contínuo

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Abstract: Satellite altimetry has revolutionized the monitoring of sea surface height (SSH) variations, enabling analyses of ocean dynamics and mean dynamic topography (MDT) at global and regional scales. This study investigates SSH variations using data from the CryoSat-2 (CS2), Sentinel-6A (S6A), and Surface Water and Ocean Topography (SWOT) missions over a time series of approximately 10 years (2014–2024), comparing them with tide gauge observations from the Permanent Tide Gauge Network for Geodesy at the EMFOR (Fortaleza), EMSAL (Salvador), EMMAC (Macaé), and EMIMB (Imbituba) stations. An absolute approach with spatial extrapolation was employed to harmonize in situ and satellite data. The results show good agreement between altimetric and tide gauge measurements, with residuals consistent with instrumental uncertainties (on the order of centimeters). The Salvador tide gauge station exhibited the smallest residuals (0.01±0.04 m), highlighting the high precision of the SWOT mission, which showed the best agreement with tide gauge data. Estimates of MDT also showed dispersions of only a few centimeters, confirming the high sensitivity and effectiveness of altimetric missions in monitoring local ocean dynamics.
Keywords: Satellite altimetry; Tide gauges; Sea surface height; Mean dynamic topography .

Resumo: A altimetria por satélite tem revolucionado o monitoramento das variações das altitudes da superfície do mar (do inglês, *Sea Surface Height* - SSH), permitindo análises de dinâmicas oceânicas e Topografia do Nível Médio do mar (TNMM) em escalas globais e regionais. Este estudo investiga as variações de SSH utilizando dados das missões CryoSat-2 (CS2), Sentinel-6A (S6A) e *Surface Water and Ocean Topography* (SWOT), em uma série temporal de aproximadamente 10 anos (2014-2024), comparando-as com observações maregráficas da Rede Maregráfica Permanente para Geodésia (RMPG) nas estações EMFOR (Fortaleza), EMSAL (Salvador), EMMAC (Macaé) e EMIMB (Imbituba). Foi utilizada uma abordagem absoluta, com extrapolação espacial para harmonizar dados *in situ* e satelitais. Os resultados revelam boa concordância entre as medições altimétricas e maregráficas, com resíduos compatíveis às incertezas instrumentais (ordem de centímetros). A estação maregráfica de Salvador apresentou os menores resíduos, 0,01±0,04 m, evidenciando a alta precisão da missão SWOT, que mostrou a melhor concordância com os dados maregráficos. As estimativas da TNMM também exibiram dispersões de apenas alguns centímetros, confirmando a elevada sensibilidade e eficácia das missões altimétricas no monitoramento das dinâmicas oceânicas locais.
Palavras-chave: Altimetria por satélites. Maregrafia. Altitude da superfície do mar. Topografia do nível médio do mar.

1 INTRODUCTION

Over the past five decades, Earth observation technologies via satellites have played a crucial role in understanding and modeling the planet, providing essential data for environmental and geophysical analyses (Fu and Cazenave, 2001; Stammer and Cazenave, 2017). Among these technologies, satellite altimetry (SATALT) stands out as an effective tool for measuring surface altitudes relative to a reference ellipsoid, over both oceans and terrestrial surfaces.

This technique allows for the calculation of global-scale marine gravity anomalies, including Sea Surface Height (SSH) (Jiang, Nielsen, and Andersen, 2023), Mean Sea Level (MSL), and Mean Dynamic Topography (MDT)—that is, the discrepancy between the geoid and the MSL (Hwang et al., 2002; Escudier et al., 2017). These measurements are fundamental for elucidating oceanic dynamics, climate variations, and geodynamic processes, with applications in global and regional modeling.

The evolution of SATALT reflects significant advancements in precision, resolution, and coverage, from initial missions like Seasat (1978) and Geosat (1985), which established the foundations for global SSH observations, to modern generations that incorporate advanced instrumentation to overcome limitations in coastal and polar regions. In this context, the CryoSat-2 mission, launched in 2010 by the European Space Agency (ESA), introduced the Interferometric Synthetic Aperture Radar (SARIn) altimeter, optimizing SSH measurements in areas of high variability, such as continental margins and sea ice (Srinivasan and Tsontos, 2023). Subsequently, Sentinel-6A, launched in 2020 as part of the Copernicus program by ESA and the National Aeronautics and Space Administration (NASA), enhanced the Jason reference series with higher vertical resolution (up to 2-3 cm) and orbital stability, facilitating the continuous monitoring of oceanic variations and sea-level rise trends (Donlon et al., 2021).

More recently, the Surface Water and Ocean Topography (SWOT) mission, launched in December 2022 by NASA and the Centre national d'études spatiales (CNES), represents a milestone by employing a Ka-band Radar Interferometer (KaRIn), capable of analyzing oceanic structures at scales of 15-25 km, expanding the potential for mapping MSS topography and SSH (Morrow et al., 2019).

In the transition zones between the continent and the ocean, including continental coasts and isolated islands, fluctuations in sea surface height are assessed through observations anchored to fixed terrestrial benchmarks, generally obtained via tide gauges, which record sea level at specific locations. These, in situ, measurements act as an independent basis for verifying data from satellite altimetry, although they depend on assumptions regarding the vertical immobility of the lithosphere and a conventional vertical datum (Mitchum, 1994).

However, comparative analyses between tide gauge and altimetric records face obstacles, as these datasets do not share the same vertical reference frame and are collected at non-coincident sites, requiring interpolation techniques for spatial harmonization (Liebsch et al., 2002). These comparisons can be performed in either relative or absolute modes: in the relative perspective, the emphasis is on the shared identification of oceanic patterns, forgoing standardization to a common vertical reference—an approach particularly advantageous in locations lacking nearby continuously operating Global Navigation Satellite System (GNSS) stations (Giehl, 2020; Montecino et al., 2017). On the other hand, in the absolute mode, the data are tied to the Earth's center of mass, i.e., the same geodetic reference frame, enabling assessments of satellite stability and absolute variations in elevation, contingent upon the presence of GNSS stations connected to the tide gauges (Liebsch et al., 2002; Acuña and Bosch, 2003; Dalazoana, 2006; da Silva and de Freitas, 2014; Mitchum, 1998).

In the Brazilian context, the Brazilian Continuous Monitoring Network of GNSS Systems (RBMC) was strategically positioned with stations adjacent to those of the Permanent Tide Gauge Network for Geodesy (RMPG), promoting absolute reference levels and optimizing the fusion of terrestrial observations with orbital data, thereby allowing for a comparison between tide gauge and satellite altimetry techniques (Giehl, Dalazoana, and Santana, 2022).

Previous studies have demonstrated the feasibility of comparisons between altimetric and tide gauge data. For example, Liebsch et al. (2002) analyzed sea surface heights using multi-mission altimetry and tide gauge observations in the southern Baltic Sea region. Similarly, Giehl, Dalazoana, and Santana (2022) conducted an absolute comparison between data from the Sentinel-3A satellite and RMPG tide gauges at the Imbituba, Arraial do Cabo, Salvador, Fortaleza, and Santana stations. Furthermore, Pandžić et al. (2024) performed a comprehensive review of the contributions of satellite altimetry and tide gauges to the assessment of sea-level trends in the Adriatic Sea, placing them in Mediterranean and global contexts.

The main objectives of this study were to perform absolute analyses of sea surface height variations using the CryoSat-2, Sentinel-6A, and SWOT missions, analyzing a time series of approximately 10 years (from 2014 to 2024, adjusted for data availability), with an emphasis on deriving high-resolution SSH products. Additionally, these satellite data are compared with sea level (SL) observations from the RMPG stations—specifically EMFOR (Fortaleza), EMSAL (Salvador), EMMAC (Macaé), and EMIMB (Imbituba), as they represent a varied geographical distribution along the Brazilian coast—to validate regional estimates and quantify discrepancies at coastal and oceanic scales using data extrapolation. Finally, the study explores the MDT derived from these missions, evaluating its capability to map dynamic gradients along the Brazilian coast and contribute to the refinement of local oceanographic models.

2 METHODOLOGICAL APPROACH

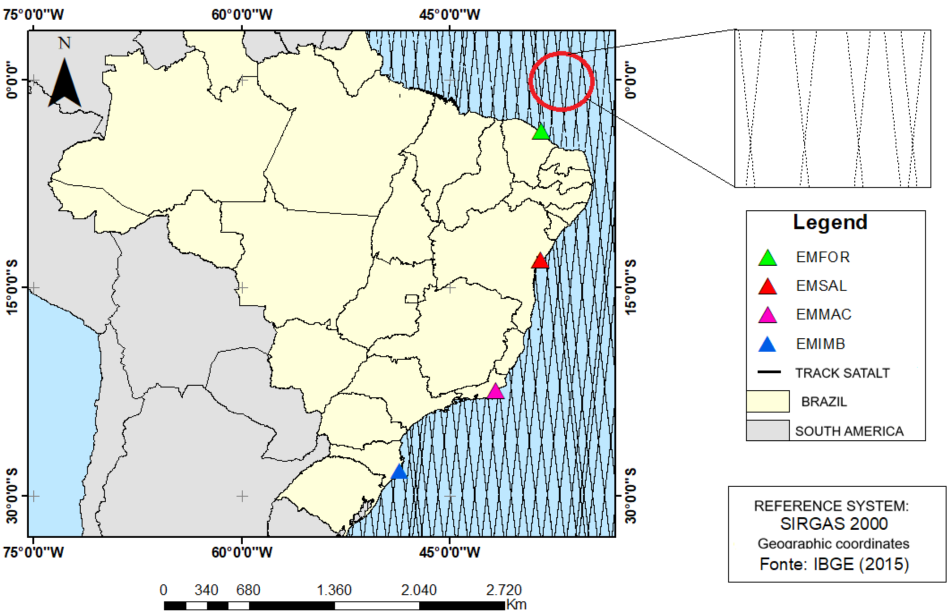
In the following sections, the methods employed in conducting this study will be detailed, including the procedure for determining SSH using satellite altimetry SATALT techniques. Analyses of different altimetric missions will also be presented, as well as a comparison between the SSH values estimated from tide gauge observations and the MDT derived from these distinct missions.

2.1 Study Area

In the present study, tide gauge data were used from the EMFOR, EMSAL, EMMAC, and EMIMB stations, all of which are members of the Permanent Tide Gauge Network for Geodesy (RMPG) and managed by the Brazilian Institute of Geography and Statistics (IBGE) (Figure 1). The selection of these stations aimed to ensure a representative spatial distribution along the Brazilian coast, including stations located in the Northeast, Southeast, and South regions of the national coastline.

In the Southeast region, the choice of the EMMAC station was based on two main criteria: (i) the proximity between the satellite altimetry tracks and the location of the tide gauge, which enables a more accurate assessment of satellite altimetry (SATALT) data and its subsequent comparison with tide gauge observations; and (ii) the fact that the Macaé–RJ region constitutes an important offshore hub, where various hydrographic survey operations are conducted, thus making it a strategic area with direct application in coastal studies.

Figure 1 - Location map of the RMPG stations used in this study.



Source: Authors (2025).

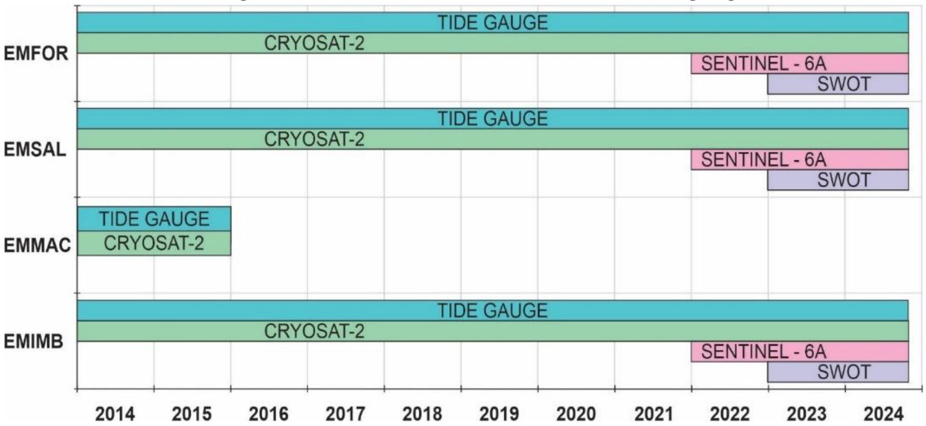
2.2 Acquisition of Satellite Altimetry (SATALT) Data

For the development of this study, altimetry data from the Sentinel-6A (S6A), CryoSat-2 (CS2), and SWOT missions were used. These data were obtained through the Copernicus Marine and Environment Monitoring Service (CMEMS). The time series considered for each mission varied according to its availability: the S6A mission covers the period from April 2022 to October 2024; the CS2 mission spanned from January 2014 to October 2024; and the SWOT mission has data available between November 2023 and October 2024.

The differences in the temporal extent of the data reflect the launch order of the missions. The CS2 mission was the first to be launched, followed by the S6A and SWOT missions. For this reason, the CS2 mission dataset presents a broader temporal coverage, making it more suitable for long-term time series analyses.

Due to this greater coverage, only data from the CS2 mission were used in the analyses regarding the Macaé Tide Gauge Station (EMMAC), which ceased operations in December 2015. Considering this period, the S6A and SWOT missions do not offer adequate temporal coverage, precluding their use in this specific timeframe (January 2014 to December 2015), as illustrated in Figure 2.

Figure 2 - Time series of altimetric and tide gauge data.



Source: Authors (2025).

The following altimetric variables were analyzed: sea surface height (SSH_{ALT}), which is the relationship between the MSL and the reference ellipsoid; and sea level anomaly (SLA_{ALT}), which corresponds to the separation between the instantaneous surface and the mean sea surface. These data were processed and provided by CMEMS, with a sampling rate of 1 Hz and a spatial resolution of 0.25° × 0.25°, corresponding to a resolution of approximately 7 km along the satellite orbits.

The analyzed variables were provided in the .nc (Network Common Data Form - NetCDF) format. For reading, extracting the variables (SSH_{ALT} and SLA_{ALT}), and exporting the geographic coordinates in the SIRGAS 2000 reference system, the Broadview Radar Altimeter Toolbox (BRAT GUI) software, version 4.2.1, was used, with data exported in ASCII format.

The altimetric data were previously corrected and made available by CMEMS, aiming to minimize atmospheric effects (ionosphere, dry and wet troposphere) and geophysical effects (solid earth, ocean, and pole tides, ocean loading, and sea state variations). These corrections, together with orbital adjustments, ensure data reliability and allow for comparisons between different missions by reducing the influence of systematic errors. Detailed information regarding the correction process of the altimetric products can be found in the quality information document. Additionally, information about the altimetric products, the missions involved, and data access methods are available on the Copernicus service portal (CMEMS, 2025).

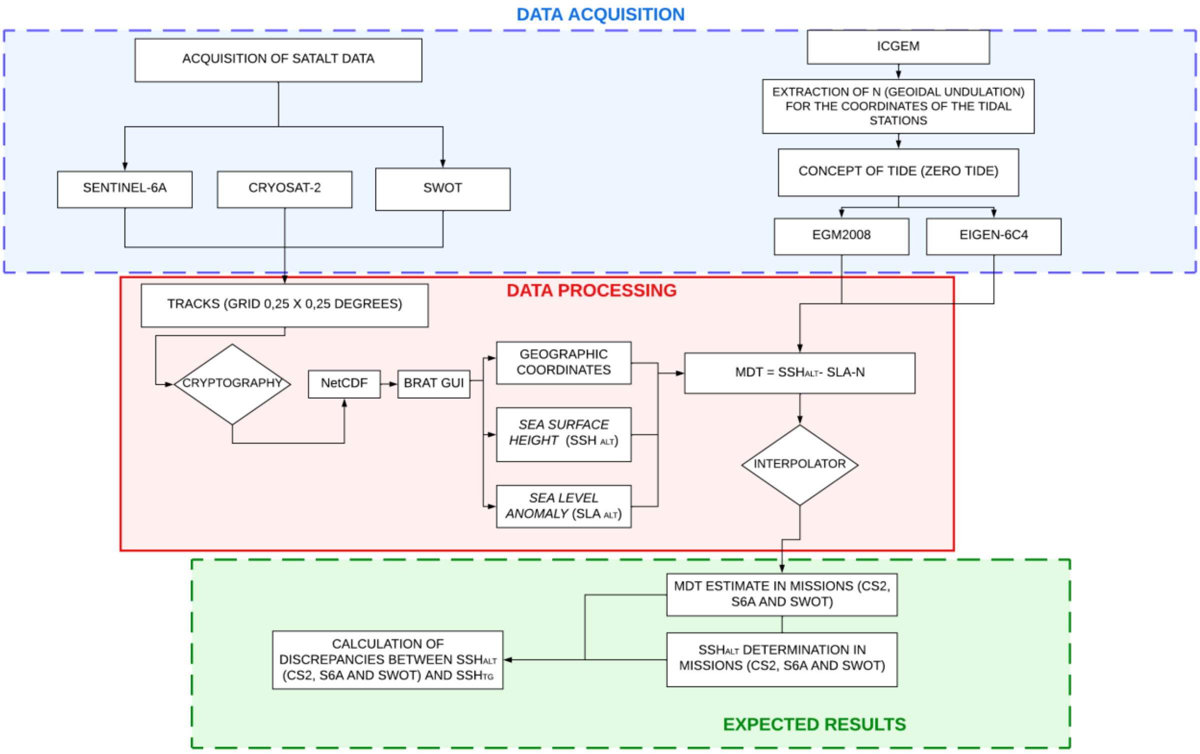
SSH values were extracted from the satellite tracks, and their values were estimated based on data extrapolation to the tide gauge regions; this extrapolation was performed using a geostatistical interpolator. The extrapolation processes, as well as the estimation of sea surface heights for each tide gauge, will be further detailed in the following section. Thus, the SSH was determined and the MSS topography was estimated for each tide gauge using the CS2, S6A, and SWOT missions.

Furthermore, to obtain the geoid undulation (N) values for each analyzed tide gauge station, the calculation service of the International Centre for Global Earth Models (ICGEM) was used (ICGEM, 2025). The Zero Tide concept was adopted, which is compatible with the altimetric data already corrected for the direct effects of ocean tides. Two Global Geopotential Models (GGM) were considered: EGM2008, used for the CS2 and S6A missions, and EIGEN-6C4, adopted for the SWOT mission.

2.2.1 PROCESSING OF ALTIMETRIC VARIABLES DERIVED FROM SATELLITE ALTIMETRY (SATALT)

Figure 3 represents the methodological flowchart of the steps for determining the MDT, SLA_{ALT}, and SSH_{ALT} for each mission and tide gauge station analyzed during this study.

Figure 3 - Methodological flowchart of the steps for determining MDT, $SSH_{ALT}$and SLA_{ALT} using SATALT.



Source: Authors (2025).

The SSH_{ALT}values provided by the CMEMS database use the Topex/Poseidon (T/P) ellipsoid as the reference ellipsoid. However, the Brazilian Geodetic System (SGB) and the SSH information derived from tide gauge data are referenced to the GRS80 ellipsoid. Therefore, to harmonize and unify the reference system, the SSH values obtained by SATALT were converted to the GRS80 ellipsoid, as described by the formula from Renganathan (2010):

$$\delta h = h_1 - h_2 = -((a_2 - a_1)(cos\Psi)^2 + (b_2 - b_1)(sin\Psi)^2) \quad (1)$$

Where δh corresponds to the difference between the heights $h_1$and h_2 referred to the T/P and GRS80 ellipsoids; the variables $a_1$and $a_2$are the semi-major axes; $b_1$and $b_2$are the semi-minor axes of the T/P and GRS80 ellipsoids, as shown in Table 1; and Ψ corresponds to the geocentric latitude of the point of interest. In this study, the discrepancy between the T/P reference ellipsoid and the GRS80 was significant, approximately 64 cm; therefore, this difference was accounted for in the MDT calculations.

Table 1 – Ellipsoidal parameters.

Ellipsoid	T/P	GRS80
a (m)	6378136,3	6378137,0
b (m)	6356751,600563	6356752,31414

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

To extrapolate the $\mathrm{SSH_{ALT}}$ and $\mathrm{SLA_{ALT}}$ data to the tide gauge regions, it was necessary to estimate the gaps between the satellite tracks using a mathematical interpolator. For this purpose, Universal Kriging (UK) was employed, as it accounts for the spatial variability of the data. This model is based on variograms, which quantify the relationship between distance and the similarity of data points. According to studies by Campos (2018), this methodology proved efficient in analyzing the computational representation of bathymetric data from nautical charts in the Potiguar Basin region. The results demonstrated that kriging provided better representativeness compared to the local polynomial, inverse distance weighting, and minimum curvature interpolators used in the research.

Thus, the extrapolation process was performed using the Geostatistical Analyst tool in ArcGIS software, version 10.8, by the Environmental Systems Research Institute (ESRI). This tool enabled the determination of sea surface heights associated with the geographic coordinates of each tide gauge station.

With the standardization of all variables—including the application of necessary corrections through the Copernicus service, data extrapolation, and the unification of the reference ellipsoid—it became possible to establish the correspondence between the different reference surfaces within the scope of SATALT. This step was fundamental for estimating the variations in MDT and SLA associated with each altimetric mission, as described in Eq. (2) (GGOS, 2025):

$$MDT = SSH_{ALT} - SLA_{ALT} - N \quad (2)$$

Where MDT corresponds to the mean dynamic topography, SSH_{ALT} refers to the sea surface height from each mission, SLA_{ALT}corresponds to the sea level anomaly derived from altimetric data, and N refers to the Geoid Undulation. Finally, the SSH_{ALT}values were compared with the sea surface height values estimated through tide gauge observations SSH_{TG} to evaluate the discrepancies between the techniques.

2.3 Tide Gauge Data Acquisition

The sea level observation data used in this study were extracted from the RMPG database, available on the IBGE portal (IBGE, 2025). The study encompasses the sea level variations from the Fortaleza, Salvador, Macaé, and Imbituba stations. The period of tide gauge observations comprises a time series from January 2014 to October 2024. Operations at the Macaé tide gauge were interrupted starting in January 2015; therefore, the data for this station are limited to the period from January to December 2014.

The measurements are provided with a one-minute recording frequency, organized into compressed daily files that internally contain files in the ".txt" format. Consequently, the manual download process becomes a laborious task, especially when dealing with long-duration sea level data series. For instance, to obtain a full year's worth of data, it would be necessary to download and decompress 365 files. The files follow a naming convention in the format xxxaammdd.zip, where:

xxx represents the station identifier: MAC for Macaé; IMB for Imbituba; SAL for Salvador; SAN for Santana; FOR for Fortaleza; ARC for Arraial do Cabo; and BEL for Belém; aa corresponds to the year of collection; mm indicates the month of collection; and dd refers to the day of collection.

To facilitate pre-processing, an R software script was created to standardize the data sampling rate to every 5 minutes and to unify all files into a single annual data file.

In this study, information on the primary Vertical Control Points (VCPs) associated with the studied tide gauges was also collected, as well as the ellipsoidal and normal heights extracted from the Geodetic Database (BDG) managed by IBGE, as shown in Table 2. Furthermore, data from the monitoring reports on sea level (SL) variations at the RMPG stations also served as a theoretical basis.

All information regarding the acquisition, availability, and processing of tide gauge data can be consulted in publications on the RMPG[1] platform.

Table 2 – List of Vertical Control Points (VCPs) and geometric and normal heights used in the study.

Stations	VCPs	Ellipsoidal heights (m)	Normal heights (m)
Fortaleza	4336A	-5,366	3,671
Salvador	3640A	-8,661	2,411
Macaé	3086U	-3,408	3,388
Imbituba	3012X	3,354	2,045

Source: IBGE (2015, 2019, 2023a, 2023b).

2.3.1 PROCESSING OF SEA SURFACE HEIGHTS THROUGH TIDE GAUGE OBSERVATIONS

Although IBGE provides a database with water level information for all stations in the network, this database contains gaps in measurements due to periods of station inactivity or sensor failures. To mitigate these issues, it was necessary to predict the missing data. To this end, Python and R scripts were used to remove outliers (±3σ rule), fill "NaN" values, filter high frequencies, and resample the data, ensuring temporal compatibility with satellite altimetry measurements, as presented by Giehl (2020).

The process of predicting missing data was performed by calculating Synthetic Tides (STs), derived from tide gauge observations from 2014 to 2024 for the EMFOR, EMSAL, and EMIMB stations. The EMMAC station showed a lack of data during certain periods between 2014 and 2015, also requiring the prediction of missing values.

STs correspond to sea level (SL) variations predicted from a set of harmonic components or tidal constituents. These components are calculated from SL observations and enable tide prediction for a specific point in time. In this way, it was possible to predict SL values for periods where no tide gauge data were available.

Harmonic components describe SL variation primarily due to astronomical effects (caused by the influence of the Sun and the Moon) and shallow water effects. The gravitational attractions exerted by the Sun and the Moon act on the deeper water masses of the oceans, generating a forced elevation that propagates toward coastal areas (Pawlowicz, Beardsley, and Lentz, 2002), and tidal variation in coastal zones is further influenced by reduced water depth. The processing of STs was performed using the tidem function, included in the R oce package and developed by Kelley (2018).

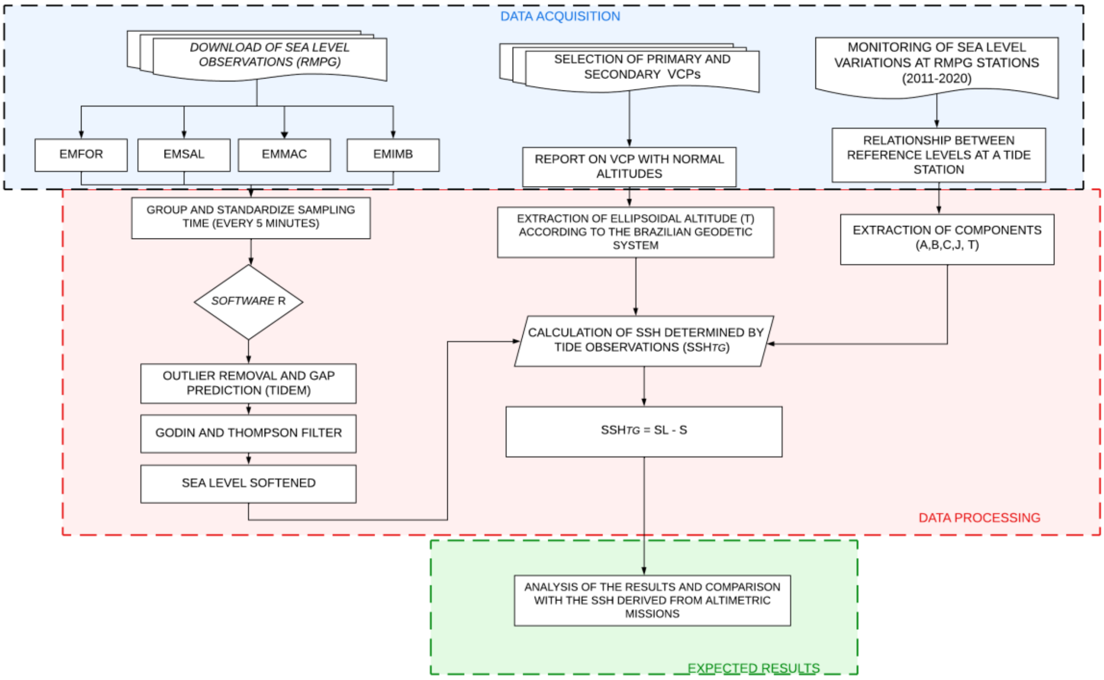
The package provides a range of functions focused on the analysis of sea level time series, as well as coastal, topographic, and oceanographic property data, such as sea surface temperature. This function extracts the sine and cosine components of the tidal frequencies present in the tide gauge observations, allowing for the calculation of the amplitude and phase of the tidal components, which enables the construction of STs. Furthermore, the function automatically selects 69 tidal constituents considered standard by Foreman (1977), based on frequency ranges (astronomical and shallow water) and the duration of the analyzed time series.

Statistical analysis aims to highlight the spatial and temporal behavior of the series. Thus, it becomes possible to understand how atmospheric and oceanographic phenomena manifest in each analyzed period and in each of the regions that make up the study area. Therefore, with the objective of attenuating astronomical components and smoothing water level values, Thompson and Godin filters were applied. The Thompson filter, proposed in 1983, allows for the smoothing of frequencies of interest and optimizes performance through the selection of calculation parameters (Thompson, 1983; Costa, 2010). The Godin filter (1972) corrects data bias and is based on the application of three moving averages. However, as a disadvantage, it excessively dampens oscillations at frequencies lower than the diurnal band by approximately 40% (Costa, 2010).

Figure 4 represents the methodological flowchart of the steps for determining sea surface heights through tide gauge observations (SSH_{TG}) for each station analyzed during this study.

[1] https://www.ibge.gov.br/geociencias/informacoes-sobre-posicionamento-geodesico/rede-geodesica/10842-rmpg-rede-maregrafica-permanente-para-geodesia.html?=&t=publicacoes

Figure 4 - Methodological flowchart of the steps for determining sea surface heights through tide gauge observations.

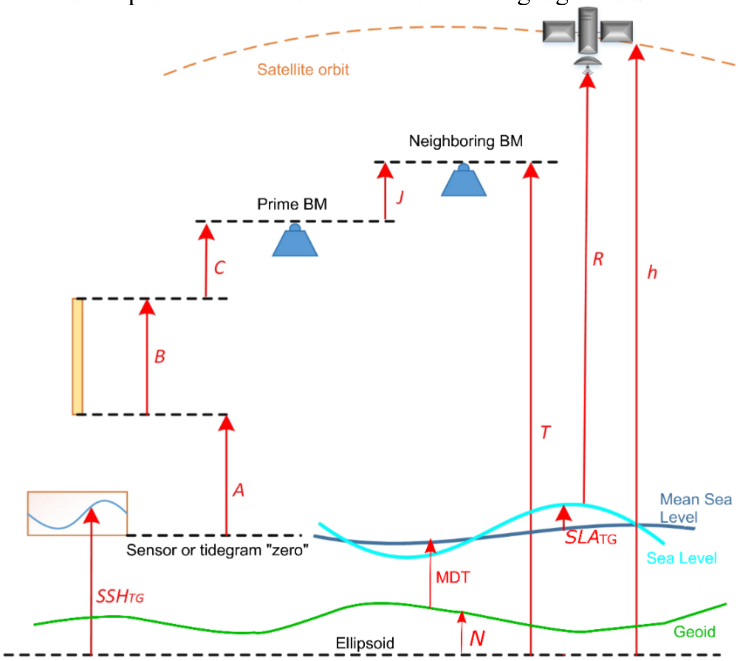


Source: Authors (2025).

After applying the prediction functions, removing spurious data, and smoothing the SL observations, these were referenced to the Brazilian Geodetic System (SGB) (GRS80 ellipsoid / SIRGAS 2000). In this way, the SSH values for the tide gauge stations (SSH_{TG}) were obtained as shown in Eq. (3) and (4) and Figure 5.

$$SSH_{TG} = SL - S \quad (3)$$
$$S = A + B + C + J - T \quad (4)$$

Figure 5- Relationship between reference surfaces in tide gauge and SATALT techniques



Source: Adapted from IBGE (2016), Lu, Qu e Qiao (2014) e Giehl, Dalazoana e Santana (2022).

Where SSH_{TG} represents the sea surface height relative to the SGB reference ellipsoid; the variable SL corresponds to the sea level variation relative to the sensor zero/tide gauge datum; A represents the offset between the tide gauge "zeros" and the tide staff, resulting from sensor calibration (Van de Casteele Test); B corresponds to the nominal reading of the staff pin/top; C to the height difference from the staff pin/top to the primary vertical control point (obtained through geometric leveling of the tide staff); J corresponds to the height differences between the primary and neighboring vertical control points; T represents the ellipsoidal height of the neighboring vertical control point; SLA_{TG} is the sea level anomaly, i.e., the separation between the instantaneous surface and the mean sea surface obtained through reference surfaces in the context of the tide gauge technique; R represents the distance between the satellite and the instantaneous sea surface, corrected for effects affecting this quantity; h is the satellite altitude relative to the reference ellipsoid; N is the geoid undulation extracted from different GGM (Global Geopotential Models); and finally, MDT corresponds to the Mean Dynamic Topography, i.e., the separation between the instantaneous sea level and the geoid.

Table 3 presents the reference levels adopted at the RMPG stations located in the cities of Fortaleza, Salvador, Macaé, and Imbituba, considering the concept of mean tide.

Table 3 - Detailed description of each component associated with the RMPG reference levels.

Component	Imbituba (m)	Fortaleza (m)	Salvador (m)	Macaé (m)
A (m)	0,983 ± 0,023	3,257 ± 0,036	5,043 ± 0,066	0,161 ± 0,036
B (m)	2,016 ± 0,001	6,030 ± 0,001	4,015 ± 0,001	3,013 ± 0,001
C (m)	0,488 ± 0,000	0,264 ± 0,000	0,233 ± 0,000	1,498 ± 0,001
J (m)	4,458 ± 0,000	0,057 ± 0,000	0,270 ± 0,000	-0,101 ± 0,001
T (m)	7,788 ± 0,003	-5,480 ± 0,001	-8,449 ± 0,002	-3,556 ± 0,002
S (m)	0,157 ± 0,023	15,088 ± 0,036	18,010 ± 0,066	8,119 ± 0,071

Source: IBGE (2015, 2019, 2023a, 2023b).

Finally, the SSH_{TG} values were compared with the data obtained through altimetry missions to evaluate the discrepancies between the techniques. Mean values, standard deviations, and correlation coefficients between the variables were calculated, allowing for a quantitative analysis of the consistency between the sea level observation methods.

3 RESULTS AND DISCUSSION

In this section, the results obtained from the absolute analysis of SSH variations are presented and discussed, based on data from tide gauge measurements and satellite altimetry. To enhance the visualization of the variability of the parameter under study, the graphs are displayed at different scales, allowing for a more detailed interpretation of the observed nuances and trends. The time interval covered by the analysis spans from January 2014 to October 2024, ensuring a comprehensive and updated evaluation of the investigated phenomena.

Figures 6, 7, 8, and 9 represent the variations in meters of the values determined through the S6A, CS2, SWOT missions, and tide gauge for each analyzed station. All surfaces were converted to the GRS80 reference ellipsoid, in accordance with the SGB.

Table 4 presents the mean variations of sea surface heights obtained through tide gauge measurements ($\mathrm{SSH_{TG}}$) and altimetry ($\mathrm{SSH_{ALT}}$), as well as the residuals representing the discrepancy between the sea surface height values determined by altimetry satellites — specifically $\mathrm{SSH_{CS2}}$, $\mathrm{SSH_{S6A}}$, $\mathrm{SSH_{SWOT}}$ — and the values obtained through tide gauge ($\mathrm{SSH_{TG}}$). Additionally, the mean values of the MDT determinations for each altimetry mission are presented.

Finally, the correlations between the two techniques are analyzed to evaluate the consistency and the relationship between satellite and tide gauge measurements.

Figure 6- SSH variations in meters through SATALT and tide gauge (TG) techniques at EMIMB.

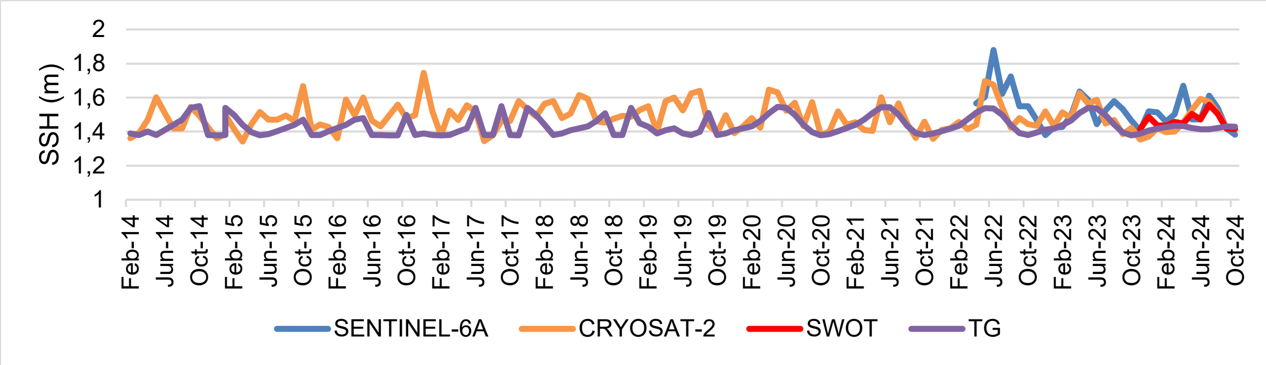


Figure 7 - SSH variations in meters through SATALT and tide gauge (TG) techniques at EMFOR.

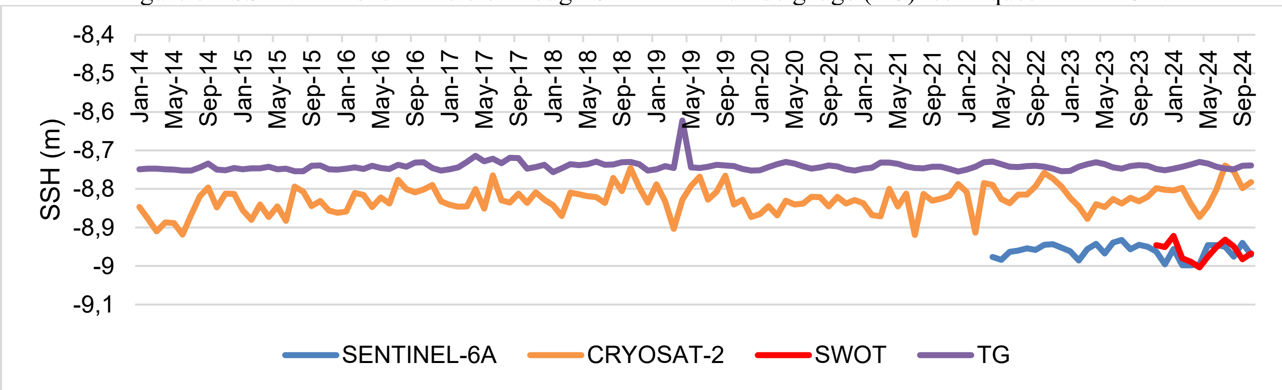


Figure 8 - SSH variations in meters through SATALT and tide gauge (TG) techniques at na EMSAL.

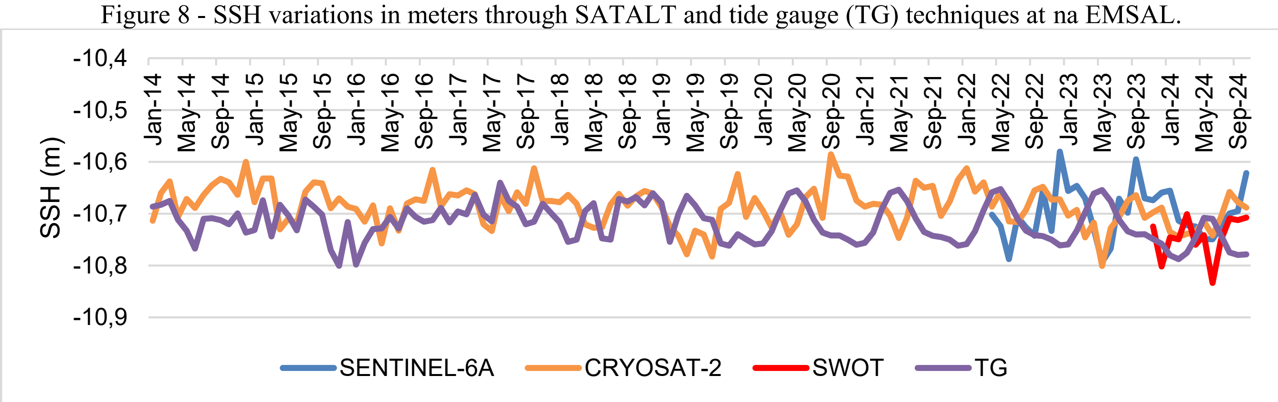
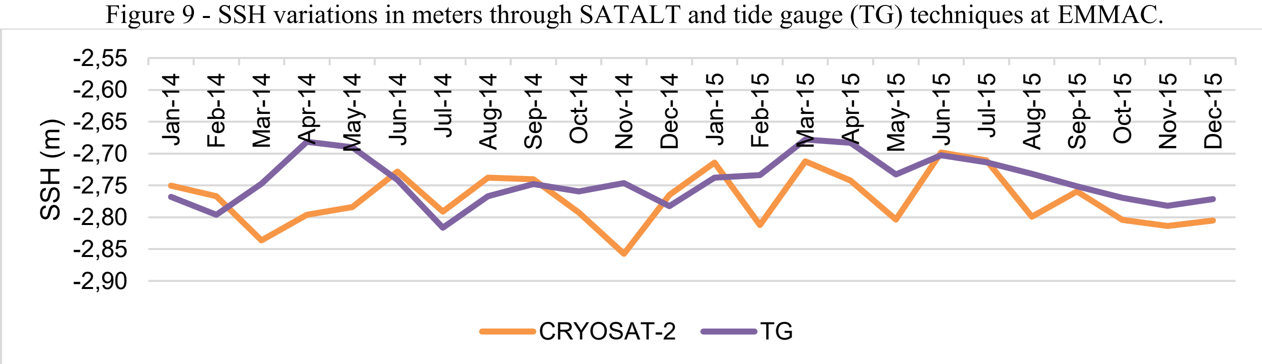


Figure 9 - SSH variations in meters through SATALT and tide gauge (TG) techniques at EMMAC.



Source: Authors (2025).

Table 4 - Means of the determinations of SSH_{ALT}(m), SSH_{TG} (m), mean of the residuals ($SSH_{ALT} - SSH_{TG}$) (m), mean values of the MDT estimates, and correlation coefficient between the techniques.

Stations	Altimetry missions	Mean SSH_{ALT}(m)	Mean SSH_{TG} (m)	Mean of residuals ($SSH_{ALT} - SSH_{TG}$) (m)	MDT_{ALT} (m)	Correlation coefficient
Imbituba	CryoSat-2	1,48±0,08	1,43± 0,05	0,05 ± 0,08	0,45 ±0,01	0,94
	SWOT	1,46 ±0,04		0,04± 0,14	0,44±0,02	0,98
	Sentinel-6A	1,53±0,11		0,09 ± 0,10	0,45± 0,03	0,97
Macaé	CryoSat-2	-2,77± 0,04	-2,74±0,04	-0,03± 0,05	0,24±0,01	0,89
Salvador	CryoSat-2	-10,69±0,04	-10,72±0,04	0,03±0,06	0,54±0,09	0,90
	SWOT	-10,74±0,04		0,01±0,04	0,52±0,00	0,95
	Sentinel-6A	-10,70±0,05		0,03±0,08	0,53±0,00	0,91
Fortaleza	CryoSat-2	-8,83±0,03	-8,74±0,01	-0,18±0,04	0,49±0,02	0,96
	SWOT	-8,96±0,02		-0,22±0,03	0,47±0,00	0,99
	Sentinel-6A	-8,96±0,02		-0,16±0,02	0,48±0,02	0,97

Source: Authors (2025).

As illustrated in Figure 6 and detailed in Table 4, the SSH variations obtained by the altimetry missions SSH_{CS2}, SSH_{SWOT} and SSH_{S6A}at the Imbituba station showed similar means over the years, with values of 1.48 ± 0.08 m, 1.46 ± 0.04 m, and 1.53 ± 0.11 m, respectively. This proximity is evident in the graph, where the SSH variations of the CS2 and SWOT missions differ by only 2 cm in absolute values. Although the SWOT mission presented residuals with greater variability (14 cm standard deviation), the differences relative to the tide gauge data are smaller when compared to the other two SATALT missions. SSH_SWOT showed lower uncertainty, approximately 4 cm around the mean. The mean SSH obtained through tide gauge SSH_{TG}in Imbituba was 1.43 m, with a variability around the mean of 5 cm.

At the Fortaleza tide gauge station, as shown in Figure 7 and Table 4, the mean values for the SSH_{CS2}, SSH_{SWOT} and SSH_{S6A}missions were -8.83 ± 0.03 m, -8.96 ± 0.02 m, and -8.96 ± 0.02 m, respectively. It is observed that the SSH variations for the SWOT and S6A missions were constant, and the difference between the mean analyzed in the CS2 mission was 13 cm, which is greater than the values found in Imbituba. The variation of SSH_{TG} was -8.741 ± 0.01 m. Of the four tide gauge stations analyzed, Fortaleza presented the highest residual values; decimetric values are observed for the residuals, while the other stations show values of centimetric magnitude.

In Salvador, the mean sea surface height values for the SSH_{CS2}, SSH_{SWOT} and SSH_{S6A} missions were -10.69 ± 0.04 m, -10.74 ± 0.04 m, and -10.70 ± 0.05 m, respectively. As observed in Figure 8, there was little variability between the missions. The mean SSH_{TG} in Salvador was -10.718 m, with a variability around the mean of ±4 cm. It is noteworthy that the CryoSat-2 and SWOT missions presented the lowest uncertainties, at approximately ±4 cm. Recent results on SSH determination by SATALT corroborate these findings, such as the study by Giehl, Dalazoana, and Santana (2022), who reported a mean SSH value of -10.93 m for the Sentinel-3A mission in the period from November 2017 to April 2020.

At the Macaé tide gauge station, whose services were discontinued in 2015, comparison was only possible with the CS2 mission, which was launched before the other analyzed missions. According to the results expressed in Figure 9 and Table 4, the mean variation of $SSH_{CS2}$was -2.772 ± 0.04 m, while the mean obtained by the tide gauge technique was -2.74 ± 0.04 m.

According to Dalazoana (2006), the temporal and spatial variations of the MSL (Mean Sea Level), and consequently of SSH and MDT, result from ocean dynamics and vertical crustal movements. Temporal variations result from changes in atmospheric pressure, temperature, among other factors, while spatial variations are caused by ocean currents, variations in water density and temperature, as highlighted by Sánchez (2020, p. 85). Accordingly, Table 4 presents the MDT variations estimated by the altimetry missions for each station, showing that the uncertainties or dispersions around the mean are on the order of centimeters at all analyzed stations.

Additionally, it is observed that at the Salvador station, the MDT variations obtained by the SWOT and S6A missions were 0.52 ± 0.0003 m and 0.53 ± 0.0034 m, respectively, presenting smaller deviations compared to the other studied stations.

Figures 10, 11, 12, and 13 present the spatio-temporal variations of the residuals, i.e., the discrepancies between the tide gauge and SATALT data. Specifically, the differences $SSH_{CS2} - SSH_{TG}$, $SSH_{S6A} - SSH_{TG}$, $SSH_{SWOT} - SSH_{TG}$, determined by the CS2, S6A, and SWOT missions, respectively, are displayed for each tide gauge station considered in the study.

Figure 10 - Spatio-temporal variations of the residuals between satellite altimetry and tide gauge data (SSH_{ALT} - SSH_{TG}) at EMIMB.

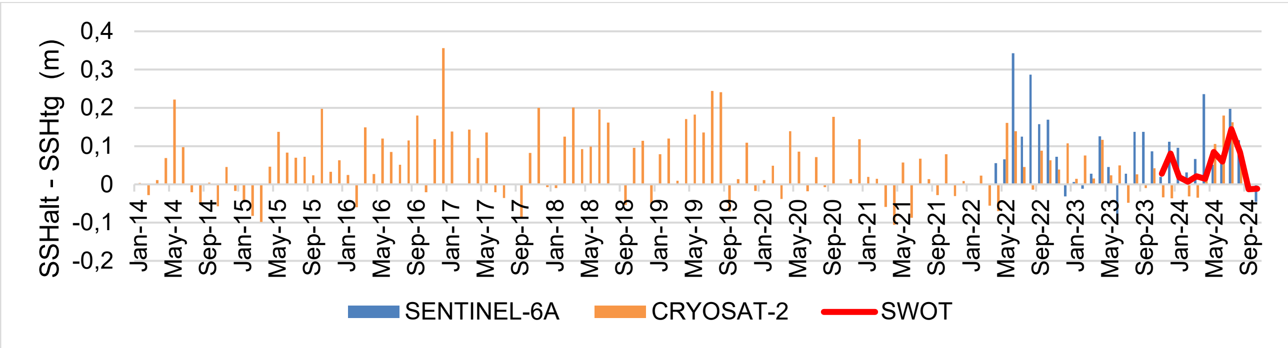


Figure 11 - Spatio-temporal variations of the residuals between satellite altimetry and tide gauge data (SSH_{ALT} - SSH_{TG}) at EMFOR.

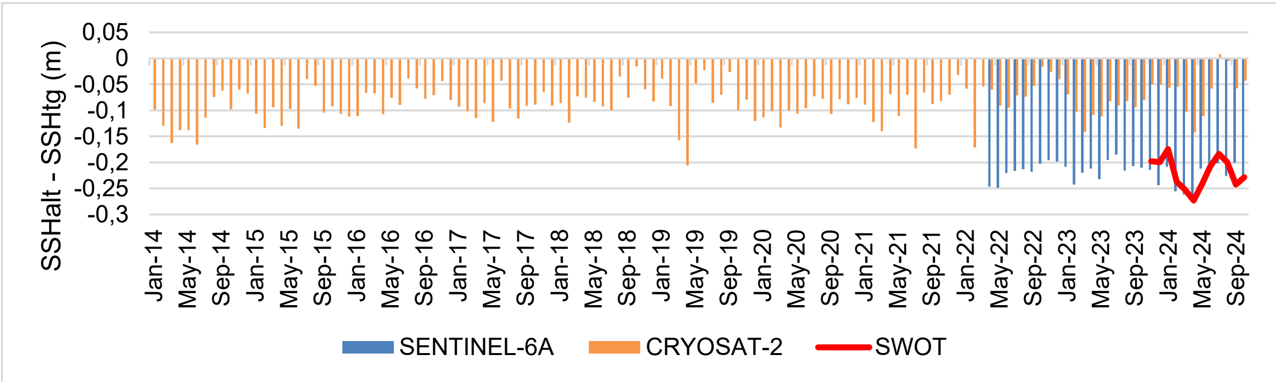
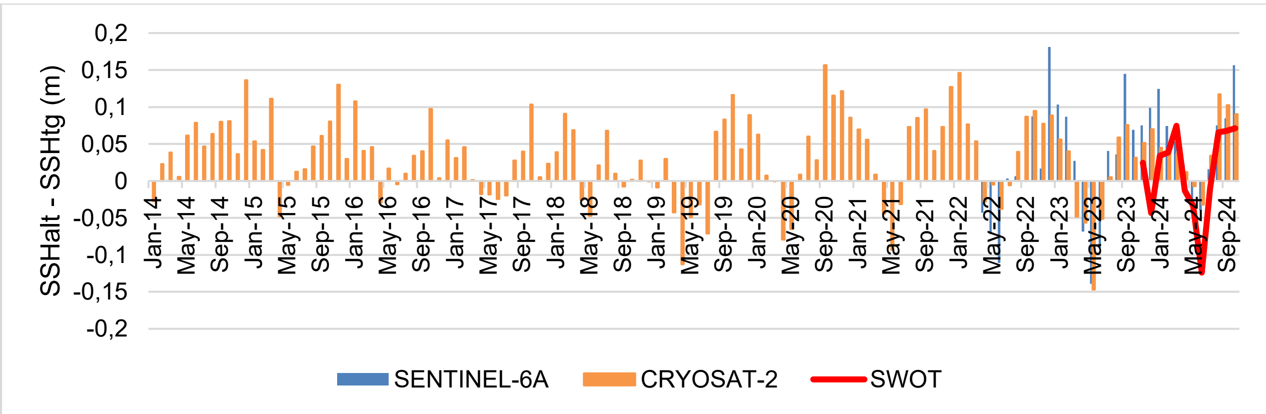
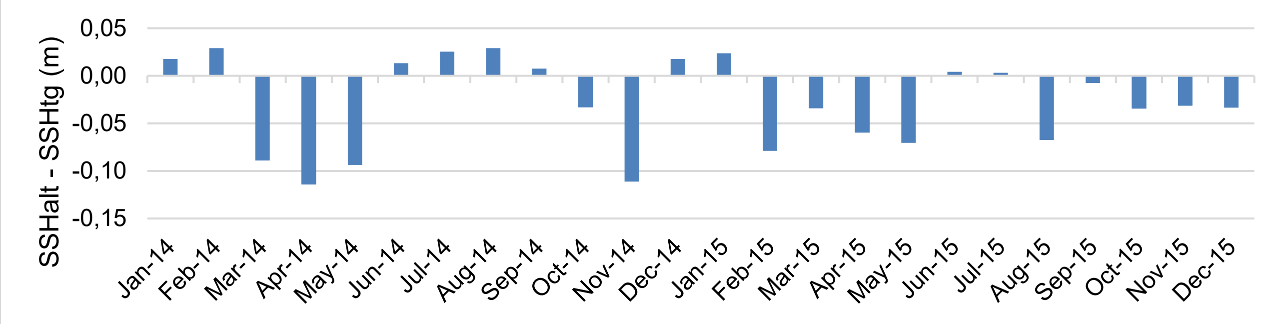


Figure 12 - Spatio-temporal variations of the residuals between satellite altimetry and tide gauge data (SSH_{ALT} - SSH_{TG}) at EMSAL.



Source: Authors (2025).

Figure 13 - Spatio-temporal variations of the residuals between satellite altimetry and tide gauge data (SSH_{ALT} - SSH_{TG}) EMMAC.



Source: Authors (2025).

At the EMIMB station, the comparative analysis of SSH revealed that the SWOT mission presented the smallest discrepancy relative to the tide gauge data. As detailed in Figure 10 and Table 4, the residuals observed for the different missions were: 0.05 ± 0.08 m, 0.04 ± 0.14 m, and 0.09 ± 0.10 m for $SSH_{CS2} - SSH_{TG}$, $SSH_{SWOT} - SSH_{TG}$ e $SSH_{S6A} - SSH_{TG}$, respectively. This result demonstrates that the discrepancy of the SWOT mission relative to the tide gauge was only 4 cm, indicating greater precision in the SSH estimation.

EMFOR was the station that presented the highest residual values when compared to the other stations. According to Figure 11 and Table 4, the discrepancies were: -0.18 ± 0.04 m, -0.22 ± 0.03 m, and -0.16 ± 0.02 m for $SSH_{CS2} - SSH_{TG}$, $SSH_{SWOT} - SSH_{TG}$ e $SSH_{S6A} - SSH_{TG}$, respectively. This result proved to be consistent with those found in the study by Giehl, Santana, and Dalazoana (2022), in which they obtained a residual of 25 cm at the same analyzed station when comparing Sentinel-3A and tide gauge data.

Such more pronounced discrepancies in the northeast region, evidenced through EMFOR, may be related to the higher tidal amplitudes in the region; whereas in the south of the country, tidal amplitude values are lower, justifying the residual results found at EMIMB.

In turn, EMSAL presented the best results in terms of means and dispersions, with values of 0.03 ± 0.06 m, 0.01 ± 0.04 m, and 0.03 ± 0.08 m for the differences $SSH_{CS2} - SSH_{TG}$, $SSH_{SWOT} - SSH_{TG}$ e $SSH_{S6A} - SSH_{TG}$, respectively. At EMMAC, as shown in Figure 13 and Table 4, the residual value for $SSH_{CS2} - SSH_{TG}$ was -0.03 ± 0.05 m.

Regarding the correlation coefficients, all stations presented correlations classified as strong to very strong, according to the scale proposed by Shimakura (2006), when comparing the altimetric data obtained by SATALT. However, the Macaé station presented the lowest correlation, with a value of 0.89 (strong correlation), a result possibly associated with the absence of data from 2015 onwards, which reduced the dataset available for analysis.

4 CONCLUSION

Based on the results presented, it is concluded that the altimetry measurements from the CS2, SWOT, and S6A missions demonstrate good agreement with the tide gauge data at the analyzed stations, highlighting the robustness and reliability of the techniques for determining sea surface height (SSH) over the studied period (2014–2024). The discrepancies between the techniques, expressed by the mean residuals, are at levels compatible with the uncertainties inherent to the methods, being more pronounced at the Fortaleza station. The station with the lowest data availability is Macaé; thus, the discontinuity of tide gauge services may have impacted the correlation coefficient between the time series.

The Salvador tide gauge station (EMSAL) stood out for presenting the smallest comparison residuals, with the SWOT mission demonstrating the best agreement with the tide gauge data. This was also observed at the Imbituba station and provides evidence of the potential of the data derived from this mission, despite its still short time series. Additionally, MST variations were estimated with precision on the order of centimeters, reinforcing the sensitivity and effectiveness of altimetry missions in capturing and monitoring local ocean dynamics.

The correlation coefficients, classified as strong to very strong (Shimakura, 2006), confirm the consistency between the altimetric and tide gauge data. This result validates the integration of these methodologies as a robust approach for sea level monitoring. For future studies, it is recommended to determine the MST using tide gauge data and subsequently compare the results with global reference models, such as DTU22MDT and CNES-CLS22, which are models generated from the integration of multi-mission data.

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Author Contributions

Author L. M. S. was responsible for conceptualization, research investigation, data processing, writing the original draft, and performing reviews and editing. Author R. D. assisted in the definition of the idea, as well as in the reviews and supervision of this article.

Conflicts of Interest

The authors declare no conflicts of interest.

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