Analysis of Dynamic Effects on the Brazilian Vertical Datum

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Additional information is available at the end of the chapter

Abstract

This chapter presents a methodology of analyzing the dynamic effect from mean sea level variations, based on Global Navigation Satellite System (GNSS) data, velocity models, tide gauge observations, and satellite altimetry data. GNSS observations were processed in order to obtain the variation of up coordinate required to identify the possible crust movements. Velocity model served as a comparative basis to verify the obtained results from the GNSS data processing and served as a basis for analyzing the time periods without GNSS information. Tide gauge data were used to evaluate the sea level temporal evolution in the Imbituba Brazilian Vertical Datum (I-BVD). Satellite altimetry data were used for checking the results from the GNSS and the tide gauge time series. The analyses were based on time series of observations by GNSS from 2007 until 2016, tide gauge from 1948 until 1968 and 2001 until 2016, and satellite altimetry data from 1991 until 2015 from different missions. As basis for the analysis, it used GNSS SIRGAS-CON stations, the SIRGAS velocity model (VEMOS), and NUVEL velocity model. Considering the discrimination of the crust vertical movement (GNSS processing) from the results obtained with the tide gauge observations, it was observed that there is an evidence of mean sea level (MSL) rising approximately +2.24 ± 0.4 mm/year.

Keywords: mean sea level rising, crustal movement, GNSS time series and data processing, satellite altimetry, velocity model, SIRGAS-CON

1. Introduction

Nowadays, Geodesy provides fundamental reference basis and quantities for using in modern earth observation systems. The main contributions involve the basis for understanding geo-kinematics and control of mass redistribution. Several complementary sources of information

coming from geodetic observations associated with Earth's rotation control of variations in time of positions and gravity field, which reflects mainly in the geokinematic aspects, in the gravity field variations, and in the Earth's rotation.

Global geodetic observing system (GGOS), established by the International Association of Geodesy (IAG), is constituted by the scientific basis and by the geodetic infrastructure needed for global changes monitoring. This, in the present, consists in the main line in the global interaction of Geodesy with several human knowledge fields, coordinated by the IAG [1]. The three central themes of GGOS related to global changes are [1]: Theme 1 – unified global height system (IHRS); Theme 2 – geohazards monitoring; Theme 3 – sea level changes, variability, and forecasting.

In 2012, the United Nations (UN) in its regional conference in Bangkok recommended the adoption of GGOS. The UN Resolution (A/RES/69/266) in February 26, 2015 by considering the coordinated approach of IAG fixed the basic elements of the Global Geodetic Reference Frame (GGRF) as realization of the Global Geodetic Reference System (GGRS) inside the UN-GGIM context. The IAG established the International Height Reference System (IHRS) by its Resolution No. 1 of IAG in July 2015 [2] and its global realization is being discussed inside the GGOS [3]. With basis in the specifications given by IAG in April, 2016 about the GGRS, the coordinates of a point P in the Earth's surface must be given by its geometric coordinates specified by the vector $\vec{X}$ (X, Y, Z) in agreement with ITRS/ITRF and by a physical part linked to the geopotential space by considering the geopotential value in the point, $W_p(\vec{X})$. It is intended that the specification in the geopotential space is to be contained by the International Height Reference Frame (IHRF), realization of the IHRS. It is expected that GGRF as having an overall consistency of at least one centimeter in its realization and space/temporal control in the order of millimeter per year [4].

One of the most important aspects in the global changes discussions is associated to mean sea level (MSL) evolution, especially when observing the evolution in shore areas, in view of the direct impacts on the coastal areas that usually present highest concentration of human occupation. This is emphasized in [5].

From the geodetic point of view and considering mainly GGOS themes 1 and 3, it is necessary to discuss the geokinematic aspects of the ocean-continent interaction, fundamental for the vertical reference system (VRS) definition and realization within a global consistency [6]. The continents interactions with the oceans and the atmosphere must be analyzed in relation to Earth's dynamic response, in order to allow secular and periodic movements discrimination and sporadic loading effects such as those associated with the meteorological fronts passage [7, 8]. In a modern view, the vertical datum (VD) should be related to a unique global reference [2] based on a univocal value of geopotential and that the primary vertical coordinates in the vertical reference networks (VRNs) are the geopotential numbers. The issue of univocal value was discussed in [9]. The current requirements regarding VRSs and VRNs have their foundation expressed mainly in the assumptions of the GGOS. To this end, a new working group was established in the context of GGOS in 2016: strategy for the realization of the IHRS (Chair L. Sanchez) [10].

Two fundamental steps for linking each national vertical network to IHRS/IHRF exist. They are the understanding of the relationship of each national vertical datum with the specified W_0 value and the temporal variations, respectively. Considering the Imbituba Brazilian Vertical

Datum (I-BVD), the first aspect was faced by [11] by determining geopotential numbers from GPS satellite surveying and disturbing potential modeling as well as [12] by fixed solution of the geodetic boundary value problem (GBVP) in the Brazilian vertical datum. The second aspect was partially studied by [13] considering short series of satellite altimetry, tide gauge observations, and I-BVD geocentric positioning. This chapter concentrates more in the second aspect because more than 90% of the Brazilian Fundamental Vertical Network (B-FVN) with about 65,000 benchmarks and about 180,000 km of leveling lines is referenced to the I-BVD. Therefore, in this work, we used time series of Global Navigation Satellite System (GNSS) positioning in relation to I-BVD. These geocentric coordinates series are then associated with tide gauge and satellite altimetry time series, aiming to determine the temporal evolution on I-BVD in the IHRS, from the effects related to the crust movement and to local MSL evolution. The discrimination of these movements in the sea level trends by tide gauges can be realized by determining the tide gauge geocentric position with GNSS continuous positioning. For this, the continuous GNSS station must be installed close to the tide gauge [14–16].

2. Study area and data sets

2.1. Imbituba Brazilian Vertical Datum

According to [17, 18], Brazilian vertical network was deployed in early 1945, in Santa Catarina, through spirit leveling. Torres Datum, in Rio Grande do Sul, south Brazil, was taken as a reference, with a provisional character, because it was only defined with 1 year of sea level observations (1919, 1920). In 1949, Inter-American geodetic survey (IAGS) began the deployment of a tide gauge stations network along the Brazilian coast.

In 1958, Torres datum was replaced by Imbituba datum, for having a longer time series. Imbituba datum was defined by the MSL annual mean value from 1949 to 1957 [19], in the Imbituba Harbor, based on the assumption that the MSL materialized the geoid. The monthly and annual averages of the IAGS tide gauge network are stored in the Permanent Service for Mean Sea Level (PSMSL). The sea level observations from Imbituba, after 1969, have not been recovered yet. The existing observations at PSMSL database are related to the period from 1949 to 1969.

From the 1980s, with the advent of modern space techniques, it has been shown that there are differences between the MSL and the geoid, called the Sea Surface Topography (SSTop). In 1997, the Federal University of Paraná, together with the Brazilian Institute of Geography and Statistics (in Portuguese IBGE), started with different multiparametric campaigns in the datum area, that was carried out over the years. These include GPS positioning, atmospheric pressure monitoring, earth and ocean tides, as well as the recovery of historical altimetric references, tide gauge station reactivation, gravimetry and geodetic observations densification in the contiguous region involving the Imaruí Lagoon system and the search for the link between B-FVN and IHRS [8, 17, 18, 20–25].

After I-BVD establishment, no changes were made in its definition, although there are observations in Imbituba and other stations, for much longer periods [26]. In order to correct the

problems between the geodetic surveys and the sea level observation, in 1994 the Brazilian Institute of Geography and Statistics (in Portuguese IBGE) started the operation of tide gauge stations with geodetic characteristics. In 1999, the harbor authorities in Imbituba resumed sea level conventional observation, and in 2001, IBGE installed tide gauge and meteorological digital equipment to accompaniment I-BVD [27]. At the time of I-BVD definition, the inclusion of gravity observations and SSTop were not considered, the same happened in the majority of VDs in other countries [17]. **Figure 1** shows the location of I-BVD, where it stands out: an image that defines the city of Imbituba and the location of the meteorological, tide gauge, and GNSS stations; location of Imbituba in the State of Santa Catarina (SC); location of Santa Catarina in the country and the continent.

I-BVD involves several fundamental reference levels for the study of its evolution and historical links. Dalazoana carried out an extensive work of recovering ties between reference levels in I-BVD [17], allowing the integration of new observations with modern sensors to the historical reference levels. This study was fundamental for the development of new research in Imbituba. Ferreira performed a SSTop estimation in the I-BVD based on the Imaruí lagoons system average surface adjustment to the Earth gravitational model 1996 (EGM1996) [22]. Palmeiro followed the studies, implementing the integration of free and fixed solutions of the GBVP based on terrestrial and marine gravimetry [23], and derived from satellite altimetry as well as global geopotential model (GGM) [3, 28, 29], which allowed an estimation of SSTop aiming the connection of the B-FVN to IHRS according to GGOS current directives. Palmeiro et al. showed that the association of local gravimetric geoids with the intended global geoid involves a series of associated problems [12]. These are the consequences of the different reference levels (RLs) involved in addition to the resolutions of the various used databases, as can be seen in [25].
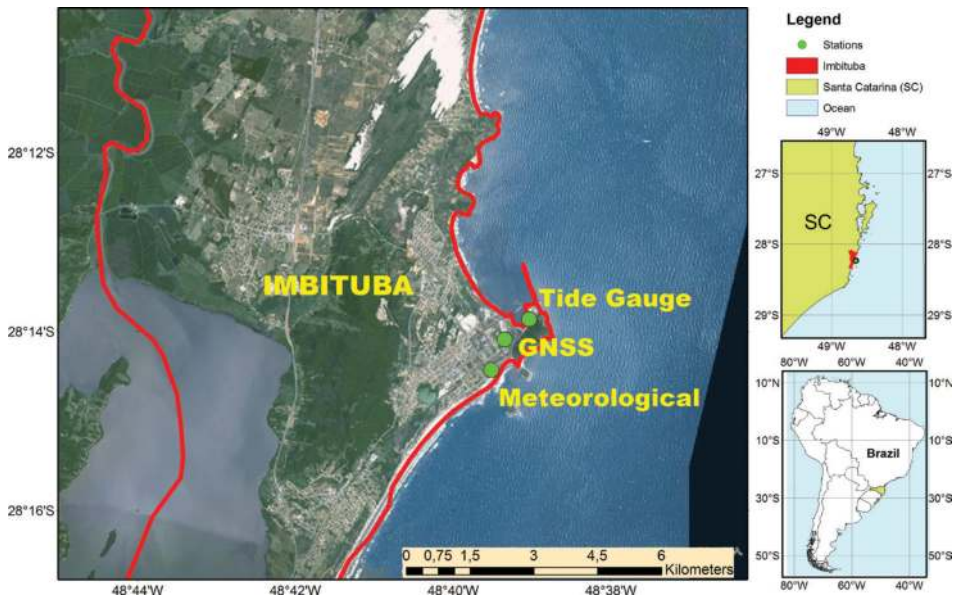
Figure 1. Location of I-BVD in SC where meteorological, tide gauge, and GNSS stations are installed.

The compatibility study of different data sources, such as tide gauge observations and satellite altimetry data, which reflect the oceans dynamic surface should also be considered. Dalazoana highlighted that the existence of discrepancies cannot be fully explained by the Earth's dynamic effects [17], but these are also associated with the different reference systems used.

GNSS monitoring in the I-BVD was established aiming to evaluate the crust dynamic behavior in the region. In Imbituba, near the tide gauge, the IMBT station of SIRGAS-CON (SAT–94,024–International Code, IBGE database) was materialized in 2007. This station was established as successor to the IMBI station (SAT–91,854) where GPS positioning campaigns were carried out. The campaigns at the IMBI station were sporadic, processed with the Bernese 5.0 software, carried out in at least 10 days of continuous observations (1997, 2000, and 2005) [30]. The processing strategy involved the use of precise orbits and antenna calibration parameters, application of tidal correction models, and ocean loading for positions and velocities estimated.

The two stations (IMBI and IMBT) were connected with 17 days of GNSS observations, along with geodetic and topographical methods and cross leveling. During this campaign, it also performed the Van de Casteele test [31]. It is noteworthy that the RLs vertical control and the tide gauge geocentric position determination were essential for the connection of these stations.

2.2. Tide gauge observations

Sea level registrations in the form of monthly mean values of the Permanent Service for Mean Sea Level (PSMSL) are available from September 1948 to December 1968, and daily mean values of the University of Hawaii Sea Level Center (UHSLC) are available from August 2001 to December 2007, and hourly mean values of the RMPG (Permanent Tide Gauge Network for Geodesy) are available from November 2006 to January 2016, these registers were considered to MSL analysis. However, during this period, some tide gauges registrations were irregular with significant interruptions

2.3. GNSS data

Data from 35 Brazilian stations of RBMC (Brazilian Network for Continuous Monitoring) and belonging to GNSS SIRGAS-CON network were selected to support the data processing for obtaining the IMBT GNSS position time series comprising the period from 2007, GPS week 1443, when the IMBT GNSS station was established, to 2016, GPS week 1877. The observations for these stations are available for approximately 10 years. For three of these stations, coordinates and velocities are used in the IGb08 reference frame, an IGS-specific realization of the ITRF2008.

2.4. Satellite altimetry data

For the present analysis T/P, JASON-1 and JASON-2 missions data for cycles 001-364, 001-259, and 001-262, respectively, as provided by [32] were used. The cycles cover the period from September 1992 to February 2015. This period includes approximately 23 years. According to [33], to the measurements of the satellite altimetry missions were applied real geophysical corrections (e.g. for tides, atmospheric delays, and for the inverse barometer effect).

3. Methodology

3.1. Geocentric position

To meet the global demands, [34] presented the Enterprise for Verification of Anomalies in Mean Sea Level by Satellite Altimetry and Tide Gauge Records in the North Atlantic (EVAMARIA) in order to identify and verify sea level anomalies. The authors used 8 years of TOPEX/POSEIDON (T/P) data for comparison with GPS and associated tide gauge data. Häfele et al. addressed the issues [35] related to the EVAMARIA project, in addition to the tide gauge and GPS time series, to verify the crust movement and sea level variations.

In a current view, the location of a point in Earth's surface is defined by its position in a geocentric reference system for a given epoch. This implies that the observation time must be taken into account; the definition time of the Geodetic Reference Systems (GRSs) and the temporal variations of the coordinates for their reductions to the GRS realization time. The lack of knowledge of one of these aspects implies associated problems with the observation techniques combination that are usually at different times and GRSs [36, 37].

In Brazil, studies have been developed over time for VD geocentric position monitoring, within these, we can cite [8, 17, 18, 20–25, 38–44]. They addressed issues related to the use of GPS tracking near the tide gauge to determine the datum geocentric position in the context of the SIRGAS project. The MSL evolution stems from two distinct phenomena: the MSL eustatic movement concerning the geocenter that is largely associated with oceans thermal expansion, and crust tectonic movements along the shoreline, especially the vertical elevation (plate deformation) or crustal subsidence [42].

The MSL in a given location presents deviations from the global average due to the winds, ocean currents, among other factors. The MSL spatial variation is difficult to compare between the referred heights to the VDs. It is also necessary to consider the relative movements due to the periodic differential loading of the tide effects on the crust [45].

With a long period of oceanic tide observations and the tide gauge geocentric position fixation, defined at a certain epoch, secular effects determination can be made by comparison with reference historical levels and the association of crust velocity models and MSL evolution. These procedures allow discrimination between epyrogenic and crustal movements, and between eustatic movements and MSL variations.

According to [17], the GNSS positioning of an RL, associated with spirit leveling allows the zero reference of a tide gauge to a geocentric GRS, as shown in **Figure 2**.

Figure 3 shows a scheme of a local leveling network within a system for MSL measurement without the possible effects of crustal vertical movement. In **Figure 3**, it is observed that for possible detection of crust movements, a GNSS station and an absolute gravimeter are considered next to the tide gauge, besides LRs with overlapping targets for leveling and the tide staff next to the
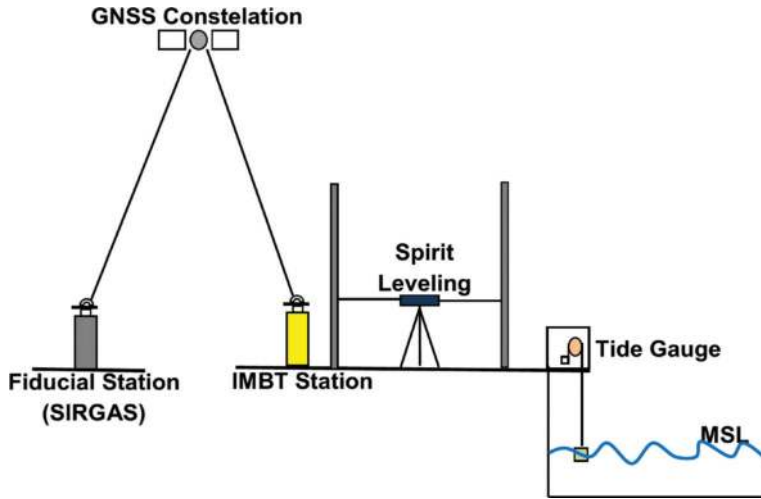
Figure 2. Imbituba tide gauge geocentric position monitoring via GNSS observations and spirit leveling. Source: Da Silva [25].
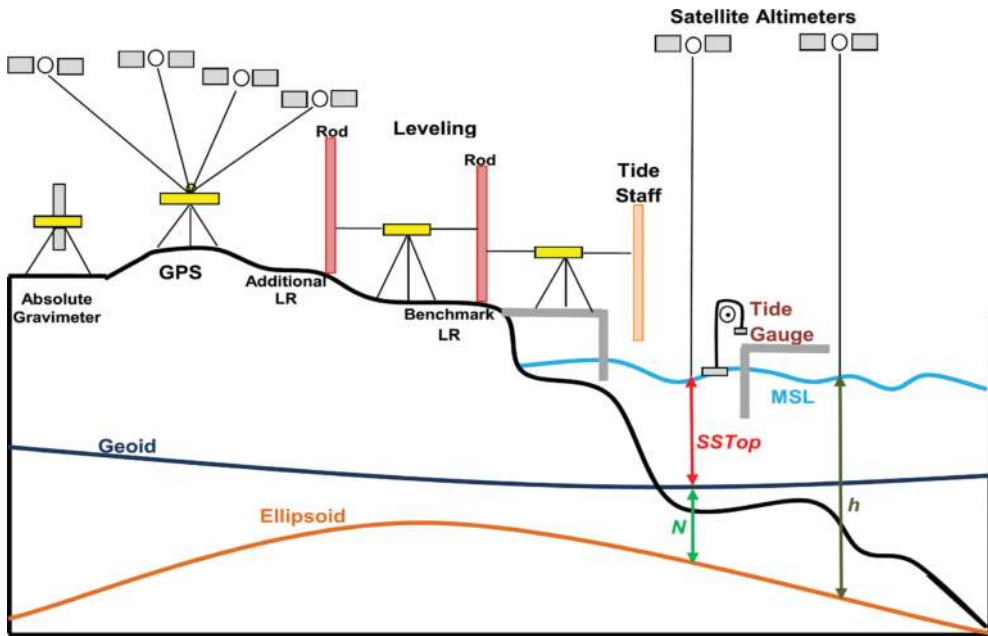

Figure 3. Schematic of required leveling between various benchmarks at a tide gauge station to compare with satellite altimetry.

tide gauge. Another point presented is the question of satellite altimeters, which do not suffer influence of the crust movement. This scheme shown in **Figure 3** is important for linking different sensors, and it is the main support of methodology.

According to [46], the basic idea of combining results from several different techniques is to avoid systematic errors from a specific technique, the combination being the only way to achieve reliability along with accuracy.

3.2. Vertical displacements

Currently, geodetic structures have three components defining the point position in space, in addition of the temporal definition component. SIRGAS is an example based on ITRF2000 [47]. The SIRGAS coordinates can be used as constrain in GNSS processing, but rather it must be reduced to the time of the satellite observations from the geophysical or geodetic models of plate movements [46].

Based on stations' velocities, it is possible to update the station coordinates, from the reference epoch to any other, or knowing the observation epoch, it is possible to determine the coordinates for the reference epoch. It is worth mentioning some details regarding the coordinates update process:

• Differences between the various achievements of ITRF as of the Helmert transformation parameters (7 or 14);

• The fiducial stations coordinates at the GRS definition epoch can be transformed to the observation epoch with known velocities;

• The new stations coordinates must be reduced to the ITRF yyyy (year), the velocities of the new stations are unknown, being necessary to interpolate as of some velocity model.

A method to estimate the horizontal velocities is presented in the SIRGAS Velocity Model [VElocity MOdel of Sirgas (VEMOS)]. It is worth noting that from VEMOS2009 [48], vertical velocities are not obtained because they cannot be interpolated with regional models due to local deformations, tectonic movements, and hydrological, glacial, and meteorological effects. This model was updated for VEMOS2015 [49], with it is possible to obtain the vertical velocities, since the calculation is based on GNSS measurements.

In the South American (SOAM) plate, particularly in Brazil, intraplate crustal movements are small compared to regions with intense tectonic activities. In the peripheral zones of the plate, there are relative movements with different directions and magnitudes, generating several types of geological structures [50]. For the combination of these geological structures is indicated the Geophysical model No Net Rotation–Northwestern University VELocity model 1A (NNR-NUVEL-1A) [51, 52].

3.3. Detection of crust movement using GNSS data

As a result of these investigations, a dedicated processing of periods from 2007 to 2016 was performed. The GNSS processing strategy is characterized by Bernese software version 5.2; ionosphere free double difference observations; CODE combined orbits, satellite clock offsets and Earth orientation parameters used; elevation cutoff angle set to 10°; tropospheric delay predicted using the global mapping function (GMF), the Dry_GMF, and Wet_GMF, both available as standard options in the Bernese; practically unconstrained estimates of residual zenith delays for 2 hours intervals; ocean tide loading, and atmospheric loading model according to [53]. There are different criteria to select the baselines to be processed in one session; the adopted in this chapter were using the stations that have maximum number of common observations, weekly processing of coordinate of each session is reduced to the average day of each processed GPS week. Normal equations of all epochs were combined using the ADDNEQ program. More details of the GNSS processing are described in [25, 53].

3.4. Comparison between tide gauge and satellite altimetry observations

In order to compare the tide gauge observations with the ocean sea level variability, a dedicated procedure for the altimetric sea surface height residuals extrapolation toward the tide gauge position was developed and applied [25], for this it was realized:

1. In order to elaborate the time series, the tide gauge observations were concatenated using Python, since RMPG observations are taken every 5 minutes; the tide gauge data sets were filtered with a low-pass filter, symmetrical and centered on the hour integer value, with the objective of separating noises or interferences in the observations within the time domain.

2. The differences among in the zero reference of the digital sensor, tide staff, and the analogue sensor in Imbituba were verified for the integration of the tidal series.

3. For the sea level series resampling in Imbituba at the same time of the satellite altimetry SSH series, it was fulfilled with cubic splines. So, it was necessary to develop scripts for readings and concatenation of the data. Firstly, a Python script was developed to read the data. After this process, a consistency check is performed and it is imported into the developed MySQL database.

4. The SSH values come with Julian day, so the tide gauge series were been put in the same time reference. In this processing, the Julian day 0 was established as at 12:00 TU (noon) on January 1, 2000.

The SSH data used for analysis were considered within the ±3σ range. Values SSH > 3.0 m were eliminated. Transformation of the SSH data defined on the ellipsoid of the T/P, JASON-1, and JASON-2 missions to the GRS80 ellipsoid.

4. Results and discussion

The IMBT station is the object of study of this research. Thus, **Table 1** shows the velocity results the VEMOS2009 and VEMOS2015 models and estimation via GNSS processing in the Bernese 5.2. Using the geophysical and geological models, it was possible to obtain the SOAM plate rotation vectors, as well as the plate spherical coordinates **Table 2**.

It should be noted that the calculated values in **Tables 1** and **2** derived of the stations velocities used in the processing represent the Brazilian stations movement in a more realistic way.

In order to compare tide gauge observations with SSH series, the satellite trail closest to the tide gauge was considered. Comparison was made considering 71 cells closest to the tide gauge. It should be noted that the cells comprises located up data (SSH) to approximately 500 km from the coast. Therefore, the most important is to consider the nearest cell where the observations of standard deviation are still within acceptable values because they have not been affected by coastal effects, and application of the differential tidal correction [56].

In particular in shore areas, where the comparisons with the tide gauges are performed, these corrections can improve considerable errors. **Table 3** presents the comparison of characteristics before and after the differential tidal correction. The comparative results of the cell with the best results are highlighted to JASON-2 mission. **Figure 4** shows two comparisons of tide gauge daily registrations with the JASON-2 altimeter data. It should be that the altimeter data was applied the tide correction and the extrapolation to nearest area of tide gauge.

Considering the GNSS processing to detect crust movements possible, the result was used to remove these movements from the tide gauge observations and thus to carry out the absolute comparison of the tide gauge data with the satellite altimetry data.

It should be noted that the employed data and methods were allowed to distinguish the crust movement from the MSL relative variation, as well as to estimate the MSL absolute increase. These were used to determinate the I-BVD geocentric position.

Analyzing the 2007–2016 period, we obtained 5.26 ± 0.11 mm/year for the tide gauge series, −3.02 ± 0.39 mm/year for the GNSS processing and 2.23 ± 0.42 mm/year for the satellite altimetry data processing. These results were essential for the crust movement and MSL relative variations distinction, enabling the obtained time series integration of tide gauge observations and satellite altimetry data. **Figure 5** shows the time series integration of the tide gauge observations

Model	V_{Lat} (mm/y)	V_{Long} (mm/y)	h (mm/y)	V_X (mm/y)	V_Y (mm/y)	V_Z (mm/y)
VEMOS2009	12.00	−2.60	—	1.80	−6.00	10.60
VEMOS2015	14.20	−3.80	−3.40	−0.37	−5.30	14.14
Processing	16.18	−3.87	−3.02	−0.39	−5.69	12.56

Table 1. Derived velocities, the VEMOS2009 and VEMOS2015 models and the Bernese processing for IMBT station.

Model	Plate	Δx (s/MA[*])	Δy (s/MA)	Δz (s/MA)	Φ[o]	Λ[o]	Ω[o]/MA
NNR-NUVEL-1[a]	SOAM	−0.060	−0.087	−0.050	−25.24[1]	235.57[1]	0.1164[1]
APKIM2008	SOAM	−0.231	−0.367	−0.153	−19.40[2]	237.80[2]	0.4600[2]
Calculated	SOAM	−0.157	−0.112	−0.089	−24.80	215.64	0.2126

Source: [1]Refs. [51–52, 54–55]; [2]Ref. [49].
[a]A; [o]Degree; [*]MA - Millions of years.

Table 2. SOAM plate rotation vectors and spherical coordinates.

Analyses	Before correction	After correction
Cell	478	478
Correlation coefficient	0.93	0.96
Standard deviation (mm)	69	50
Distance from the Coast	77	77

Table 3. Comparison of before and after tide differential correction.
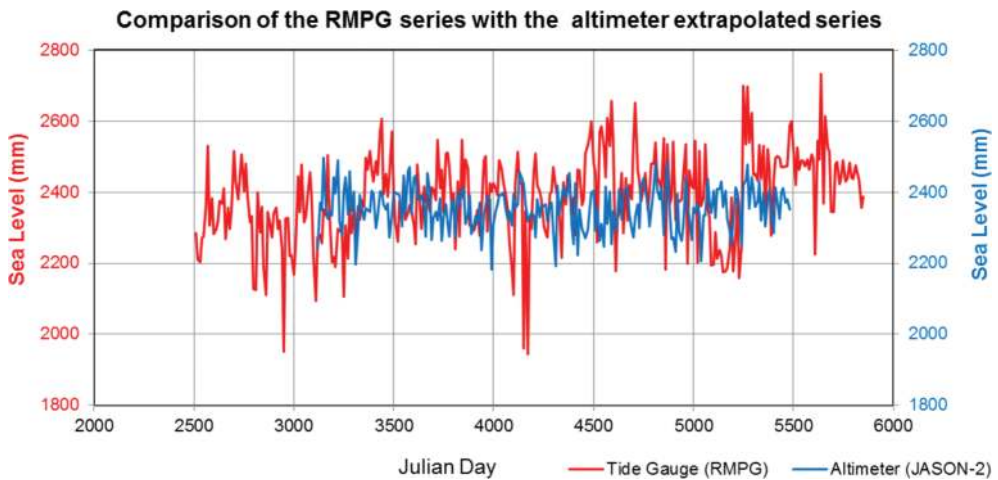
Figure 4. Extrapolated series of the JASON-2 altimeter data with differential tidal correction.

and the altimetric mission's data, in Julian Day. In order to concatenate the averages that were in Julian days for monthly averages, a script in Python was developed.

The MSL time series presented in **Figure 5** has already made the correction of the crust movements, as well as a tide gauge observations filtering, the considered averages as outliers were eliminated and replaced by satellite altimetry data. **Figure 6** shows MSL estimate from 1948 to 2016.
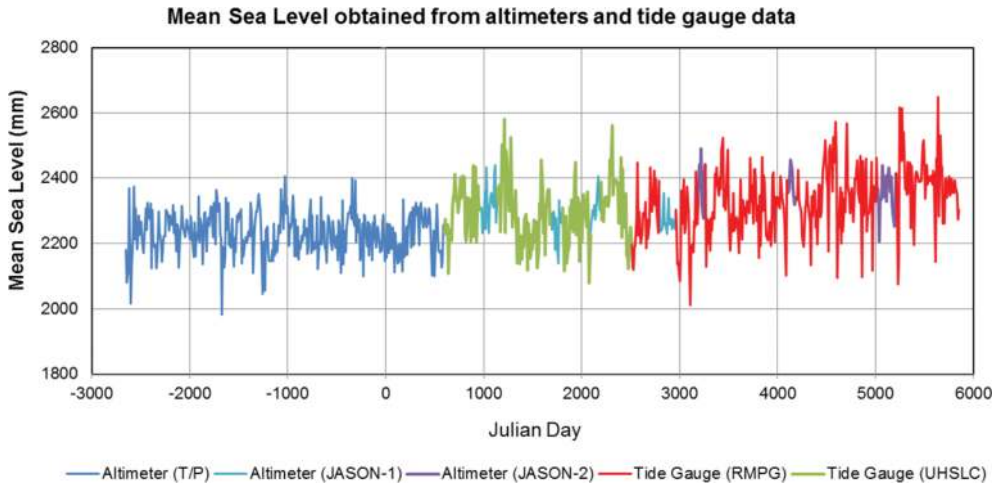
Figure 5. Tide gauge observations of temporal series and satellite altimetry data at the same instant.
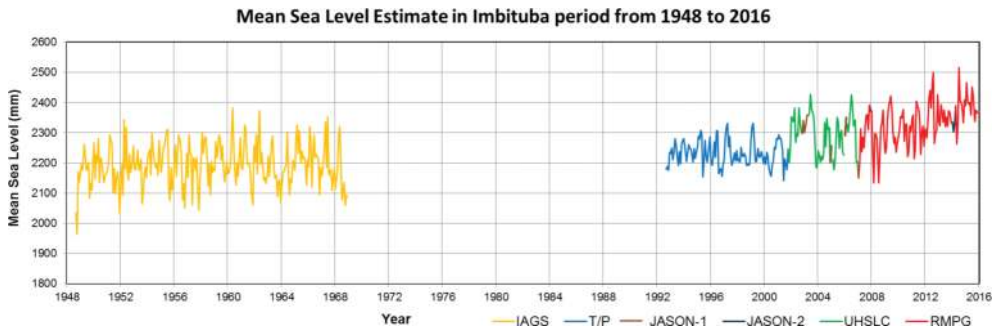

Figure 6. Mean sea level time series on I-BVD.

From the obtained results, it was evidenced that there is an MSL evolution in the I-BVD region by the determination of temporal variation resulting of approximately +2.24 ± 0.4 mm/year. There was also agreement with based studies on tide gauge observations and satellite altimetry data. These studies were already mentioned in this research.

5. Conclusion

Imbituba sea level shows remarkable changes within the time analyzed period. The GNSS observations time series processing made it possible to generate its own velocity model as well as to compare with the proposed models by SIRGAS, and geophysical and geological velocity models.

For a better analysis of the mean sea level, we analyzed data from satellite altimetry of different missions with tide gauge observations. These allowed a better I-BVD evolution analysis comparing the SSH values time series related to the located cells along the satellite track and the tide gauge sea level observations integrated with GNSS positioning time series.

I-BVD temporal evolution can be modeled from long time series (over 5 years) of satellite altimetry data, GNSS, and tide gauge observations. This assertive is in accordance with the integration vision to the IHRS. Therefore, the based results on the I-BVD geocentric position analysis showed an elevation rate of +2.24 ± 0.4 mm/year. This value is in agreement with global information of mean sea level elevation, stands out that evidenced the MSL evolution in the I-BVD region determining the tide gauge geocentric position temporal variation associated the time series analysis of tide gauge observations and satellite altimetry data.

Acknowledgements

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References

[1] GGOS–The Global Geodetic Observing System. Introducing GGOS – Additional Information: GGOS [Internet]. Available from: http://www.ggos.org/ [Accessed: June 6, 2017]

[2] IAG – International Association of Geodesy. Home: IAG and IUGG Resolutions – IAG Resolutions Prague, Czech Republic 2015. Resolution n°1 for the Definition and Realization of an International Height Reference System (IHRS) [Internet]. Available from: http://iag.dgfi.tum.de/fileadmin/IAG-docs/IAG_Resolutions_2015.pdf [Accessed: July 06, 2017]

[3] IAG – International Association of Geodesy. IAG Office – IAG GGGOS [Internet]. Available from: http://iag.dgfi.tum.de/index.php?id=253 [Accessed: June 10, 2017]

[4]   Sanchez L, Sideris MG. Vertical datum unification for the International Height Reference System (IHRS). Geophysical Journal International. 2017:570-586

[5]   Smith J, Wigginton N, Ash C, Fahrenkamp-Uppenbrink J, Pennisi E. Changing oceans: Introduction to special ISSUE. Science. 2010;**328**:1497. DOI: 10.1126/science

[6]   De Freitas SRC. SIRGAS-WGIII activities for unifying height systems in Latin America. Revista Cartográfica. 2015;**91**:75-91

[7]   Vandam TM, Blewitt G, Heflin MB. Atmospheric pressure loading effects on global positioning system. Journal of Geophysical Research. 1994;**99**:23939-23950

[8]   Luz RT, Bosch W, De Freitas SRC, Heck B, Dalazona R. Evaluating the Brazilian vertical datum through improved coastal satellite altimetry data. Michael Sideris. (Org.). IAG Series: Observing our Changing Earth. 2009;**133**(1):735-741

[9]   Sánchez L. Towards a vertical datum standardization under the umbrella of global geodetic. Journal of Geodetic Science. 2012;**2**(4):325-342

[10]   IAG – International Association of Geodesy. IAG Newsletters – January 2016: 5. Structure of GGOS [Internet]. Available from: http://www.iag-aig.org/index.php?tpl=text&id_c=44&id_t=671 [Accessed: July 07, 2017]

[11]   Ferreira VG, De Freitas SRC. Geopotential numbers from GPS satellite surveying and disturbing potential model: A case study of Parana. Brazilian Journal of Applied Geodesy. 2011;**5**:155-162

[12]   Palmeiro AS, De Freitas SRC, Dalazoana R. Análise do vínculo do Datum Vertical Brasileiro a um Sistema Global de Altitudes. Revista Brasileira de Cartografia. 2013;**6**(65): 1097-1111

[13]   Dalazoana R, De Freitas SRC, Baez JCS, Luz RT. Brazilian vertical datum monitoring– Vertical land movements and sea level variations. In: Rizos C, Tregoning P, editors. Dynamic Planet Monitoring and Understanding a Dynamic Planet with Geodetic and Oceanographis Tools. 130th ed. New York: Springer; 2007. pp. 71-75

[14]   Yildiz H, Andersen OB, Simav M, Aktug B, Ozdemir S. Estimates of vertical land motion along the south western coasts of Turkey from coastal altimetry and tide gauge data. Advances in Space Research: Elsevier. 2013:1572-1580

[15]   Guo J, Wang J, Hu Z, Liu X, Kong Q, Zhao C. Vertical land movement over China coasts determined by tide gauge and satellite altimetric data. Arabian Journal of Geosciences. 2016;**9**(168):1-12. DOI: 10.1007/s12517-015-2219-3

[16]   Zerbini S, Raicich F, Prati CM, Bruni S, Del Conte S, Errico M, Santi E. Sea-level change in the Northern Mediterranean Sea from long-period tide gauge time series. Earth-Science Reviews: Elsevier. 2017;**167**:72-87

[17]   Dalazoana R. Estudos dirigidos à análise temporal do Datum Vertical Brasileiro [thesis]. Universidade Federal do Paraná; 2006. 202 p. Available from: http://acervodigital.ufpr.br/bitstream/handle/1884/3922/TESE_REGIANE_DALAZOANA.pdf?sequence=1&isAllowed=y

[18] Luz RT. Estratégias para modernização da componente vertical do Sistema Geodésico Brasileiro e sua integração ao SIRGAS [thesis]. Universidade Federal do Paraná; 2008. 228 p. Available from: http://www.sirgas.org/fileadmin/docs/Roberto_Teixeira_Luz_Tese_de_Doutorado.pdf

[19] Alencar JCM. Datum Altimétrico Brasileiro. Caderno de Geociências. 1990;**5**:69-73

[20] Cordini J. Aspectos Geodinâmicos no Datum da Rede Altimétrica do SGB [thesis]. Universidade Federal do Paraná; 1998. 183 p. Available from: http://www.acervodigital.ufpr.br/bitstream/handle/1884/34977/T%20-%20JUCILEI%20CORDINI.pdf?sequence=1&isAllowed=y

[21] Miranda FA. Contribuição para a Análise do Campo da Gravidade na Região do Datum Vertical Brasileiro [dissertation]. Universidade Federal do Paraná; 2006. 133 p. Available from: http://acervodigital.ufpr.br/bitstream/handle/1884/13357/disserta%C3%A7%C3%A3o_completa_final%282%29.pdf?sequence=1&isAllowed=y

[22] Ferreira VG. Análise da Componente Anômala do Geopotencial no Datum Vertical Brasileiro com base no sistema lagunar de Imauri, SC [dissertation]. Universidade Federal do Paraná; 2008. 116 p. Available from: http://acervodigital.ufpr.br/bitstream/handle/1884/15142/VAGNER%20GON%C3%87ALVES%20FERREIRA%20%282008%29.pdf?sequence=1&isAllowed=y

[23] Palmeiro AS. Análise do Vínculo do Datum Vertical Brasileiro a um Sistema Global de Altitudes com Base em Soluções Fixadas e Livres do PVCG [thesis]. Universidade Federal do Paraná; 2011. 159 p. Available from: http://acervodigital.ufpr.br/bitstream/handle/1884/32327/R%20-%20T%20-%20ALESSANDRA%20SVONKA%20PALMEIRO.pdf?sequence=1&isAllowed=y

[24] Da Silva LM, De Freitas SRC, Dalazoana R. Análise de Séries Temporais Maregráficas correlacionadas com observações GNSS do Datum Vertical Brasileiro de Imbituba-SC. Revista Brasileira de Cartografia. 2016;**68**:73-90

[25] Da Silva LM. Análise da Evolução Temporal do Datum Vertical Brasileiro de Imbituba [thesis]. Universidade Federal do Paraná; 2017. 270 p. Available from: http://acervodigital.ufpr.br/bitstream/handle/1884/47347/R%20-%20T%20-%20LUCIANA%20MARIA%20DA%20SILVA%20.pdf?sequence=1&isAllowed=y

[26] Luz RT, Guimarães VM. Dez Anos de Monitoramento do Nível do Mar no IBGE. In: III Colóquio Brasileiro de Ciências Geodésicas; 6 a 9 de maio; Curitiba. Universidade Federal do Paraná; 2003

[27] Luz RT, De Freitas SRC, Dalazoana R, Miranda FA, Palmeiro AS, Jamur KP. Possibilidades de Integração de dados Gravimétricos à Rede Altimétrica do SGB para Cálculo de. In: I Simpósio Brasileiro de Ciências Geodésicas e Tecnologias da Geoinformação; Recife. Universidade Federal de Pernambuco; 2006

[28] Ihde J, Amos M, Heck B, Kersley B, Schöne T, Sánchez L, Drewes H. Conventions for the Definitions and Realization of a Conventional Vertical Reference System (CVRS)

[Internet]. Available from: http://whs.dgfi.badw.de/fileadmin/user_upload/CVRS_conventions_final_20070629.pdf [Accessed: June 25, 2017]

[29]   Ihde J, Barzaghi R, Marti U, Sánchez L, Sideris M, Drewes H, Foerste C, Gruber T, Liebsch G, Pail R. Report of the ad-hoc group on an International Height Reference System (IHRS). In: Drewes H, Hornik H, editors. Travaux de l'AIG 39 [Internet]. IAG Reports 2011-2015. Available from: http://www.dgfi.tum.de/media/jahresbericht/publications/03f544613917945245041ea1581df0c2.pdf [Accessed: July 8, 2017]

[30]   De Freitas SRC. Estratégias para uma nova definição do Datum Vertical Brasileiro e realização da Rede Vertical Brasileira visando suas integrações com o SIRGAS. In: II Simpósio Brasileiro de Geomática Presidente Prudente–SP; UNESP. Presidente Prudente; 2007. pp. 440-446

[31]   Instituto Brasileiro de Geogarfia e Estatística. Relatório Individual de levantamentos Geodésicos no Porto de Imbituba [Internet]. 11/06/2007-19/06/2007. [Accessed: July 18, 2017]

[32]   DGFI–Deutsches Geodätisches Forschungsinstitut. An Open Altimeter Database [Internet]. Available from: http://openadb.dgfi.tum.de/index.php?id=172 [Accessed: November 15, 2016]

[33]   Schwatke C, Bosch W, Savcenko R, Dettmering D. OpenADB–An open database for multi-mission altimetry. In: EGU; Vienna. Austria; 2010

[34]   Bosch W, Drewes H, Häfele P, Kaniuth K, Kaniuth R, Kuhn M, Stuber K, Tremel H. The EVAMARIA project: Identification and verification of sea level anomalies in the North America. In: Drewes H, Dodson AH, Fortes LPS, Sanchez L, Sandoval P, editors. International Association of Geodesy Symposia: Vertical Reference System. 124th ed. Springer; 2002. p. 238-243. DOI: 10.1007/978-3-662-04683-8

[35]   Häfele P, Huber S, Kaniuth K. Vertical crustal movements of tide gauges sites around the North Atlantic Ocean. In: Drewes H, Dodson AH, Fortes LPS, Sanchez L, Sandoval P, editors. International Association of Geodesy Symposia: Vertical Reference System. 124th ed. Springer; 2002. p. 244-248. DOI: 10.1007/978-3-662-04683-8

[36]   Sideris MG. Introduction. Global Geodetic Observing System – GGOS Book. Springer; 2020. p. 2009

[37]   Plag HP, Pearlman M. Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020. Dordrecht Heidelberg London New York; ed. 1, 2009. 332 p. DOI: 10.1007/978-3-642-02687-4

[38]   Drewes H, Sanchez L. Sistemas de Referência Cinemáticos em Geodésia – Definición, Realización y Mantenimiento. In: Congreso Internacional de Ciencias de la Tierra; Outubro–2004; Santiago Chile. 2004

[39]   De Freitas SRC, Cordini J, Krueger CP, Santos MC. The geocentric position of the Brazilian Vertical Datum. In: International Symposium on Marine Positioning: "United Nations Year of the Oceans"; Florida Institute of Technology Melbourne, FL, USA: Proceedings of INSMAP98; 1998. pp. 230-240

[40] De Freitas SRC, Cordini J, Krueger CP, Santos MC. The geocentric position of the Brazilian vertical Datum. IAG (International Association of Geodesy) Series; Sanso F. (Org.). 1999;**120**(Coletânea de Artigos)

[41] De Freitas SRC, Dalazoana R, Luz RT, Heck R, Ferreira VG, Palmeiro AS. Refining Brazilian vertical datum by integrating satellite altimeter data and local geopotential anomalous component. In: IUGG/XXIV; 2007

[42] Da Silva LM, De Freitas SRC. Os Efeitos Dinâmicos e a Evolução Temporal do Datum Vertical Brasileiro de Imbituba. In: Reunion Sirgas 2013; Outubro - 2013; Cidade do Panamá. SIRGAS; 2013. Available form: http://www.sirgas.org/fileadmin/docs/Boletines/Bol18/22j_da_Silva_de_Freitas_2013_Efectos_dinamicos_Imbituba.pdf

[43] Da Silva LM, De Freitas SRC. Estimativa da posição atual do Datum Vertical Brasileiro de Imbituba a partir de dados maregráficos, observações GNSS e Altimetria por Satélites. In: Simpósio Sirgas 2015; 16-20 de Novembro de 2015; Santo Domingo. SIRGAS; 2015. Available form: http://www.sirgas.org/fileadmin/docs/Boletines/Bol20/30_DaSilva_et_al_2015_Datum_vertical_brasilero.pdf

[44] Da Silva LM, De Freitas SRC. Movimentos da crosta inferidos da análise de séries temporais GNSS de um segmento das estações brasileiras pertencentes à RBMC. In: Sirgas 2016; Novembro de 2016; Quito - Equador. SIRGAS; 2016. Available form: http://www.sirgas.org/fileadmin/docs/Boletines/Bol21/32_DaSilva_DeFreitas_2016_Moviemientos_serires_temposrales_Brasil.pdf

[45] Farrel WE. Deformation of the earth by surface loads. Reviews of Geophysics and Space Physics. 1972;**10**:761-797

[46] Costa SMA. Integração da Rede Geodésica Brasileira aos Sistemas de Referência Terrestres [thesis]. Univerdade Federal do Paraná. 1999:154

[47] Teixeira NNA. Análise geodésica de deformações da crosta em regiões de grandes barragens a partir de deslocamentos tridimensionais obtidos pelo sistema de posicionamento global [thesis]. Universidade Federal do Paraná. 2005:294

[48] Drewes H, Heidbach O. The 2009 horizontal velocity model for South America and the Caribbean. Geodesy for Planet Earth, International Association of Geodesy Symposia. 2012;**136**:657-664. DOI: 10.1007/978-3-642-20338-1_81

[49] Sánchez L, Drewes H. Crustal deformation and surface kinematics after the 2010 earthquakes in Latin America. Journal of Geodynamics. 2016:1-23. DOI: 10.1016/j.jog.2016.06.005

[50] Perez JAS, Monico JFG, Chavez J. Velocity field estimation using GPS precise point positioning: The south American plate case. Journal of Global Positioning System. 2003;**2**(2):90-99

[51] De Mets C, Gordon R, Argus DF, Stein S. Current plate motion. Geophysical Journal International. 1990;**101**:425-478

[52] De Mets C, Gordon R, Argus DF, Stein S. Effect of recent revision to the geomagnetic reversal time scale on estimates of current plate motion. Geophysical Research Letters. 1994;**21**(20):2191-2194

[53] Dach R, Lutz S, Walser P, Friedez P. Bernese GNSS Software Version 5.2. University of Bern: Astronomical Institute; 2015. p. 884. DOI: 10.7892/boris.72297

[54] Drewes H. Combination of VLBI, SLR and GPS determined station velocities for actual plate kinematic and crustal deformation models. Geodynamics, IAG Symposia, Springer. 1998;**119**:377-382

[55] Drewes H, Meisel B. An actual plate motion and deformation model as a kinematic terrestrial reference system. Geotecnologien Science Report. 2003;**3**

[56] Le Provost C. Ocean tides. In: LL F, Cazenave A, editors. Satellite Altimetry and Earth Sciences: A Handbook of Techniques and Applications. Academic Press; 2001. p. 267-303