Revista Brasileira de Cartografia
ISSN 1808-0936 |https://doi.org/10.14393/revbrascartogr
Brazilian Society of Cartography, Geodesy, Photogrammetry and Remote Sensing

Assessment of Local Vertical Variation Aimed at the Integrity of Tide Gauge Time Series

Avaliação da Variação Vertical Local Voltada à Integridade de Séries Temporais Maregráficas

Everton Gomes dos Santos [1], Salomão Soares [2] e Ivandro Klein [3,4]

1 Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro, Brasil. everton.santos@ibge.gov.br
ORCID: https://orcid.org/0000-0002-8730-7755

2 Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro, Brasil. salomao.soares@ibge.gov.br
ORCID: https://orcid.org/0000-0003-4826-776X

3 Instituto Federal de Santa Catarina, Florianópolis, Brasil. ivandroklein@gmail.com
ORCID: https://orcid.org/0000-0003-4296-592X

4 Universidade Federal do Paraná, Programa de Pós-Graduação em Ciências Geodésicas, Curitiba, Brasil.

Received: 06.2022 | Accepted: 10.2022

Abstract: Tide gauge time series are fundamental to integrating height and bathymetric reference systems. Therefore, it is essential to separate signals of non-oceanic origin from such observations. This paper aims to evaluate the local vertical motion variation of regions that host tide gauge stations by considering aspects of the quality of the leveling network and temporal analysis. The leveling network of Imbituba's Tide Gauge Station was evaluated according to quality control widely used in Geodesy. Thus, the following analyses were performed: residuals, internal reliability, redundancy number, and overall model test. For the evaluation of the vertical variation of the geodetic stations, a preliminary classification was made concerning the construction type, the magnitude of the temporal variation rates, outlier detection, and confidence level. The quality control routines applied indicated that the network behaved homogeneously, and the observations had better than expected accuracies. Most residuals were less than 0.5 mm, and partial redundancies were classified as "sufficient" $(0.1 \leq r_i \leq 0.3)$ and "good" " $(0.3 \leq r_i \leq 1)$. The overall model tests showed that the observations are better than the ones established in the pre-analysis. The vertical variation of the geodetic stations classified as A and B showed an average vertical variation rate of +0.02 mm/year and no outlier. In contrast, the class C stations, after the identification and separation of outliers, 53% of the class sample, showed an average vertical variation rate of -0.17 mm/year, indicating a characteristic of settlement. It was evident that temporal monitoring is indispensable to the corrections for determining integral tide gauge series, free of influences of non-oceanic origin.

Keywords: Geodetic control. Adjustment of observations. Vertical motion. Geodetic networks.

Resumo: As séries temporais maregráficas são fundamentais à integração dos sistemas altimétricos e batimétricos de referência. Logo, é fundamental separar os sinais de origem não oceânica de tais observações. O objetivo desse trabalho é avaliar a variação da movimentação vertical local de regiões que abrigam estações maregráficas considerando aspectos sobre a qualidade da rede de nivelamento e a análise temporal. A rede de nivelamento da Estação Maregráfica de Imbituba (SC) foi avaliada segundo controle de qualidade amplamente utilizado na Geodésia. Assim, foram realizadas as análises dos resíduos, da confiabilidade interna, do número de redundância e do teste global do ajustamento. Para a avalição da variação vertical das estações geodésicas fez-se classificação preliminar em relação ao tipo construtivo, a magnitude das taxas de variação temporal, da frequência de outliers e nível de confiança. Os controles de qualidade aplicados indicaram que a rede comportou-se de forma homogênea e as observações têm precisões melhores do que o esperado. A grande maioria dos resíduos foram inferior a 0,5 mm e as redundâncias parciais classificadas como "suficiente" $(0,1 \leq r_i \leq 0,3)$ e "boa" $(0,3 \leq r_i \leq 1)$. Os testes globais mostraram que as observações estão melhores que a estabelecida na pré-análise. A variação vertical das estações geodésicas classificadas como A e B apresentaram taxa média de variação vertical de +0,02 mm/ano e nenhum *outlier*; enquanto as estações classe C, após a identificação e separação de *outliers*, 53% da amostra da classe, apresentaram uma taxa média de variação vertical de -0,17 mm/ano, indicando uma característica de recalque. Ficou evidente que o acompanhamento temporal é indispensável às correções para determinação de séries maregráficas integras, livres de influências de origem não oceânica.

Palavras-chave: Controle geodésico. Ajustamento de observações. Variação vertical. Redes geodésicas.

1 INTRODUCTION

The geodetic control of tide gauge stations (GCTGS) implemented by IBGE (2010) aims to detect and quantify vertical movements of non-oceanic origin. Above all, movements concerning the Earth's crust or punctual local movements. Such movements can occur through subsidence or uplift, thus implying changes in the position of the sensor support structures, among other aspects that can affect tide gauge observations. The GCTGS makes it mainly possible to perform the necessary corrections to determine an integral series of sea level variations. For this, it must be carried out periodically to have a reliable spatial and temporal follow-up.

When establishing a leveling network around the tide gauge station in port regions, the first difficulty encountered is identifying stable locations for implementing benchmarks, since ports are usually built with great landfill techniques. Regarding this difficulty, several daily changes in ports result in the excessive destruction of benchmarks. Dalazoana (2005, p.65-69) carried out a historical survey of the benchmarks implanted in the Port of Imbituba (SC) since 1948, noting the high rate of destruction, which corroborates this statement regarding the vulnerability of these implantations in environments with dynamic characteristics, like ports.

That said, the GCTGS (IBGE, 2010) proposes a minimum condition for the installation of benchmarks to guarantee the preservation of the results from the tide gauge observations and surveys with Global Navigation Satellite System (GNSS) receivers. The superabundance of survey marks provides the ideal condition for a network of vertical control points. According to IBGE (2021), the Imbituba tide gauge station currently has 26 benchmarks distributed between the Port of Imbituba (SC) and the city center.

The update of the Specifications and Standards for Geodetic Surveys Associated with the Brazilian Geodetic System (IBGE, 2017) includes the activities of the GCTGS, incorporating new technologies. For example, the digital level made the activity more efficient and economical, mainly for surveys requiring greater rigor and precision. The document, as mentioned earlier, divides scientific geometric leveling (SGL) into two basic types: geodetic control of tide gauge stations and linkage between tide gauge stations. Although the focus of these two groups is aimed at meeting the needs of the GCTGS, both can be applied in surveys that require better accuracies than the High Precision Height Network - HPHN, i.e., $3\,mm\sqrt{D_{km}}$ where D is the distance in kilometers of a leveling line. A recent exemple was the estabilishment of the Geodetic Network of Coastal Reference – CNCR (SANTOS, 2021).

The design of networks for the control, detection, and quantification of non-oceanic signals is carried out in a way that allows the best conditions for surveying field observations, maintaining the necessary rigor to link the mean sea level to the Brazilian Geodetic System (BGS). Furthermore, it allows the integration of geodetic benchmarks into observations from other platforms, such as gravimetry, satellite altimeters, and Global Navigation Satellite Systems (GNSS) positioning.

In this sense, the GCTGS requires a physical infrastructure that guarantees the long-term stability of survey marks. When designing (materializing) the temporal control circuits of the vertical component, some vital care are taken. These range from the material chosen for manufacture devices and plates, their format, and the implantation locations. Regarding the latter, which is directly linked to the physical structure, there still needs to be a Brazilian standard to classify the benchmarks according to these aspects. However, some authors have recommended improving the stability of survey marks deployed in Brazil and internationally.

The document Monitoring the Mean Sea Level Variation at Stations of the Permanent Tide Network for Geodesy 2001-2020 (IBGE, 2021) provides some fundamental guidelines regarding these aspects that serve as a subsidy for discussions in this research. Furthermore, studies that address issues related to the vertical variation of benchmarks are also discussed in FNCG (2011), Hailegeberel et al. (2018), and IBGE (2016).

The tide stations are an essential element in the interface between heights (land part) and depths (oceanic part), and vertical control networks make the interlocutions between the different magnitudes. The objective of this work is to evaluate the local vertical variation aimed at the integrity of the tide gauge time series, considering aspects of the quality of the leveling network and temporal analysis using measurements carried out at the Imbituba tide gauge station in Santa Catarina State between the years 2015 and 2022 as an

 DOI: http://dx.doi.org/10.14393/rbcv74n4-66090

example. The application of reliability measures (redundancy numbers, internal reliability, among others) to scientific geometric leveling endorses the results of the adjustments that are analyzed from a temporal perspective, thus adding a new condition: the classification regarding the location and construction method of the benchmark. That is, the rate of benchmark's vertical variation and its class are compared, and the results are evaluated. The benchmark classification was based on international experiences, and the results of this research are a possible guide to contribute to the updating of the manual for the standardization of survey marks IBGE (2008).

2 FUNDAMENTAL CONCEPTS ABOUT SCIENTIFIC GEOMETRIC LEVELING, THE QUALITY OF GEODETIC NETWORKS, AND THE VERTICAL STABILITY OF SURVEY MARKS

In this section, concepts related to scientific geometric leveling, aimed at the geodetic control of tide gauge stations, are discussed, and some quality indicators are used in the adjustment of observations applied to the present work. Furthermore, a brief explanation of aspects related to controlling vertical variation in geodetic stations aimed at the integrity of tide gauge time series is given.

2.1 Scientific geometric leveling

Scientific Geometric Leveling (SGL) is associated with standard geometric leveling procedures with more rigorous vertical survey procedures, calibrated instruments, and systematic corrections compatible with high precision requirements (LUZ, 2008, p 69). In this sense, a more rigorous methodology is adopted with specific controls and procedures that provide limit values that align with what is established by the Specifications and Standards for Geodetic Surveys Associated with the Brazilian Geodetic System (IBGE, 2017).

During the execution of a leveling, there is a concern about mitigating the so-called random, systematic, and gross errors. Recommendations to reduce such errors, as well as the practice of geometric leveling, are widespread in the specialized literature. Examples include IBGE (1983, 2017), McCormac (2007), and Torge and Muller (2012), among others. In addition to the consolidated guidelines, additional care is taken for the SGL to ensure the required rigor. Adopting equipment such as a digital level with a precision of 0.3 mm per kilometer of double leveling, a non-extendable tripod, and a pair of non-extendable invar staffs. Some of these procedures are:

a) lengths of sights approximately equidistant and not greater than 30 m – to minimize the effect of curvature, atmospheric refraction, and collimation;
b) reject the reading of staffs below 0.50 m and above 2.80 m, respectively – to reduce the effects caused by reverberation and error in staffs verticality;
c) sight-reading in the sequence reverse, forward, forward, reverse (RFFR) – this condition reduces effects caused by the sinking of the staff and level (differential settlements);
d) do not perform readings in different environments at the same time, especially above water surfaces or other fluids or even specular surfaces (for example, dry and flooded asphalt);
e) avoid the beginning and end of the survey in the first and last hours of the day; as in these periods, the atmosphere is disturbed due to sunrise and sunset;
f) start and finish each section with the master staff – eliminates the index error;
g) adoption of the average of five consecutive uninterrupted readings – brings more reliability to the electronic measurement since each staff is read ten times (RFFR) and compared to each other;
h) the occupancy time of the stations must be as short as possible, and the place chosen to park the equipment and the staff must be as stable as possible - avoids that possible accommodations suffered by the instruments, due to their weight, influence the results of the readings;
i) the equipment must be protected from direct solar radiation, using an umbrella next to it and avoiding measurements under adverse atmospheric conditions (e.g., rain and strong winds). It is

recommended to acclimatize the equipment to the environmental conditions before the measures – it prevents the lateral incidence of the sun's rays from introducing an angular lag in the line of sight;

j) always carry out collimation of the equipment at the beginning of the measurement activities, and in the case of carrying out measurements in different periods, perform new collimation;

k) observe compliance with the maximum differences established for the survey to control the collection of observations - difference: of the measurements of the two aft/forward sights, of the gap between consecutive measurements (foreward ~ aft-forward), maximum tolerable between the accumulated back and foresight lengths for the section and per span and maximum acceptable between leveling and double-run leveling the leveling run.

The specifications mentioned above were facilitated through the adoption of digital equipment. They allow the elimination of basic errors, such as the reading storage and the verification of the verticality of the invar staff. Moreover, they provide information control and organization of information quickly and automatically. However, some factors hinder the execution of the surveys; for example, the staffs used are composed of bar codes that are read at the digital level. Sometimes there may be an irregular distribution of luminosity on the staff that makes it difficult or impossible to take the readings, causing delays in the measurement.

The vertical control of survey marks around the tide gauge stations requires a systematic application of the SGL. The Permanent Geodetic Tide Gauge Network (PGTGN), in this sense, follows the recommendations of the International Oceanographic Commission (IOC), which establishes the precision of $1\,mm\sqrt{D_{km}}$ this type of control (IOC, 2006, p. 31). These recommendations are followed with some adaptations according to IBGE (2010) that were improved after 2015. Preliminary results of the analysis of the historical series of the adjustments of the control circuits of some tide gauge stations were able to point out possible shakes (caused by human action or the structure), settlements, and uplifts (related to movement in the vertical direction of the ground) of the respective benchmarks in the order of tenths of millimeters per year, as described in IBGE (2013, p 28-29; 2016, p 21-22).

Another example to be highlighted about the large-scale application of the SGL was made within the Geodetic Coastal Reference Network (GCRN) scope. In this work, other adaptations to the SGL were used, as seen in Soares, Santos, and Luz (2018). Through the methods used, it was possible to obtain errors in the closing of sections and circuits below the established tolerance, thus revealing the excellent quality of the survey and confirming the expected homogeneity for the network defined in the pre-analysis (SOARES et al., 2019). Additional information on the application of the SGL and the GCTGS can be consulted in IBGE (2010, 2016, and 2021).

2.2 Residuals

The difference in level measured between two points (leveling run) by geometric leveling is not univocal, as it depends on the path traveled during the measurement. This is because the different equipotential surfaces are not parallel in the positions of the levels. In turn, the collimation lines of the levels are tangent to the equipotential surface of the gravity field (DE FREITAS; BLITZKOW, 1999). In addition to issues of a purely physical nature, there are, during the practice of spirit leveling, factors that influence the observation's quality, as already reported in section 2.1. All these factors can cause outliers and various random, systematic, and gross errors in the observations, which are largely addressed by the specialized literature.

The vertical observations collected in the field are later used to calculate different types of heights. As a result, they undergo the observation adjustment process, a tool widely used in geodetic science, which seeks to estimate the values of specific unknown parameters through a single solution (COLLISCHONN, KLEIN, MATSUOKA, 2012). In this sense, the Least Squares Method (LSM) is an optimization technique that minimizes the sum of squares of the weighted residuals, resulting in the maximum likelihood and minimum variance for the estimated parameters when the data follow a normal distribution (GHILANI, 2010). Once the adjustment is made, information is provided that guides the reliability analysis and quality control.

The weighting of the residuals consists of the respective weights of the observations. In the case of the vertical component, the inverse of the leveled distance value, in kilometers, is usually used. When considering this perspective, it is essential to note that depending on the nature or behavior of random errors, the LSM may or may not be the best-unbiased estimator (KLEIN, 2012). Alternative approaches to LSM adjustment in height networks can be found, for example, in Suraci, Oliveira, and Klein (2019) or Suraci and Oliveira (2020).

Considering such statements, Gemael, Machado, and Wandresen (2015) define the residual (v_i) as the difference between the estimated (adjusted) value for a quantity and an observed value of this quantity. In this sense, in the leveling runs, the quality of the result of the adjustment applied to them must consider the values resulting from the residuals referring to each difference observed. Given this conception, as mentioned earlier, the quality can be evaluated through the standardization of residuals according to distances, that is, relative errors, to estimate the relative accuracies of each leveling section (IBGE, 2019).

2.3 Internal Reliability

Internal reliability quantifies the smallest fraction of a given error existing in the observation or in the model, in which it is possible with a certain level of probability to be detected (KUANG, 1996). According to BAARDA (1968), the minimum value of the detectable error is estimated statistically by the relationship given by Eq. (1):

$$\nabla l_{0i} = \frac{\delta_0}{\sqrt{r_i}} \sigma_{li} \ ,(i=1, \ \dots, n) \tag{1}$$

where .∇l_{0i} is the minimum value of the detectable error, l_i the observation, δ_0 the non-centrality parameter of the model, σ_{li} the standard deviation of the i-th observation, and r_i its redundancy number.

By looking at Eq. (1) the influence exerted by redundancy number in the gross error detection is evident, that is, the influence of the network geometry on the minimum value of the detectable error. Other quantities that also have a significant influence on the minimum value of the detectable error are the standard deviation (σ_{li}), related to the precision of the observations, the level of significance (α), and the power of the test (γ), from which the non-centrality parameter of the model (δ_0) (MORAES, 2001). Eq. (1) assumes that the weight matrix of observations is a diagonal matrix. Since in practice the magnitude of the gross error is unknown, the values of ∇l_{0i} and δ_0 are also unknown. The degrees of freedom (q) of the test is known (in the individual analysis of each observation: $q = 1$). Having these three components determined (α, γ, q), it is possible to find the non-centrality parameter of the corresponding model in the chi-square distribution ($\lambda = \lambda_0 = f\ (\gamma_0, \alpha_0, q)$), then, it is considered that in the univariate normal distribution $\delta_0 = \sqrt{\lambda_0}$ (KLEIN, 2012).

The significance level corresponds to the rate of "false positives" (false alarms), while the power of the test corresponds to the probability of correct detection of the error. In general, we adopt $\alpha = 0{,}1\%$ and $\gamma = 80\%$, which results in λ_0=17,075 for $q = 1$ – see, for example, Baarda, (1968); Rofatto, Matsuoka and Klein (2018).

The way to detect a significant error in an observation (l_i) is to analyze the relationship between the estimated error value adhering to the observation (∇l_i) and the minimum detectable error value, that is if $\nabla l_i \geq \nabla l_{0i}$ means that there is an error in the observation (KUANG, 1996). The calculation is performed through Eq. (2), which relates the residual (v_i) of the observation with its redundancy number (r_i).

$$\nabla l_i = \frac{|v_i|}{r_i} \ ,(i = 1, \dots, n) \tag{2}$$

Additional information about the internal reliability measure, as well as the model's non-centrality parameter, can be found in the following references: Baarda (1968), Baarda (1973), Kuang (1996), Moraes

(2001), Ghilani (2010) and Klein (2012).

2.4 Redundancy number

The redundancy of observations in an adjustment process is fundamental to improving the accuracy of the estimated results and detecting possible errors in the models or the observations, enabling quality control of the adjustment (TEUNISSEN, 2006). In this sense, it is possible to estimate the controllability of the observations of a geodetic network through the so-called redundancy number. With this measure it is possible to detect gross errors and outliers in the observations and aspects of the network geometry (GHILANI 2010, p .441).

There are two main categories for redundancy numbers: partial and relative. The first is the elements of the main diagonal of the ***R*** matrix, expressed by Eq. (3), which in practice is the contribution made by each observation to the total redundancy of the adjustment (KLEIN, 2012):

$$R = \sum_v P \tag{3}$$

where: $\sum_v$ is the matrix of covariances of the vector of the residuals and P is the matrix of the weights of the observations. The ***R*** matrix trace is the total redundancy number itself (number of redundant observations or degrees of freedom), expressed by $r = n - u$, when "n" is the number of observations and "u" is the number of unknown parameters.

A gradation of the observation's control range of partial redundancies (r_i) is presented by Mürle and Bill (1984; p. 48) apud Moraes (2001, p. 200) in which a classification is made to determine the control of the observations concerning gross errors. Table 01 presents these intervals and the classification in terms of controllability.

Table 1: Intervals for observation control

Break	**Controllability**
$0 \leq r_i < 0.01$	Without
$0.01 \leq r_i < 0.1$	Bad
$0.1 \leq r_i \leq 0.3$	Enough
$0.3 \leq r_i < 1$	Good

Source: Mürle E Bill (1984, p. 48) apud Moraes (2001, p. 200)

The second category, that is, the average or relative redundancy ($\overline{r}$) is defined as the quotient of the trace of the ***R*** matrix by the number of observations (n) expressed by Eq. (4) (GHILANI 2010, p. 441). This author maintains that redundancy numbers with values starting from 0.5 are usually sufficient to guarantee that a given observation is considered reliable.

$$\overline{r} = \frac{\sum_{i=0}^{n} r_i}{n} = \frac{n-u}{n} \tag{4}$$

Given the statements mentioned above, Nowak and Odziemczyk (2018) argue that the geometric configuration of the network, referring to it first-order design, should contain as many redundant observations as possible, as this will result in a positive impact on the final accuracy of the network. However, this is only sometimes possible to be achieved geometric leveling due to the high costs involved or issues related to local geographic conditions. Rofatto, Matsuoka, and Klein (2018) also discuss the design of leveling networks considering reliability measures.

2.5 Overall model test

The overall model test is an indicator of goodness of fit of the residuals. Through the application of this test, it is possible to indicate possible errors (for example, gross and systematic) in the set of observations and even errors in the mathematical model. In other words, check if the model is consistent with the observations or if the system is poorly conditioned (COLLISCHONN et al., 2015).

Aspects related to the quality of adjustment can be pointed out by comparing the a priori reference variance σ_0^2 with the a posteriori reference variance ($\hat{\sigma}^2$) (GEMAEL; MACHADO; WANDRESEN, 2015, p. 138–139). The same authors add that comparing σ_0^2 with $\hat{\sigma}^2$ and obtaining a significant discrepancy at a certain confidence level indicates that adjustment problems exist. It is worth noting that the (arbitrary) choice of a specific value for σ_0^2 (e.g. $\sigma_0^2 = 1$) does not affect the result in the values of the estimated parameters.

Considering such placements, once there are discrepancies, one must determine whether they are significant or not. The analysis is performed using the hypothesis test based on the chi-square distribution (χ^2). The two possible tests are: two-sided and one-sided. In both, the value of a test statistic is calculated, which is given by Eq. (5) (KLEIN, 2012):

$$\chi_c^2 = \frac{\hat{\sigma}^2}{\sigma_0^2}(n-u) \tag{5}$$

For the case of the two-sided test, the hypotheses must be tested:

a) Null

- H_0: $\sigma_0^2 = \hat{\sigma}_0^2$ – the a priori and a posteriori variances do not differ statistically at the significance level α

b) Alternative

- H_1: $\sigma_0^2 \neq \hat{\sigma}_0^2$ – the a priori and a posteriori variances differ statistically at the α significance level.

If the value of χ_c^2 is within the confidence interval (with associated probability $1-\alpha$) the null hypothesis is not rejected. This comparison is made by Eq. (6):

$$\chi^2_{(n-u),\frac{\alpha}{2}} < \chi_c^2 < \chi^2_{(n-u),1-\frac{\alpha}{2}} \tag{6}$$

In cases where the null hypothesis is rejected, the possible causes must be investigated to detect what may be affecting the adjustment quality. Gemael, Machado, and Wandresen (2015, p. 139) argue that such causes may be: the presence of huge residuals, inappropriate stochastic model, poorly conditioned system, the existence of computation errors in the adjustment process, unsuitable functional model, and the occurrence of gross and systematic errors.

2.6 Aspects related to the vertical stability

The benchmarks deployed to compose a height network suffer over time actions that can cause the displacement of the station reference so that the materialized information is modified. Among these actions, we can mention repression, subsidence, demolition, construction in its surroundings, weathering, and even vandalism. In this subsection, concepts related to vertical stability control are discussed and summarized in the following topics: benchmark classification, determination of temporal variation rates, outlier detection, and confidence interval.

2.6.1 BENCHMARK CLASSIFICATION

According to Hailegeberel et al. (2018), recent studies have shown that when benchmarks suffer the effects of movement from the ground, they cause more significant impacts on the vertical component than the horizontal component since often the ground movements are in the vertical direction. In this sense, to reduce the evident vulnerability of benchmarks to the variation of their vertical positions, Luz and Guimarães (2003) recommend the implantation of the mentioned stations in places as stable as possible as a rocky substrate.

The standard for standardization of survey marks (IBGE, 2008) specifies the guidelines for the construction and materialization of geodetic stations employing spiked plates, landmarks, or pillars to guarantee their stability and durability. However, this standard does not classify the stations' stability according to the structure built and the type of implantation site. A classification of this nature is found in Hailegeberel et al. (2018), which directs the management and risk assessment of using a network based on stability and its general definitions. Table 02 presents the classification mentioned above.

Table 2: Classification and general definitions of geodetic landmarks

Stability class	General definitions
Class A	More reliable, height is expected to be maintained for a long time
Class B	Will likely maintain altitude for a long time
Class C	May maintain altitude for a long time but subject to surface movement
Class D	Unknown or questionable stability

Source: Adapted from Hailegeberel et al. (2018)

Briefly, class A benchmarks are precisely those installed on rocky outcrops or places with foundations set in rock. The benchmarks classified as B are profound rod-type monuments that some countries have used for decades and those installed on concrete foundations. The benchmarks classified as C are low-depth concrete monuments. Finally, the benchmarks classified as type D are frames or plates placed on sidewalks, pavements, light structures, and above pipes. Figure 1 presents the exemplification of geodetic stations of each mentioned class that can be found in the IBGE's Geodetic Database (GDB).

Figure 1– Example of geodetic stations according to their classification. In the upper part of the figure are shown, respectively, benchmark type A (metallic plate measuring 06 cm in diameter set in rock) and benchmark type B (special deep rod-type landmark with the reference point marked in the center of the stainless steel rod that perforated the ground to an anchor depth of 9.25 m). At the bottom of the figure are shown, respectively, benchmark type C (frame built in concrete fixed to the ground with an average depth of 100 cm with a metal plate fixed on its top) and benchmark type D (metal plate measuring 06 cm in diameter nailed to the base of concrete from a monument with unknown foundation located in the median of a road).

Source: Authors (2022).

The Specifications and Standards for Geodetic Surveys Associated with the Brazilian Geodetic System (IBGE, 2017, p. 33), in section 3.4, recommends shaking verification to confirm the original position of the benchmarks as described in the survey mark report available on the page of the institution. The temporal analysis dealt with in this standard is fundamental for the quality of works that Brazil's height network as a reference.

Another relevant mechanism regarding the temporal monitoring of the stability of a leveling run can be performed through the so-called "triplets" (IGN, 2017) used, for example, in the French height network. It is a set of three benchmarks spaced a maximum of one kilometer apart, periodically revisited with geometric leveling to control internal stability and GNSS to provide absolute stability. To the PGTGN, in 2016, an adaptation of such mechanisms inserted in the tide gauge stations' control leveling runs was used. A similar procedure is also being used in the GCRN (SOARES, SANTOS, and LUZ, 2018). It is worth noting that such procedures are still under analysis and new adaptations, therefore providing

2.6.2 DETERMINATION OF RATES OF TEMPORAL VARIATION

For the geodetic control of tide gauge stations (GCTGS), the repeatability of measurements is essential to determine the benchmarks' temporal variation rates. With the frequency of measurements, it is possible to monitor the uplift and subsidence rates of the stations, even allowing the port's partner to be activated in places susceptible to movements outside the expected standard. Rates are determined from simple linear regression, according to Eq. (7) (ZERVAS, 2009):

$$x_i = bt_i + a + \epsilon_i \tag{7}$$

where, $x_i$is the dependent variable, that is, the annual differences estimated by the regression line, b is the slope of the regression line, t_i is the independent variable that represents the time in a fraction of years, a corresponds to the intersection of the regression line with the axis of the gaps and represents the estimate of the residual value, determined by the difference between the response variable represented by the observed gap (x) and the response variable estimated by the regression line (x_i). The slope of the regression line used to determine the trend can be expressed according to Eq. (8):

$$b = \frac{\sum_i (t_i - T)(x_i - X)}{\sum (t_i - T)^2} \tag{8}$$

where T is the mean of t_i and X is the mean of x_i .

The standard error of the trend can be expressed according to Eq. (9) (ZERVAS, 2009):(s_b)

$$s_b = \frac{\sqrt{\sum (x_i - X)^2 - b \sum (t_i - T)(x_i - X)}}{\sqrt{(n-2) \sum (t_i - T)^2}} \tag{9}$$

where n is the sample size represented by the total number of years of observed raw heights.

2.6.3 OUTLIER DETECTION

The understanding of the term outliers, within the scope of this research, will follow the general view that in a given sample, it is about inconsistent observations that stand out from the analyzed set, diverging from the expected patterns. These divergences can carry relevant information that needs to be analyzed separately and not merely treated as noise commonly associated with inaccuracies (FONSECA, 2011). This understanding follows the recent definition proposed by Rofatto (2020): "outlier is an observation that has moved away from its most likely value to the point of not belonging to the stipulated mathematical (functional and stochastic) model". That is, the rejection of outliers must include reanalysis without these observations, which require further evaluation, as they may indicate critical specific problems.

There are several methods in the specialized literature for the determination of outliers. According to SEO (2006), the most used methods are Tukey, standard deviation, and normalized standard distribution (Z score).

The Tukey method, widely known as the quartile method, and its graphical representation, known as the boxplot, is robust and less sensitive to extreme values, unlike other methods that use the mean and standard deviation. From the interquartile (IQR) that corresponds to the interquartile difference (Eq.10), the lower (Eq.11) and upper (Eq.12) internal limits are determined.

$$IQR = Q3 - Q1 \tag{10}$$

$$L_{inf} = Q1 - 1{,}5 * IQR \tag{11}$$

$$L_{sup} = Q3 + 1{,}5 * IQR \tag{12}$$

where: $Q1$ is the first quartile, $Q3$ the third quartile, IQR the interquartile, L_{inf} the lower inner limit, and the L_{sup} upper inner limit.

According to TUKEY (1977), any observation that leaves the fixed tolerance of 1.5 of the respective interquartile ranges is considered a possible outlier. Any observation beyond 3.0 units of the interquartile range is considered an extreme outlier. In practical terms, within the scope of this research, only the internal limits are used to identify probable outliers.

The Standard Deviation method assumes that the standard deviation is a measure of the degree of dispersion of values concerning the mean, using Eq. (13) (SEO, 2006) to determine the upper and lower limits of a sample, where: X is the mean and S is the sample standard deviation calculated by the square root of the variance.

$$Limites = X \pm 2 \times S \tag{13}$$

It is based on the characteristics of a normal distribution for which 95% of the data fall within that range. Any values outside these limits are characterized as outliers. This method is sensitive to extreme values and may not identify possible outliers (SEO, 2006; FONSECA, 2011, TRIPATHY SAXENA; GUPTA., 2013).

Finally, the Standardized Normal Distribution (Zscore) is a normal distribution of probabilities; that is, if it follows a normal distribution, N (μ, σ2), then Z it follows a standard normal distribution characterized by having a mean (X) equal to 0 and deviation standard (S) equals 1. It can be described as (x_i) being the result of the known data, subtracted from the average value of the sample (X); this result is divided by the standard deviation (S), according to Eq. (14). Tripathy, Saxena and Gupta. (2013) recommend considering values greater than a ± 2 as outliers for the Z result.

$$Z = \frac{x_i - X}{S} \tag{14}$$

In the case of independent observations, this procedure is similar to Tau since the standard deviation is taken as unknown a priori (see, for example, KLEIN, 2012). For each method, an iterative process is carried out to detect and remove outliers from the sample. In this way, the benchmarks with rates of vertical variation outside the limits are removed and the process is reanalyzed until there are no outliers in the series.

2.6.4 CONFIDENCE INTERVAL

For small samples (n < 30), there are no good general methods for finding confidence intervals that would contain the true value of the population mean. However, since the population is approximately normal, Student's t distribution can be used for this purpose (BEZERRA, 2018). For a small random sample taken from a normal population whose mean is μ, the 100(1-α) % confidence interval for μ is described according to Eq. (15). In other words, the probability that the Confidence Interval (CI) includes μ is equal to 1-α, called the confidence level. Usually, a confidence level of 90%, 95%, and 99% is used (FERREIRA, 2005).

$$IC_{1-\alpha}(\mu) = X \pm t_{n-1,\alpha/2}\frac{S}{\sqrt{n}} \quad (15)$$

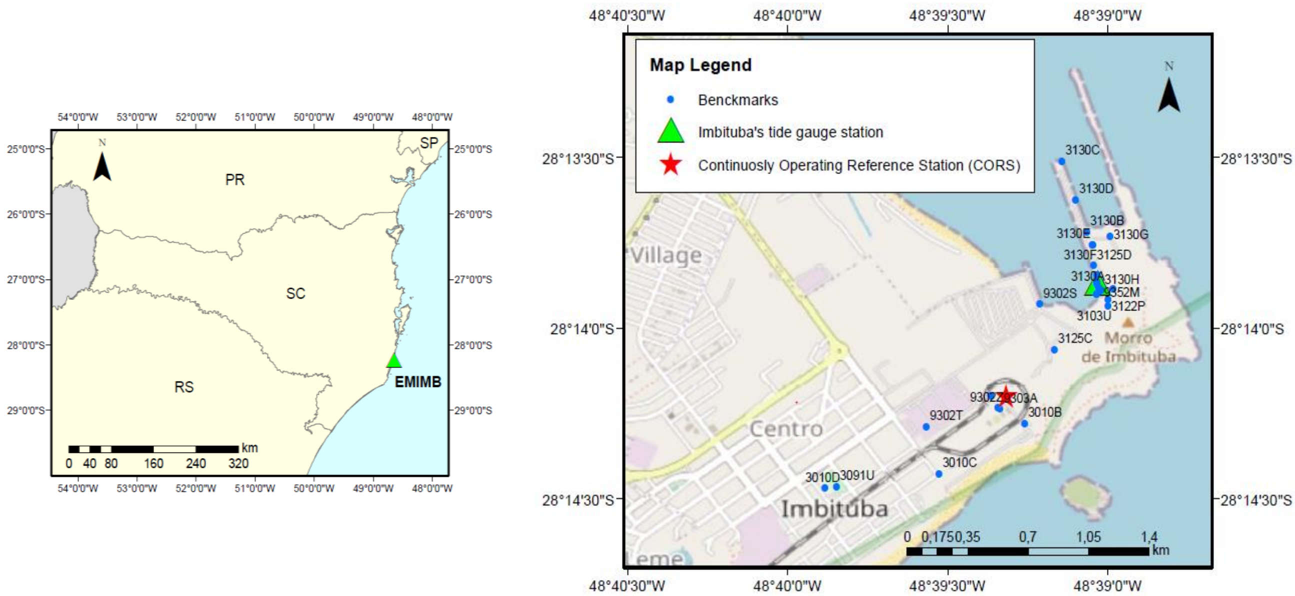
where , n, X and S represent, respectively, the sample's size, mean and standard deviation. The term $t_{n-1,\alpha/2}$ is the value that cuts off an area of the $\alpha/2$ tail on the right side of the Student's t distribution.

3 METHOD

3.1 Imbituba Tide Station

The study area of this research comprises the port of Imbituba region under the administration of SC-Parcerias S/A, and the vicinity beyond the port extending to Henrique Lage Square in the municipality of Imbituba (SC). The Imbituba Tide Station (28°13'52.30"S 48°39'2.06"W, SIRGAS2000) is located on the premises of Port, operated by the PGTGN/IBGE since 2001. Brazilian Continuous Monitoring System for GNSS Systems (BCMS), which makes up the monitoring system aimed at the spatial and temporal monitoring of the Brazilian Vertical Datum of Imbituba – BVD-I. It is worth noting that the active station IMBT-94024 of the BCMS was deactivated in April 2022, giving way to SCIM-94129.

Figure 2 – The benchmarks' Imbituba (SC) Tide Station location and spatial distribution.



Source: Authors (2022).

The Imbituba Tide Station has the following configuration concerning the instruments: Digital Data Collection Platforms (DDCP), level sensors (radar and encoder), PGTGN standard tide staff, meteorological platform (wind speed and direction sensor, temperature, precipitation, relative humidity, and atmospheric pressure) and transmission system via Geostationary Operational Environmental Satellite (GOES) and mobile telephony (GSM/GPRS), with a rate of 5 minutes (IBGE, 2021).

In addition to monitoring the temporal and spatial evolution of the BVD-I, the information generated by the Imbituba Tide Station allows for establishing relationships with the other reference levels used in the coastal region, such as the Chart Datum (IBGE, 2016). The station, as mentioned earlier, concerning the PGTGN, has a series of data of approximately 20 years that allows the performance of activities aimed at coastal management, monitoring of vulnerability to mean sea level rise, environmental studies, and monitoring and alerting of extremes events, among other aspects (IBGE, 2021).

3.2 Inputs and strategies

The observations used in the present research come from altimetric surveys carried out in the Port of Imbituba within the scope of the GCTGS by the IBGE using the specifications reported in section 2.1. The equipment used was: electronic level Leica models DNA-03 and LS-10, invar staffs, rigid tripod, and rod. The data set includes surveys carried out from 2015 to 2022 with absences in the years 2020 and 2021 due to the Covid-19 pandemic. After performing the geometric leveling in the field, the circuit's loop closure error was calculated using the tolerance of $1\,mm\sqrt{D_{km}}$, where D is the leveled distance in kilometers. Then the files were prepared for the adjustments. In this case, the Geodetic adjustment program using Helmert blocking Of Space and Terrestrial data – GHOST – was used (CRAYMER, 2017).

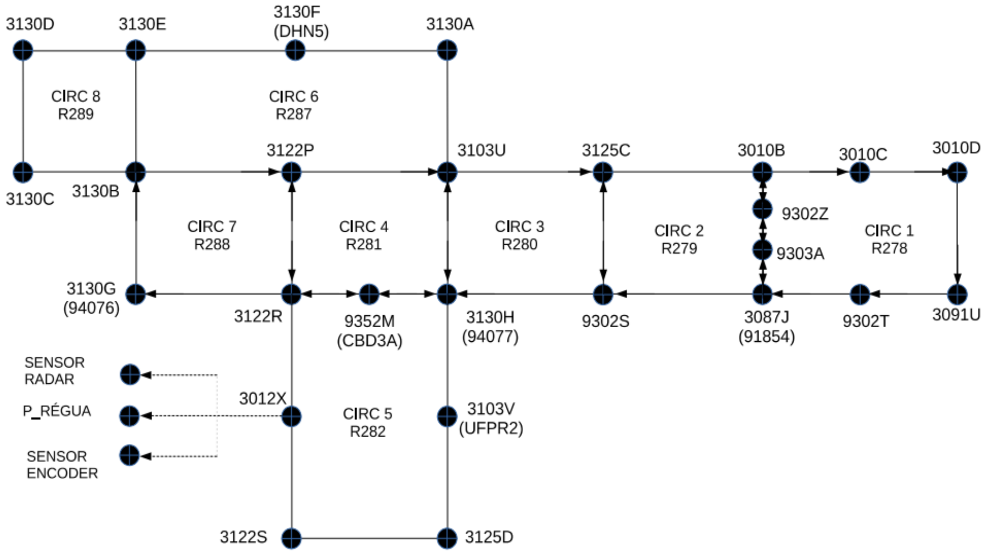
The leveling lines schematic of the Imbituba Tide Station can be seen in Figure 3 (IBGE, 2021). It is worth noting that some years have different survey configurations, either due to network expansion or climatic aspects. Observations referring to the tide gauge sensors and the tide staff are also not included in this research.

A pre-analysis was carried out to choose the reference benchmarks for the adjustment. The benchmarks preliminarily chosen for reference as a minimum and absolute constraint (individually) for the parametric adjustment followed the stability classification of Hailegeberel et al. (2018), that is, class A (3122R and 3103U) and class B (3087J). Thus, an adjustment was made at a time for each reference considered. This assumption was used to assess the agreement regarding the resulting values. The class A benchmark agreed, and RN 3122R was determined as the primary reference. The height used in the single constraint was equal to 0 m. In this way, it is possible to analyze the results in the same plane; each section's final heights are uneven.

With the results obtained in the adjustments, firstly, prior quality control of the observations was carried out through the analysis of standardized residuals, then the values obtained from the minimum value of the detectable error – Eq. (1) – and the estimated error adhering to each observation – Eq. (2) – in order to determine the internal reliability. The redundancy numbers were organized into control intervals according to Table 1, and the calculation of the average redundancy for each adjustment was performed using Eq. (6). The indication of the quality of the adjustments was made using the overall model test, two-sided, at a significance level of 5%.

Once the quality control stages of the observations were satisfied, organizing the information and analysis of the vertical temporal variation of the geodetic stations included in the circuits of the Imbituba Tide Station was carried out. For that, a preliminary classification of the geodetic stations was applied, according to Table 2. The temporal variation rate was calculated through the slope of the regression line used to determine the trend, according to Eq. (8). After that, three classical outlier determination methods were used (subsection 2.6.3) for further analysis, ending with the confidence interval as the use of the 95% confidence level for classes A, B, and C using Eq. (15).

Figure 3 - Scheme of the leveling circuits of the Tidal Station of Imbituba (SC)



Source: IBGE (2021).

4 RESULTS AND DISCUSSION

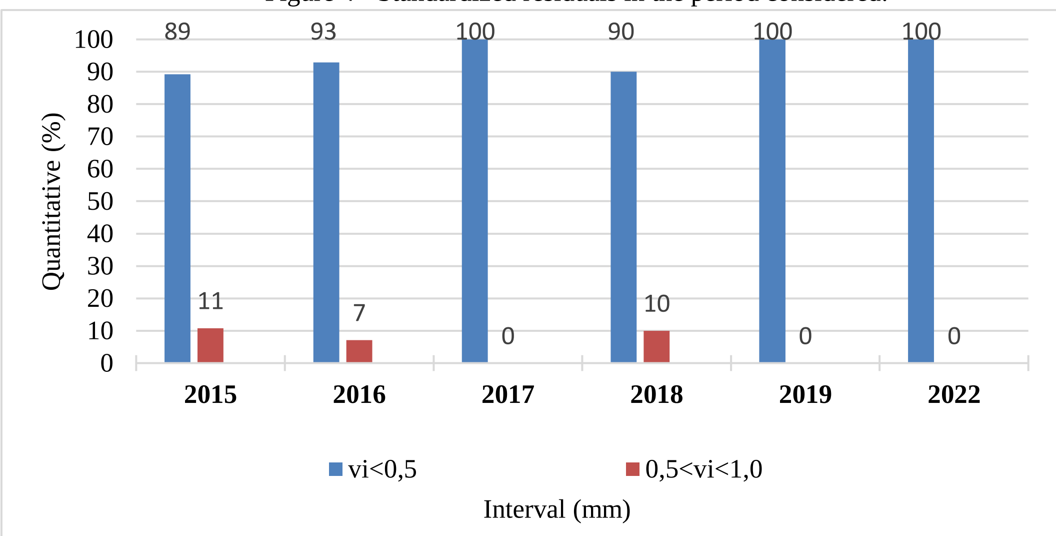
This section presents the analysis of residuals, internal reliability, redundancy number, overall model test, and vertical temporal variation.

4.1 Residual's analysis

The residual values of each observed difference are the fundamental indicator for the instantaneous determination of the occurrence of a particular error associated with a leveling line. That is, differences between observed and estimated values are verified. For the analysis in question, the residuals were standardized as a function of the length of the distances of each leveling run so that the errors related to each observation were relativized. Then, these standardized residuals were compared with the tolerance, which could not be higher than 1 $mm\sqrt{D_{km.}}$

Figure 4 presents the summary of the standardized residuals obtained in the adjustments. They were categorized into two optimized ranges to facilitate understanding. The mean, standard deviation, maximum, minimum, and amplitude of the values obtained are also shown in Table 1.

Figure 4 - Standardized residuals in the period considered.



Source: Authors (2022).

Table 1 - Statistics of standardized residues.

Statistic	**Year of survey**					
	2015	**2016**	**2017**	**2018**	**2019**	**2022**
Size	37	42	30	30	35	32
Minimum (mm)	0.01	0.01	0.01	0.02	0.01	0.03
Maximum (mm)	0.85	0.57	0.37	0.56	0.46	0.46
Amplitude (mm)	0.85	0.56	0.36	0.54	0.46	0.43
Average (mm)	0.18	0.23	0.10	0.18	0.08	0.16
Standard deviation (mm)	0.20	0.15	0.08	0.17	0.08	0.12

Source: Authors (2022).

By examining Table 1 and Figure 4, it is evident that most residuals are located below 0.5 mm, and the others are in the range of 0.5 to 1 mm. The lowest average of residual refers to the survey of the year 2019 (0.08 mm), and the highest refers to the year 2016 (0.23 mm). In general, the standardized residuals have a homogeneous behavior, showing that the analyzed lines do not indicate the occurrence of inconsistencies that significantly influence the result of the adjustments. The advantage of the standardized residuals analysis is to make a prior diagnosis of how the leveling run is being affected by a possible error or an outlier in a given observation. However, due care must be taken in the previous step of data purification to detect significant inconsistencies that may unnecessarily distort the results.

4.2 Internal reliability analysis

The internal reliability of an observation is directly related to the size of the minor detectable error of that observation once the probability levels are stipulated. By comparing the estimated error value adhering to the observation (∇l_i) and the minimum detectable error value (∇l_{0i}), it is possible to indicate whether there is a significant error in an observation (l_i), as described in section 2.2

In this sense, Table 2 summarizes the statistics of the respective maximum, average, and minimum values and each set of observations for the adjustments referring to each year.

Table 2–Maximum, average, and minimum values of the minor detectable error in the observations for each adjustment.

Adjustment/year	**Minor detectable error (mm) ($\alpha_0 = 0,1\%, \gamma_0 = 80\% \delta_0 = 4,13$)**						**Acceptance**
	Maximum		**Average**		**Minimum**		
	∇l_{0i}	∇l_i	∇l_{0i}	∇l_i	∇l_{0i}	∇l_i	
2015	6.53	0.78	3.63	0.33	0.99	0.00	yes
2016	6.54	1.54	3.01	0.41	0.58	0.01	yes
2017	6.68	0.28	3.95	0.18	1.58	0.01	yes
2018	7.30	0.99	4.08	0.34	1.95	0.07	yes
2019	6.67	0.45	3.95	0.14	1.56	0.00	yes
2022	6.60	1.36	3.49	0.37	0.58	0.01	yes

Source: Authors (2022).

Thus, it is noted that in 2018 there was the highest expected value ∇l_{0i} for maximum, average, and minimum; in 2016, the opposite was observed. In general, significant differences are not observed in each class of values referring to each adjustment; that is, there is homogeneity in the observations. When considering the magnitude of the mean values of ∇l_{0i}, these are seven to ten times higher than the values of ∇l_i. Hence the observations are more accurate than expected and do not have significant errors. Therefore, measurements from all seasons were accepted in the comparison.

4.3 Redundancy analysis

Table 3 presents the results of the redundancy numbers referring to the adjustment for each survey carried out in a year of the GCTGS.

The classification proposed by Mürle and Bill (1984, p. 48) and apud Moraes (2001, p. 200) for the observation control intervals regarding the redundancy numbers expresses the reliability of the constant observations in each survey carried out. These redundancy numbers indicate the portion of possible nonrandom error reflected in that observation's residual.

The results showed that the constraint used does not affect the partial redundancy. When analyzing the adjustments for each year, it is observed that, in general, they present partial redundancy numbers classified as "sufficient" and "good" (approximately 80%). The adjustment with the best result in the range mentioned above is for 2016 (90%), and the worst is for 2017 (74%). However, all adjustments indicate partial redundancy values predominantly in the controllability intervals that denote a better ability to identify possible errors related to the control networks.

Although the results indicate that most control leveling lines have redundancies numbers that meet the purpose of the GCTGS, it is worth mentioning the importance of the degree of freedom: given that it directly influences the a posteriori variance factor. The higher it is, the better the network redundancy. So, the surveys that presented a more significant number of values in the "sufficient" classification than in the "good" classification point to the need to increase the degrees of freedom of the observations and, in turn, provide a more rigorous analysis of the set of observations used in the adjustments of the control leveling loops. However, this is only valid for new surveys since the objective of the GCTGS is to detect the temporal variations of the vertical coordinates.

Table 3 - Partial redundancy number for the reference station in the period considered.

Reference	**Adjustment (year)**	**Classification**				**Redundancy average**
		There is not $0 \leq ri < 0.01$	**Bad** $0.01 \leq ri < 0.1$	**Enough** $0.1 \leq ri < 0.3$	**Good** $0.3 \leq ri < 1$	
3122R	2015	0	8	10	19	0.41
	2016	0	4	9	29	0.46
	2017	1	7	13	9	0.26
	2018	0	7	12	11	0.26
	2019	2	7	13	13	0.28
	2022	1	4	14	13	0.31
	Total	4	37	71	94	

Source: Authors (2022).

4.4 Analysis of the quality of adjustments

By comparing the a priori variance with the a posteriori variance, it is possible to indicate the quality of the adjustment and, therefore, test the null and alternative hypotheses. In this work, the overall model test was performed for each adjustment, referring to each year of the GCTGS, with a significance level of 5%, i.e., 95% confidence level, for the two-sided test.

Table 4 shows the values resulting from the adjustments, the calculated value of the chi-square test statistic, the confidence intervals, and the acceptance or not of the null hypothesis.

As seen in the table mentioned above, it is evident that only the adjustment for 2018 passed the hypothesis test. However, for 2018 and the other years analyzed, it can be observed that the value of the a posteriori variance is approximately five times smaller than the a priori variance. Consequently, this means that the residuals are better than expected, as seen in section 4.1. Thus, tests on the acceptance of the null hypothesis mostly fail. Nevertheless, there are no problems in the adjustments performed (in terms of high residuals); only the precisions adopted a priori for the observations are underestimated.

Table 4 - Two-sided overall model test result.

Adjustment (year)	σ_0^2	$\hat{\sigma}_0^2$	Degrees of freedom	χ_c^2	Confidence interval (1 - α = 95%)		Acceptance of the null hypothesis
2015	1	0.19	14	2.68	5.63	26.12	No
2016	1	0.18	18	3.23	8.23	31.53	No
2017	1	0.07	7	0.49	1.69	16.01	No
2018	1	0.27	7	1.89	1.69	16.01	Yes
2019	1	0.05	9	0.45	2.70	19.02	No
2022	1	0.14	9	1.29	2.70	19.02	No

Source: Authors (2022).

4.5 Analysis of vertical temporal variation

Determining the vertical variation analyzed in this research was performed using simple linear regression. Thus, the rates of change were determined for the period considered. Values have been reduced to a single reference for easier graphical viewing. Table 5 shows the results of the vertical variation with an arbitrated reference of value 0 mm for the year 2015, that is, how much was varied in the other years concerning the year 2015. This reduction was inserted to facilitate understanding the graphs, which will be presented below. Additionally, there is the variation rate in mm/year of each RN, the standard error in mm/year, the level of significance P value ("*p*-value"), and preliminary classification of the benchmarks classes, considering their constructive type described in the IBGE's geodetic database.

Table 5 - A reduced vertical variation of level references in the period (to be continued).

Benchmark	Class	Benchmarks' reduced vertical variation (mm)						Rate of change (mm/year)	The standard error (mm/year)	P value
		2015	2016	2017	2018	2019	2022			
3010B	C	0.00	0.50	0.80	0.50	0.70	0.60	0.06	0.05	0.28
3010C	C	0.00	0.20	0.20	-0.20	-0.30	-0.90	-0.15	0.03	0.01
3010D	C	0.00	-0.20	-0.20	-0.60	-0.60	-1.00	-0.14	0.02	0.00
3091U	C	0.00	0.00	-0.20	-1.00	-0.50	-1.10	-0.17	0.05	0.03
9302T	C	0.00	0.80	0.10	-0.50	-0.70	-2.30	-0.39	0.08	0.01
3103U	B	0.00	0.10	0.00	0.10	0.10	0.10	0.01	0.01	0.24
9303A	C	0.00	0.60	0.60	-0.10	-0.10	-0.60	-0.14	0.06	0.10
9302Z	C	0.00	0.60	0.60	-0.40	-0.10	-0.90	-0.18	0.08	0.08
3125C	B	0.00	0.20	0.10	-0.40	0.10	0.20	0.01	0.04	0.77
9302S	C	0.00	0.30	-0.80	-2.60	-2.40	-3.30	-0.55	0.13	0.01
9352M	C	0.00	-0.90	-2.20	-4.50	-5.00	-8.30	-1.22	0.09	0.00
3122P	B	0.00	0.10	0.00	0.10	0.10	0.10	0.01	0.01	0.24
3087J	B	0.00	0.90	0.80	0.20	0.50	0.30	-0.02	0.07	0.85
3103V	C	0.00	0.40	0.00	-0.50	-0.30	-0.90	-0.16	0.04	0.02
3125D	B	0.00	0.70	0.50	0.60	1.00	0.40	0.04	0.06	0.57
3122S	B	0.00	0.90	0.50	0.90	1.10	0.30	0.02	0.08	0.82
3012X	B	0.00	0.70	0.20	0.70	1.30	0.50	0.07	0.08	0.43
3130A	C	0.00	1.50	1.90	1.40	2.30	3.90	0.48	0.09	0.01
3130F	C	0.00	-1.40	-3.20	-13.00	-15.30	-	-4.22	0.83	0.01
3130B	B	0.00	-0.30	0.00	-0.50	-0.30	-0.20	-0.02	0.04	0.57
3130C	C	0.00	0.10	-	-	0.70	-	0.18	0.02	0.07
3130D	C	0.00	-0.70	-	-	-6.70	-	-1.75	0.26	0.09
3130E	C	0.00	-0.10	-0.20	-3.30	-2.40	-4.50	-0.71	0.16	0.01

Table 5 - A reduced vertical variation of level references in the period (conclusion)

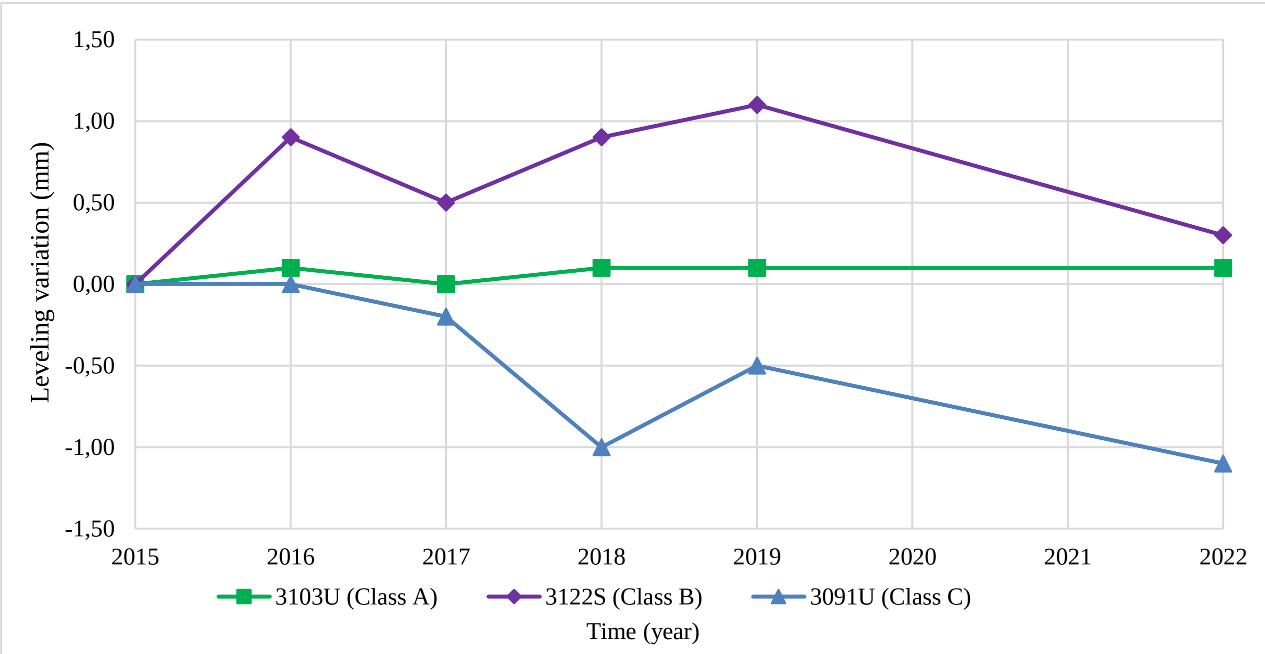
Benchmark	Class	Benchmarks' reduced vertical variation (mm)						Rate of change (mm/year) 2015	The standard error (mm/year) 2016	P value 2017
		2015	2016	2017	2018					
3130G	C	-	0,00	0,00	-0,90	-0,50	-1,30	-0,22	0,06	0,05
3130H	C	-	-	0,00	-1,00	-0,50	-1,30	-0,21	0,12	0,22

Source: Authors (2022).

The preliminary results of the time series indicate that the uncertainty about the observation in several benchmarks, regardless of the class, is high, returning statistical insignificance to the estimated rate of variation, especially when the higher classes, that is, A and B. On the other hand, benchmarks identified as outliers presented significant rates of variation for the most part. A more extended time series may provide more qualified subsidies since the greater the number of data, the smaller the standard error should be.

Figure 5 shows a sample of benchmarks of each class, which shows the stability of class A benchmarks. Despite the short investigation period, station 3122S shows a smooth uplift trend with a rate of 0.02 mm/year. The benchmark 3091U has a vertical variation rate identical to the average of Class C of -0.17mm/year, helping in the graphic visualization of the average settlement of this class.

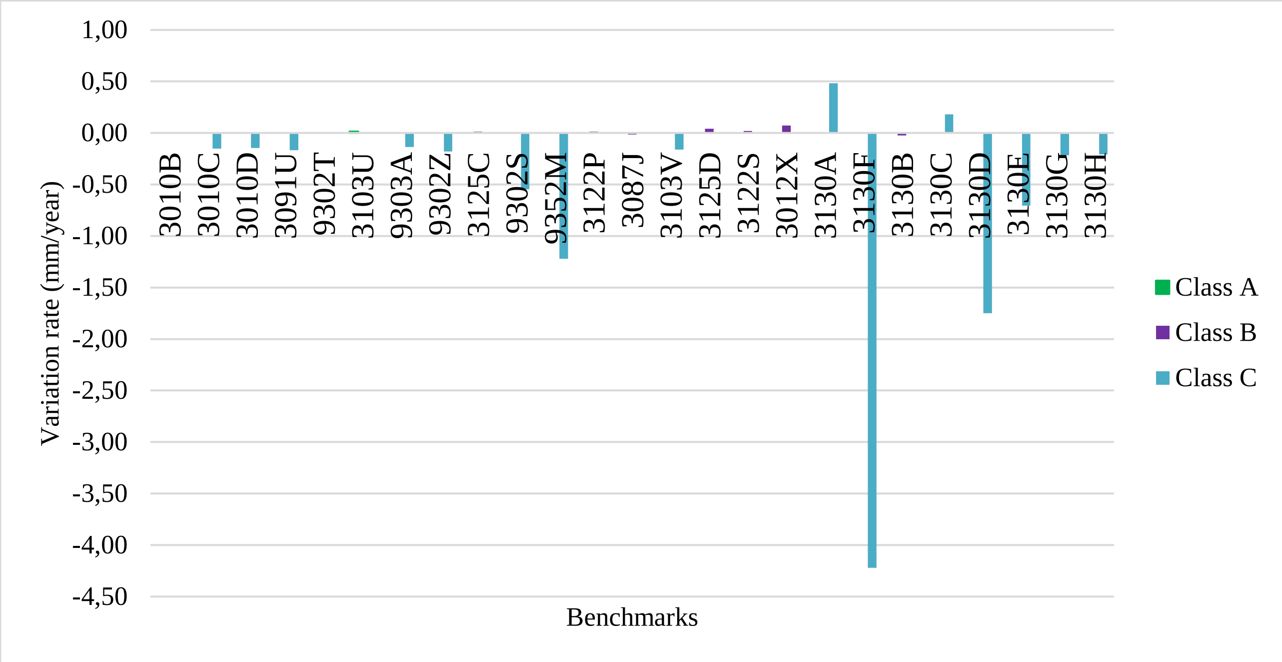
Figure 5 - A reduced vertical variation of level reference examples of each class at the Imbituba Tide Station (SC) in the period.



Source: Authors (2022).

Figure 6 presents the graphic visualization of the benchmarks' vertical variation rates. As can be seen, there is a significant difference between classes A and B to class C. Therefore, it was necessary to analyze class C separately from the other classes to minimize the influence of the trend of this class, which could hide or generate false outliers.

Figure 6 - Overview of the vertical variation rate of geodetic stations.

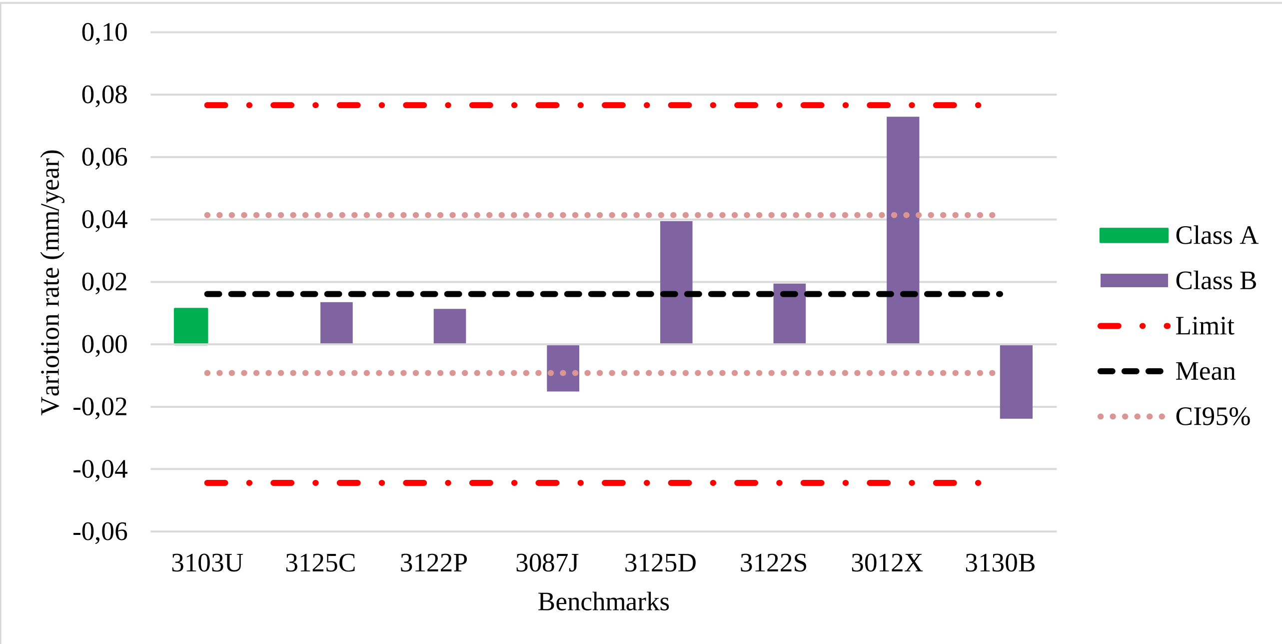


Source: Authors (2022).

Considering the need to conduct class C analysis separately and from the vertical variation rate calculated for each benchmark, the iterative process was started to detect outliers. That said, the three detection methods described in subsection 2.6.3 were used. After removing the class C benchmarks, it was found that, for classes A and B, all methods agreed with each other, and therefore no value was identified as an outlier.

Figure 7 shows the graphical representation of the analysis of the rate of vertical variation of the benchmarks classified as A and B, using the limits of the Standard Deviation method and 95% Confidence Interval.

Figure 7 - Overview of the vertical variation rate of the Class A and B geodetic stations.



Source: Authors (2022).

Despite the classes indicating similar behavior within the established Confidence Interval, it can be seen that, in the sample set, 75% of the benchmarks tend to rise, despite the average being approximately 0.02 mm/year. The rates of vertical variation of the benchmarks classes A and B are compatible. Considering this placement, benchmarks 3103U, with a rate variation of 0.01 mm/year, confirms the quality of benchmarks fixed on rocky outcrops, consolidating itself as the best option when available. On the other hand, benchmarks in places with good foundations were also presented as adequate and tend to maintain height for long periods, as is the case with the benchmarks class B 3125C and 3122P, which have a vertical rate of variation similar to that of the benchmark 3103U.

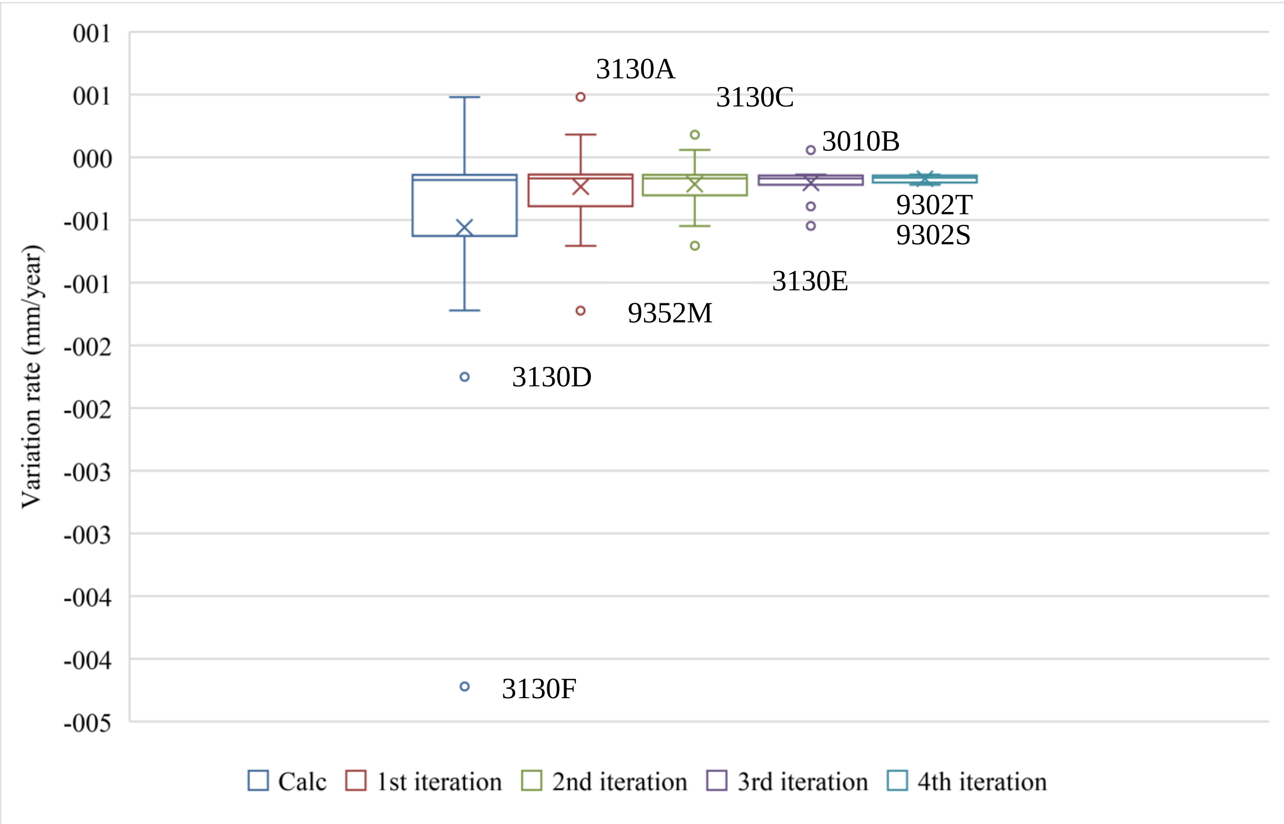
Concerning class C, at the beginning of the iterative process for detecting outliers, there were 17 benchmarks preliminarily classified in this class. The results of the process using the three outlier detection methods are summarized in Table 6. It is verified that all the methods identified the same number of outliers. However, the Tukey method (shown in Figure 8) was the most agile, requiring only four iterations after the initial calculation to achieve the same results as the other methods. The benchmarks identified as outliers will be analyzed separately later.

Table 6 - Iteration statistics for outlier detection.

Class	Method	Number of iterations	Number of outliers	Benchmarks outliers identified
C	Tukey	4	9	3130F, 3130D, 9352M, 3130A, 3130E, 3130C, 9302S 3010B and9302T
	Standard deviation	7	9	
	Zscore	8	9	

Source: Authors (2022).

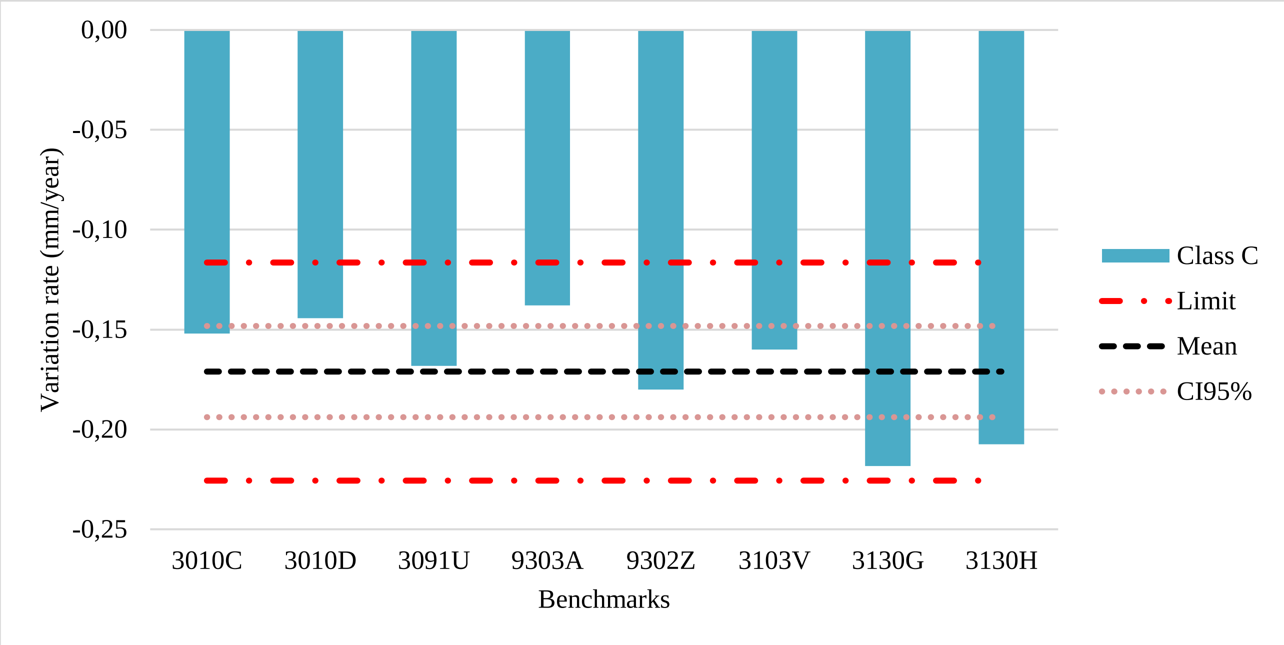
Figure 8 - Identification of outliers in the class C sample set with the Tukey method



Source: Authors (2022).

Figure 9 shows the class C sample set after removing outliers using the limits of the Standard Deviation method and 95% confidence interval. It is noticed that the benchmarks of this sample class tend subsidence since 100% of the benchmarks are in this direction. The average rate of change was -0.17 mm/year. As possible causes of this behavior, factors related to land accommodation, lowering of the water table, and even vibrations caused by machines close to the benchmarks are pointed out.

Figure 9 - Overview of the vertical movement rate of the Class C geodetic stations without outliers.



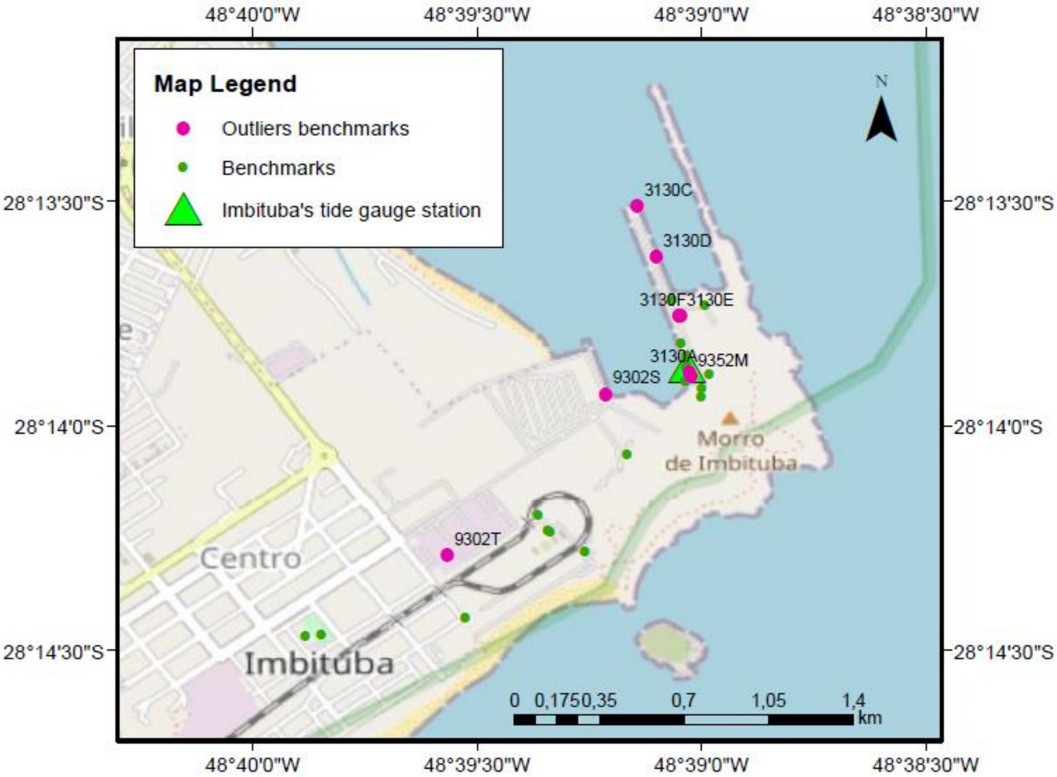
Source: Authors (2022).

Analyzing the outliers separately, that is, 53% of the total stations classified as class C, it is necessary to consider the places where these stations are fixed. Figure 10 shows their spatial distribution.

The most extreme value is the RN 3130F (-4.22 mm/year), destroyed when the building where it was located was demolished. Next to it, benchmark 3130E probably suffered major shocks with demolition. The benchmarks 3130C and 3130D, with rates respectively of 0.18 mm/year and -1.75 mm/year, are in the extension of the recently built Pier 2 and still suffering the necessary accommodations on the ground, with 3130C being in the most extreme of the pier, which may justify its inverted signal about the 3130D which is located in the middle of the structure. The benchmark 9302S (-0.55 mm/year) is an old PORTOBRAS standard station on the slab of Pier 1. In this case, the constant movement of trucks in its vicinity stands out. The benchmark 3130A, as seen with benchmark 3130C, shows signs of uplift. However, the reasons are probably different. Isolating the case of benchmark 3130A: it is in a region that suffered a small landslide; additionally, a large machine (shiploader) that was positioned in its proximity, exerting an important weight on the area, was removed to another location, this condition points to the probable cause of the temporal uplift of 0.48 mm/year. Next to it is the benchmark 9352M; during the last measurements carried out in port, it was identified that the structure in which the benchmark is fixed, located next to a substation, had a critical crack—indicating its high vertical variation rate of -1 .22 mm/year. The benchmark 9302T is an old PORTOBRAS' station with dimensions outside the standard established by the IBGE, and its own weight is a possible indicator of its subsidence (-0.39 mm/year).

In contrast to the previously analyzed benchmarks, an interesting behavior related to RN 3010B was observed. It is a classic geodesic station located on a busy roundabout at the entrance to port. Its temporal variation rate, 0.06 mm/year, is very different from the rest of its class (C). However highly compatible with the rates of the upper classes.

Figure 10 - Spatial distribution of class C geodetic stations with outliers.



Source: Authors (2022).

5 FINAL REMARKS

This work studied the variation of the vertical movement of a region that houses the tide gauge station necessary for the spatial and temporal monitoring of the VBD-Imbituba. This study was supported by the application and analysis of some quality controls used in leveling networks to know the reliability of the results of the performed adjustments. Additionally, methods for determining rates of vertical variation, detecting outliers, and applying confidence intervals were used to improve the analysis of vertical stability control of geodetic stations.

During the analysis, it became evident that several factors need to be confronted with having a more precise idea regarding the quality of the network. Each measure applied covers a different aspect of the network, so such analyses are not recommended just for a single bias.

Regarding standardized residuals, it was found that the vast majority is less than 0.5 mm. Therefore, they indicated that the analyzed leveling runs did not suffer the occurrence of inconsistencies that significantly influenced the results of the adjustments. The internal reliability showed a homogeneous behavior of the network, portraying that the conditions imposed for the survey of observations managed to guarantee better accuracies than expected, thus not presenting significant errors.

Partial redundancy numbers showed that the vast majority of values are classified as "sufficient" and "good" which reveals a better ability to identify possible errors linked to the network, consequently giving greater control. On the other hand, the relative (average) redundancy numbers place the network at a level below that recommended by Ghilane (2010), i.e., the relative redundancy values were lower than 0.5. In this sense, the analysis of the redundancy numbers in each campaign made it possible to verify isolated deficiencies in error control so that the subsequent campaigns can be planned with better redundancy and reliability.

Regarding the quality of the adjustments, the overall model tests showed that most of the adjustments did not accept the null hypothesis. However, it was found that the a posteriori variances remained lower in magnitude, about five times smaller than the a priori variance, confirming the high quality of the observations.

Due to the difficulty of identifying the constructive type of some benchmarks, it was preferred in this situation to apply the worst case, classifying them as class C. Once the classification of benchmarks was solved, it was found that the benchmarks classified as A and B have a stable average rate of vertical variation of only 0.02 mm/year, unlike class C stations, with -0.17 mm/year.

The three outlier identification methods were unanimous in identifying outliers, with the Tukey method being the one that required fewer iterations, presenting itself as a robust alternative that does not assume the normal distribution as a premise, unlike the other two methods analyzed.

The Confidence Interval was used to assess the quality of the sample mean concerning the population mean, that is, to assess what to expect from the behavior of the classes, with subsidence being the typical condition for most of the benchmarks class C, as verified after the exclusion of outliers.

Through the analysis of the outliers separately, it became evident that several factors influence the local dynamics of the vertical variation. The temporal follow-up is essential to enable the necessary corrections to determine an integral series of sea level variations free from influences of non-internal origin oceanic.

The benchmarks located in places with the best classification (A and B) were the ones with lower variations. However, this does not guarantee that this stability will be maintained over time, as port areas are very dynamic, and significant changes may occur in their structure to the point of affecting the benchmarkers present there. Factors related to local and regional geology that may affect the region's stability must also be considered.

When considering the aspects dealt with and the potentialities pointed out in this research, it became clear that the quality of the leveling network can be improved by increasing the degrees of freedom of the control leveling lines. In this sense, it is recommended to improve the geometry of the leveling network and continue the investigation presented for other sites that house the other tide gauge stations of the PGTGN. Another relevant aspect of the analysis is the vertical variation rates from the GNSS series. These need to be compared with the results of vertical surveys from Scientific Geometric Leveling. Other tests may be applied in the future, for example, an a posteriori analysis of variance for each adjustment (ANOVA) and the correlation analysis between the test statistics, according to Rofatto et al. (2020) and Bonimani et al. (2021). Finally, the analyses still need extended time series to indicate consistent results. Hence, it is possible to classify the benchmarks not only by their constructive method but also by their temporal variation.

Authors' Contribution

The authors E. G. S. and S. S. contributed with Conceptualization, Data Curation, Formal Analysis, Research, Methodology, Validation, Visualization, and Writing – initial draft and in Writing – review and editing of the work. The author I. K. contributed to Conceptualization, Formal Analysis, Validation, and Writing – review and editing.

Interest conflicts

The authors declare that there is no conflict of interest.

References

BAARDA, W. A Testing product for use in geoderic networks. Delft: Citeseer, 1968. v 2. 97p

BAARDA, W. S-transformations and criterion matrices. Delft: Netherlands Geodetic Commission, 1973. v. 4.

BEZERRA, E. Confidence intervals - small samples. CEFET/RJ. 2018. Rio de Janeiro. Available at: https://eic.cefet-rj.br/~ebezerra/wp-content/uploads/2017/07/IE05c-Intervalos-de-Confian%C3%A7a-Amostras-Pequenas.pdf. /. Accessed on: 27 Apr. 2022

BONIMANI, MLS; ROFATTO, VF; MATSUOKA, MT; KLEIN, I.; VERONEZ, MR; DA SILVEIRA JR, LG The Effect of Covariances Between Baseline Components on the Reliability of GNSS Networks:

Results for a Network with High Redundancy. Revista Brasileira de Cartografia, v. 73, no. 2, p. 666–684, 2021. DOI. 10.14393/rbcv73n2-58105

CRAYMER, M. Geodetic adjustment using Helmert blocking Of Space and Terrestrial data. 2017. Available at: http://www.naref.org/ghost/. Accessed on: 27 Apr. 2022

COLLISCHONN, C, KLEIN, I, MATSUOKA, MT Reliability studies in a geodesic network In: III Brazilian Geomatics Symposium. Presidente Prudente - SP Anais..., July 25-27, 2012. v.2. P. 374-375 ISSN 1981-6251. Available in:http://docs.fct.unesp.br/departamentos/cartografia/eventos/2012_III_SBG/_resumos/R106.pdf. Accessed on: 27 Apr. 2022

COLLISCHONN, C.; MATSUOKA, M. T.; GUZATTO, M. P.; KLEIN, I.; LIMA, E. M.;SOUZA, S. F. Análise de confiabilidade de rede GNSS e repetição de linhas-base. Revista Brasileira de Cartografia, EDUFU - Editora da Universidade Federal de Uberlandia, v. 67, n. EE, p. 41683–1703, 2015. Disponível em: <http://www.seer.ufu.br/index.php/revistabrasileiracartografia/article/view/49229>. Acesso em: 27 abr. 2022.

DALAZOANA, R. Studies aimed at the temporal analysis of the Brazilian vertical datum. 202 f. Thesis (Doctorate in Geodetic Sciences) Postgraduate Course in Geodetic Sciences, Earth Sciences Sector, Federal University of Paraná. Curitiba. 2005. Available at: https://acervodigital.ufpr.br/handle/1884/3922. Accessed on: 27 Apr. 2022

DE FREITAS, SRC; BLITZKOW, D. Altitudes and geopotential. IgeS Bulletin, Special Issue for South America, n. 9, p. 47–62, 1999.

FERREIRA, D, F. Basic Statistics. workings Publisher UFLA. 2005

FONSECA, VM Detection of outliers in sample data from an economic survey.153 f. Dissertation (Master's Course in Population Studies and Social Research) – National School of Statistical Sciences, Rio de Janeiro, RJ, 2011. Available at: https://biblioteca.ibge.gov.br/visualizacao/livros/liv81211.pdf.Accessed on: 27 Apr. 2022

FRENCH NATIONAL COMMITTEE OF GEODESY AND GEOPHYSICS (FNCGG). Quadrennial Report Of CNFGG To IUGG. 2011. Available at:https://office.iag-aig.org/doc/5d8dd34b877b7.pdf. Accessed on: 27 Apr. 2022

GEMAEL, C.; MACHADO, AML; WANDRESEN, R. Introduction to observation adjustment: geodetic applications. 2. Ed. Curitiba: UFPR, 2015. 428 p.

GHILANI, DC Adjustment computations: Spatial data analysis. 5th. ed. Hoboken, NJ: Wiley, 2010. 720 p.

HAILEGEBEREL, M.; GLASSMIRE, K.; JOHNSON, A.; SAMANT, M.; DUSEK, G. User's Guide to Vertical Control and Geodetic Leveling for COOPS Observing Systems. 1. ed. Silver Spring, 2018. 69 p. Available at: https://tidesandcurrents.noaa.gov/publications/Users_Guide_to_Vertical_Control_and_Geodetic_Leveling_for_CO-OPS_Observing_Systems-May_2018.pdf. Accessed on: 27 Apr. 2022

INSTITUT NATIONAL DE L'INFORMATION GÉOGRAFHIQUE ET FORESTIÉRE (IGN). L'entretien actuel du réseau métropolitain. 2017. Available at: https://geodesie.ign.fr/index.php?page=ernit. Accessed on: 27 Apr. 2022

BRAZILIAN INSTITUTE OF GEOGRAPHY AND STATISTICS (IBGE). Specifications and general standards for geodetic surveys. Resolution PR 22/83. Rio de Janeiro: Service Bulletin – Supplement, 1983. 12 p. Available at: ftp://geoftp.ibge.gov.br/metodos_e_outros_documentos_de_referencia/normas/bservico1602.pdf. Accessed on: 27 Apr. 2022

BRAZILIAN INSTITUTE OF GEOGRAPHY AND STATISTICS (IBGE). Standardization of geodetic landmarks. Rio de Janeiro, Aug. 2008. 27 p. Service standard no. 1/2008, of the Geosciences Directorate. Available at: https://www.ibge.gov.br/geociencias/metodos-e-outros-documentosde-referencia/normas/16466-padronizacao-de-marcos-geodesicos. html?edicao=16471&t=access-to-product. Accessed on: 27 Apr. 2022

BRAZILIAN INSTITUTE OF GEOGRAPHY AND STATISTICS (IBGE). Technical instructions for Geodetic Control of Tidal Stations - GCTGS and its vertical link to the Brazilian Geodetic System - SGB. Rio de Janeiro: Technical Manuals in Geosciences, 2010. 38 p.

BRAZILIAN INSTITUTE OF GEOGRAPHY AND STATISTICS (IBGE). Monitoring Report on Mean Sea Level Variation at stations of the Permanent Tide Network for Geodesy 2001-2012. Rio de Janeiro: Geosciences Directorate, Technical Report, 2013. 47 p.

BRAZILIAN INSTITUTE OF GEOGRAPHY AND STATISTICS (IBGE). Analysis of the Mean Sea Level at the Stations of the Permanent Geodetic Tide Gauge Network - RMPG - 2001 to 2015. Rio de Janeiro: Geosciences Directorate, Technical Report, 2016. 61 p.

BRAZILIAN INSTITUTE OF GEOGRAPHY AND STATISTICS (IBGE). Specifications and Norms for Geodetic Surveys associated with the Brazilian Geodetic System. Rio de Janeiro: Geosciences Directorate, Technical Manual, 2017. 56 p.

BRAZILIAN INSTITUTE OF GEOGRAPHY AND STATISTICS (IBGE). Altimetric network readjustment with geopotential numbers. Rio de Janeiro: Geosciences Directorate, 2nd ed. 2019. 56 p.

BRAZILIAN INSTITUTE OF GEOGRAPHY AND STATISTICS (IBGE). Monitoring of the variation of the mean sea level in the stations of the Permanent Tide Network for Geodesy: 2001-2020 / IBGE, Geodesy Coordination. - Rio de Janeiro: IBGE, 2021. 121p

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION (IOC). Manual on Sea Level Measurement and Interpretation - An update to 2006. Paris: UNESCO-IOC, Manuals and Guides N 14, 2006. v. 4. 87 p. Available at: https://unesdoc.unesco.org/ark:/48223/pf0000147773. Accessed on: 27 Apr. 2022

KLEIN, I. Quality Control in Adjusting Geodetic Observations. 322 f. Dissertation (Master in Remote Sensing). Graduate Program in Remote Sensing. Federal University of Rio Grande do Sul. Porto Alegre. 2012

KUANG, S. Geodetic Network Analysis and Optimal Design: Concepts and Applications. Chelsea: Ann Arbor Press, Inc, 1996. 368 p.

LUZ, RT Strategies for Modernization of the Vertical Component of the Brazilian Geodetic System and its Integration into SIRGAS. 207 f. Thesis (Doctorate in Geodetic Sciences). Federal University of Paraná, Curitiba, 2008. Available at: https://acervodigital. ufpr.br/handle/1884/17075. Accessed on: 10 jun. 2020

LIGHT, RT; GUIMARÃES, VM Ten years of monitoring of the Sea Level at IBGE. In: Brazilian Colloquium of Geodetic Sciences (CBCG). Curitiba: [yn], Anais... 2003. v. 3. Available at: https://www.ibge.gov.br/geociencias/metodos-e-outros-documentos-de-referencia/outros-documentos-tecnicos-geo/16390-dez-anos-de-monitoramento-do -level-of-the-sea-in-ibge.html?=&t=about.Accessed: 27 Apr. 2022

MCCORMAC, J. Topography. 5th ed. Rio de Janeiro: LTC, 2007. 408 p.

MORAES, CV of. Improvement of the design of the geodetic model for the characterization of extremes in the geometric space. 277 f. Thesis (Doctorate in Geodetic Sciences) — Federal University of Paraná, Curitiba, 2001. Available at: https://acervodigital.ufpr.br/handle/1884/32982. Accessed on: 27 Apr. 2022

MüRLE, M.; BILL, R. Zuverlässigkeits – genauigkeits- untersuchungeberner geodätischernetze. Allgemeine Vermessungs-Nachrichten, Karlsruhe, v. 91, no. 2, p. 45-62, 1984.

NOWAK, E.; ODZIEMCZYK, W. Impact analysis of observation coupling on reliability indices in a geodetic network. Reports on Geodesy and Geoinformatics, Walter de Gruyter GmbH, v. 106, no. 1, p. 1–7, Dec. 2018. DOI. 10.2478/rgg-2018-0008

ROFATTO, VF; MATSUOKA, MT; KLEIN, I. Design of geodetic networks based on outlier identification criteria: an example applied to the leveling network. Bulletin of Geodesic Sciences, v. 24, no. 2, p. 152-170, 2018. DOI. 10.1590/S1982-21702018000200011

ROFATTO, VF An Extension to Reliability Theory in Geodesy. 234 f. Thesis (Doctorate in Remote Sensing). Federal University of Rio Grande do Sul. Porto Alegre. 2020. DOI. 10.3390/rs12050860

ROFATTO, VF; MATSUOKA, MT; KLEIN, I.; VERONEZ, MR, DA SILVEIRA JR, LG A Monte Carlo Based outlier diagnosis method for sensitivity analysis. Remote Sensing, v. 12, no. 5, p. 1-41, 2020.

SANTOS, EG Integration between the High Precision Altimetric Network, the Coastal Geodetic Reference Network and the Tidal Reference Levels. 132 f. Dissertation (Master in Cartographic Engineering). Military Engineering Institute. Rio de Janeiro. 2021.

SEO, S. A Review and Comparison of Methods for Detecting Outliers in Univariate Data Sets. 56 f. Dissertation (Master of Science) - Graduate School of Public Health in partial fulfillment, University of Pittsburgh, Pittsburgh, Pennsylvania, 2006. Available at: http://d-scholarship.pitt.edu/7948/1/Seo.pdf. Accessed on: 27 Apr. 2022

SOARES, S.; SANTOS, EG; LUZ, RT Geodetic Coastal Reference Network (RGRC) as input for integration of altitudes and depths: preliminary results. In: VII Brazilian Symposium on Geodetic Sciences and Geoinformation Technologies. Recife: Anais...Recife.UFPE, 2018. p. 742–751. Available at: https://www.ufpe.br/documents/39451/1384233/Anais+do+VII+SIMGEO/2ff23c73-935d-4418-8728-fefb24630f34. Accessed on: 27 Apr. 2022

SOARES, S.; SANTOS, EG; LUZ, RT Methodological evaluation for connecting the permanent GNSS (Global Navigation Satellite System) station in Imbituba to the Brazilian Altimetric Network. In: SIRGAS Symposium. Rio de Janeiro 2019 Anais... Bulletin: No. 24. Available at: http://www.sirgas.org/fileadmin/docs/Boletines/Bol24/71_Soares_et_al_2019_Conexion_Imbituba_GNSS.pdf. Accessed on: 27 Apr. 2022

SOARES, S.; SANTOS, EG; SIQUEIRA, JCS; LIMA, MK; LUZ, RT Geodetic Coastal Reference Network: preliminary actions for the integration of altitudes and depths In. XIII Symposium on Waves, Tides, Ocean Engineering and Satellite Oceanography Anais... Instituto de Estudos do Mar Almirante Paulo Moreira. Arraial do Cabo-RJ. 2019. Available at https://www.omarsat.com.br/_files/ugd/f9878c_679a7728c2c64f87b1a53338f046ce7d.pdf. Access on: 24 May. 2022

SURACI, SS; OLIVEIRA, LC; KLEIN, I. Two aspects on L1-norm adjustment of leveling networks. Brazilian Magazine of Cartography, v. 71, no. 2, p. 486-500, 2019. DOI. 10.14393/rbcv71n2-47697.

SURACI, SS; OLIVEIRA, LC Application of L1 and L∞ norms in altimetry networks: identification of outliers and construction of the stochastic model. Revista Brasileira de Cartografia, no. 101, p. 135-153, 2020. Available in <https://doi.org/10.35424/rcato.i101.669>. Accessed on: 24 of jun. 2022

TEUNISSEN, PJG Testing theory: an introduction. 2nd. ed. Delft: VSSD Delft, 2006.147 p.

TORGE, W.; MÜLLER, J. Geodesy. 4th. ed. Berlin: Walter de Gruyter, 2012. 433 p.

TRIPATHY SS, SAXENA RK, GUPTA PK, Comparison of Statistical Methods for Outlie Detection in Proficiency Testing Data on Analysis of Lead in Aqueous Solution, American Journal of Theoretical and Applied Statistics. vol. 2, No. 6, pp. 233-242, 2013. Available at: https://article.sciencepublishinggroup.com/pdf/10.11648.j.ajtas.20130206.21.pdf Accessed on: 24 May. 2022

TUKEY, J. W. **Exploratory data analysis**. Addison-Wesley.1977. DOI. 10.11648/j.ajtas.20130206.21

ZERVAS, C. **Sea level variations of the United States 1854-2006**.Silver Spring: National Oceanic and Atmospheric Administration - NOAA, Dec. 2009. [194 p.]. (NOAA technical report NOS CO-OPS, 53). Available in:https://tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf. Access on: 24 May. 2022

 DOI: http://dx.doi.org/10.14393/rbcv74n4-66090

Main author biography

Everton Gomes dos Santos was born in Pojuca-BA, in 1983. He is a Surveyor Engineer graduated from the Federal Rural University of Rio de Janeiro (2007). Master in Cartographic Engineering from the Military Institute of Engineering (2021). He currently holds the position of Technologist in Geographic Information and Statistics at IBGE, where he works in the Geodesy Coordination with emphasis on Vertical Reference Networks and monitoring of the Mean Sea Level for geodetic purposes in the Permanent Tide Graph Network for Geodesy - RMPG. Interest in the areas of physical geodesy, physical oceanography and the environment.

.