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ARTICLE

VALIDATION OF THE DIGITAL ELEVATION MODEL (SRTM) WITH GNSS SURVEYING APPLIED TO THE MIRIM LAGOON HYDROGRAPHIC BASIN

Validação do modelo digital de elevação (SRTM) com levantamento GNSS aplicado à bacia hidrográfica da Lagoa Mirim

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Abstract:

Between 2013 and 2014, a kinematic positioning based on the Global Navigation Satellite System (GNSS) was carried out for this research work. This GNSS survey resulted in 275916 points with tridimensional coordinates in the cross-border basin area of 58205km^2 called Mirim Lagoon Hydrographic Basin, located in south of Rio Grande do Sul (Brazil) and west of Uruguay. This study aims at showing the methodology firstly and, furthermore, results regarding the validation of the vertical accuracy of the DEM SRTM through kinematic positioning by GNSS, in the Mirim Lagoon Hydrographic Basin region. Also, the GNSS surveying data was post-processed with the Precise Point Positioning (PPP) method, and the ellipsoidal height was converted into orthometric height through the software INTPT geoid. During this study, the geopotential model (EGM96) was used to transform altitude differences between two countries, Brazil and Uruguay. Results showed that the vertical mean absolute error of the DEM SRTM vary from 0.07m to ± 9.9m with average of -0.28 m. This vertical accuracy is better than the absolute vertical accuracy value of ±16m published in the SRTM data specification and validates the DEM SRTM.

Keywords: Validation; SRTM; GNSS; DEM.

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Resumo:

Em 2013 e 2014, um levantamento cinemático baseado em Sistemas Globais de Navegação por Satélite (GNSS) foi realizado no sul do Rio Grande de Sul (Brasil) e oeste do Uruguai, na região da Bacia Hidrográfica da Lagoa Mirim, uma bacia transfronteiriça com 58205km^2 de área, durante o qual foram coletados 275916 pontos com coordenadas tridimensionais. O objetivo deste trabalho é primeiramente apresentar a metodologia e, em seguida, os resultados das análises realizadas para validação da acurácia vertical do MDE SRTM através de levantamento cinemático GNSS na região da Bacia Hidrográfica da Lagoa Mirim. O conjunto de dados do levantamento cinemático GNSS foi pós-processado com o método de posicionamento por ponto preciso (PPP) e a altitude elipsoidal foi convertida para altitude ortométrica através do programa INTPT geoid. Como o estudo envolve dois países, houve a necessidade do uso de um modelo global para a conversão da altitude, o EGM96. Os resultados demonstram que os erros verticais médios absolutos do MDE SRTM variam de 0,07m a ± 9,9m, com média igual a -0,28m, o que é melhor que o valor da precisão padrão indicada em sua especificação técnica, que é ±16m, e valida o MDE SRTM.

Palavras-chave*:* Validação; SRTM; GNSS; MDE.

1. Introduction

The Shuttle Radar Topography Mission (SRTM) (Rabus et al. 2003 and Van Zyl 2001) results from a collaborative effort among the National Aeronautics and Space Administration (NASA), the National Geospatial-Intelligence Agency (NGA), the U.S. Department of Defense (DoD), the German spatial agency (Deutsches Zentrum für Luft und Raumfahrt - DLG) and the Italian spatial agency (Agenzia Spaziale Italiana - ASI). The objective was to map the Earth´s relief using Interferometric Synthetic Aperture Radar (InSAR) technology system. In the same year, 2000, the SRTM released for the first time a global digital elevation model (DEM) with high-quality resolution levels of one and three arcseconds (approximately 30m and 90 m). The Geocentric Reference System is the World Geodetic System 1984 (WGS84), and the Global Geopotential Model is the Earth Gravity Model (EGM96). For DEM SRTM development, in the Mirim Lagoon Hydrographic Basin, SRTM images were used in version 3, band C, with a spatial resolution of 1 arcsecond, roughly 30m. This relief information was processed and distributed by the U.S. Geological Survey – USGS (http://earthexplorer.usgs.gov/). The SRTM project aimed to collect near-global topographic data with absolute horizontal and vertical accuracies better than 20 and 16 m, respectively, with 90% confidence (Rabus et al. 2003 and JPL 2009).

According to Rodriguez et al. (2005), many studies have been carried out to validate the SRTM data using different GNSS surveying methods and receivers. The GNSS consists of single or dual frequency receivers deployed in static or kinematic modes. The receiver can be stationary at the ground control points (GCPs) to compute its coordinates (static mode), or a base receiver can be fixed in a known location and the other one, known as the rover, is moved over multiple unknown points with both tracking the same satellites (kinematic mode).

One of the GNSS positioning methods is the Precise Point Positioning (PPP). As stated by Azambuja (2015), this method has several applications in geodynamics, gain significantly upon GNSS network processing and over centimetric precision when taking into consideration static mode and long-term collecting data, as well decimetric precision while the kinematic mode is adopted. Considering the PPP, one fundamental requirement is the use of ephemeris and corrections of the satellite clocks, both with high precision. This information has been made available free of charge by the IGS and associated centers.

The object to be positioned might be immobile, characterizing the static positioning, or be in movement, describing the positioning by Kinematic Precise Point. In the kinematic method, the receiver collects data while it is moving, which allows estimating the coordinates and their trajectory (Monico 2008).

GNSS advancements have increased the capacity to obtain latitude, longitude and ellipsoidal height (h). However, the height supplied by satellites is related to the reference ellipsoid. The essential is a height related to an equipotential surface of the terrestrial gravity field, in this case, the orthometric height (H). The relation between these two heights is the geoidal undulation (N), i.e., for obtaining orthometric height, based on the ellipsoidal height, it is necessary to understand the geoid undulation. One of the approaches to have geoid undulation is through a geopotential model such as the EGM96. The EGM96 model is used to compute geoid undulations accurate to better than one meter concerning WGS84 ellipsoid. In Brazil, the present geoidal model is the MAPGEO2015 (IBGE 2017).

Several studies deal with the validation of Digital Elevation Models (DEMs). Purinton and Bookhagen (2017) defined in their paper validation of DEMs and comparison of geomorphic metrics on the southern Central Andean Plateau. Mukul, Srivastava and Mukul (2015) analyzed the accuracy of the elevation obtained through SRTM using international global navigation satellite system service (IGS) network. Karwel and Ewiak (2008) carried out an estimative of the accuracy of the SRTM terrain model on Poland area. Kolecka and Kozak (2014) assessed the accuracy of SRTM C- and X-Band High Mountain Elevation Data of the Polish Tatra Mountains. Agrawal et al. (2006) validated the DEM SRTM with differential GPS measurements for different terrains. Mouratidis, Briole and Katsambalos (2010) explained the SRTM 3″ DEM (versions 1, 2, 3, 4) validation using post-processed kinematic GNSS measurements, using reference stations with a maximum distance of 20km from the rover, in the North of Greece. Gorokhovich and Voustianiouk (2006) carried out an accuracy assessment of the processed SRTM-based elevation data by CGIAR using field data from USA and Thailand and its relation to the terrain characteristics. Van Niel et al. (2008) clarify the impact of misregistration on SRTM and DEM image differences. Becek (2008) investigated elevation bias of the SRTM C-and X-band DEMs. In Ludwig and Schneider (2006) approach a validation of DEMs from SRTM X-SAR for applications in hydrologic modeling was made. Marschalk et al. (2004) compared DEMs derived from SRTM / X- and C-band. Rexer and Hirt (2014) contrast free high-resolution digital elevation datasets (ASTER GDEM2, SRTM v2.1/v4.1) with accurate heights from the Australian National Gravity Database. Rodriguez, Morris and Belz (2006) performed a global assessment of the SRTM performance. Smith and Sandwell (2003) studied the accuracy and resolution of SRTM data. Sun et al. (2003) validated surface heights from shuttle radar topography mission 25 using shuttle laser altimeter, and Tachikawa et al. (2011) show a summary of validation results of the ASTER global digital elevation model version 2.

In this way, the innovation of this work is the methodology developed to achieve the suitable accuracy for the control points coordinates to validate the DEM SRTM of Mirim Lagoon Hydrographic Basin. The kinematic relative positioning method was used with a recording rate of 1 second and without reference stations for post-processing with the PPP method. This methodology can be applied to cover large areas, when the reference stations are too far from the surveyed area or when there are different geodetic reference systems (two or more countries for example). Moreover, this paper is part of a research project whose objective is the automatic determination of knickpoints and the assessment of both morphometric and hypsometric parameters of Mirim Lagoon Hydrographic Basin, employing data obtained through GNSS survey, SRTM images and geoprocessing techniques. Therefore, initially will be described the area of this specific basin, after will be presented the methodology and the results of the analyses and lastly validate the vertical accuracy of the DEM SRTM.

2. Study Area

The location of the Mirim Lagoon Hydrographic Basin is on the Atlantic coast of South America, between 31°S and 34°30'S, and into 52°W and 55°30'W. This basin is considered as cross-border since it covers an area of 58,407.78km^2, where 47% of this area is in Brazil and 53% in Uruguay. The first country covers 20 municipalities besides five departments for the second one. Figure 1 shows the location of the Mirim Lagoon Hydrographic Basin.

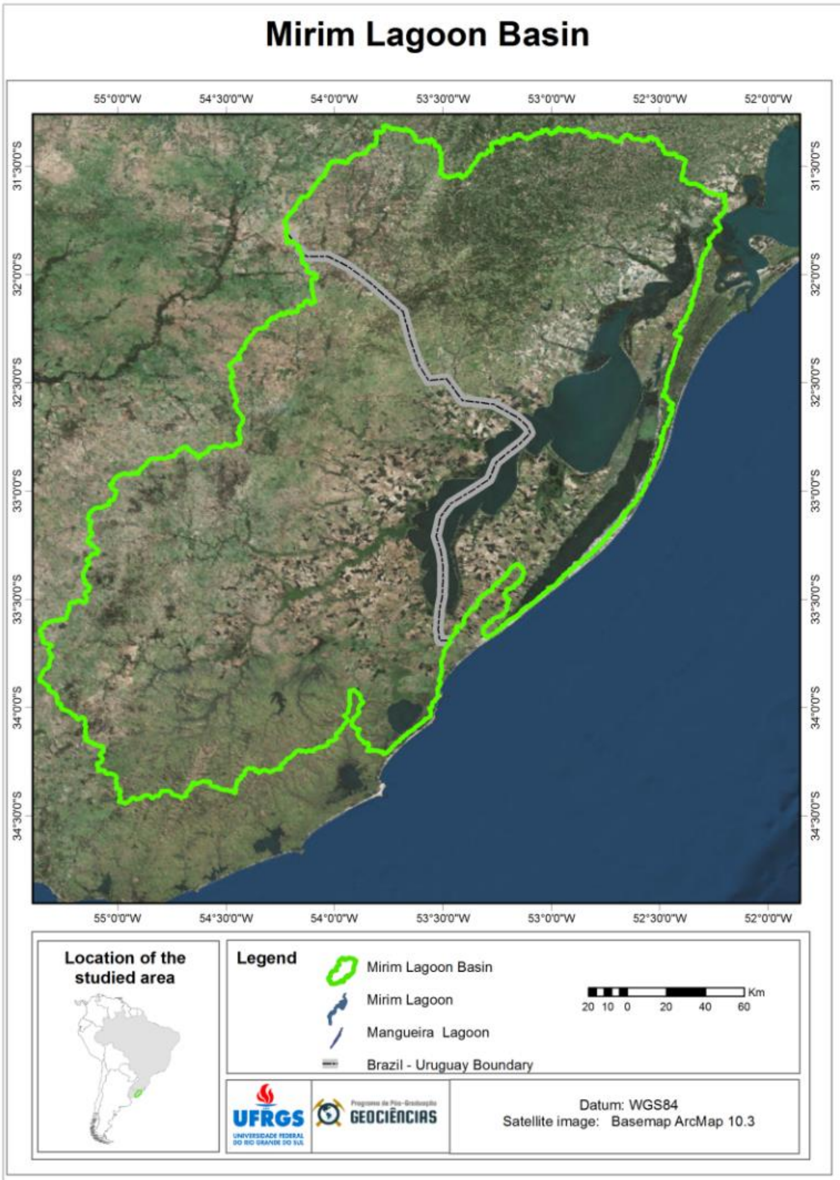

Figure 1: Location of the study area – Mirim Lagoon Hydrographic Basin.

3. Methodology

The methodology described for validation of the DEM SRTM follows the steps of GNSS data collection, post-processing of data, the transformation from geometric heights into orthometric heights, DEM SRTM mosaic, extraction of the respective points in the DEM SRTM and the statistical analyses for validation of the model. The data used in this study are the SRTM images that cover the Mirim Lagoon Hydrographic Basin and the three-dimensional (3D) coordinates of the survey points with the use of double frequency GNSS receivers. Figure 2 gives the research flowchart.

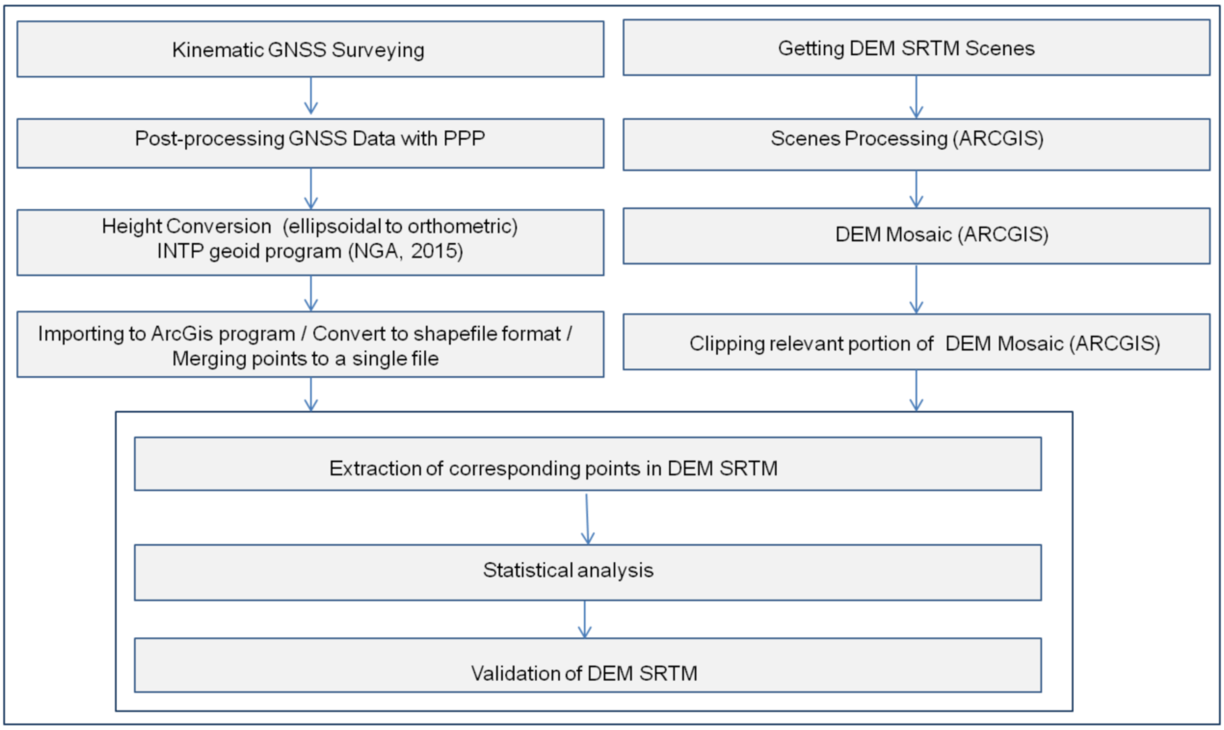

Figure 2: Research Flowchart.

3.1 GNSS data acquisition and processing

The first part of this study is concerned to obtain 3D coordinates of the ground control points (GCP´s). Since the area's size is 58407.78km^2, it was necessary to adopt the post-processed kinematic relative positioning method. The survey was carried out between 2013 and 2014, on a Kia Mohave vehicle, being the receiver fixed on the roof (Figure 3) upon a tribrach. It was used a GNSS receiver of dual-frequency (L1/L2) from Topcon Corporation, model Hiper Lite+, with recording rate of 1 second.

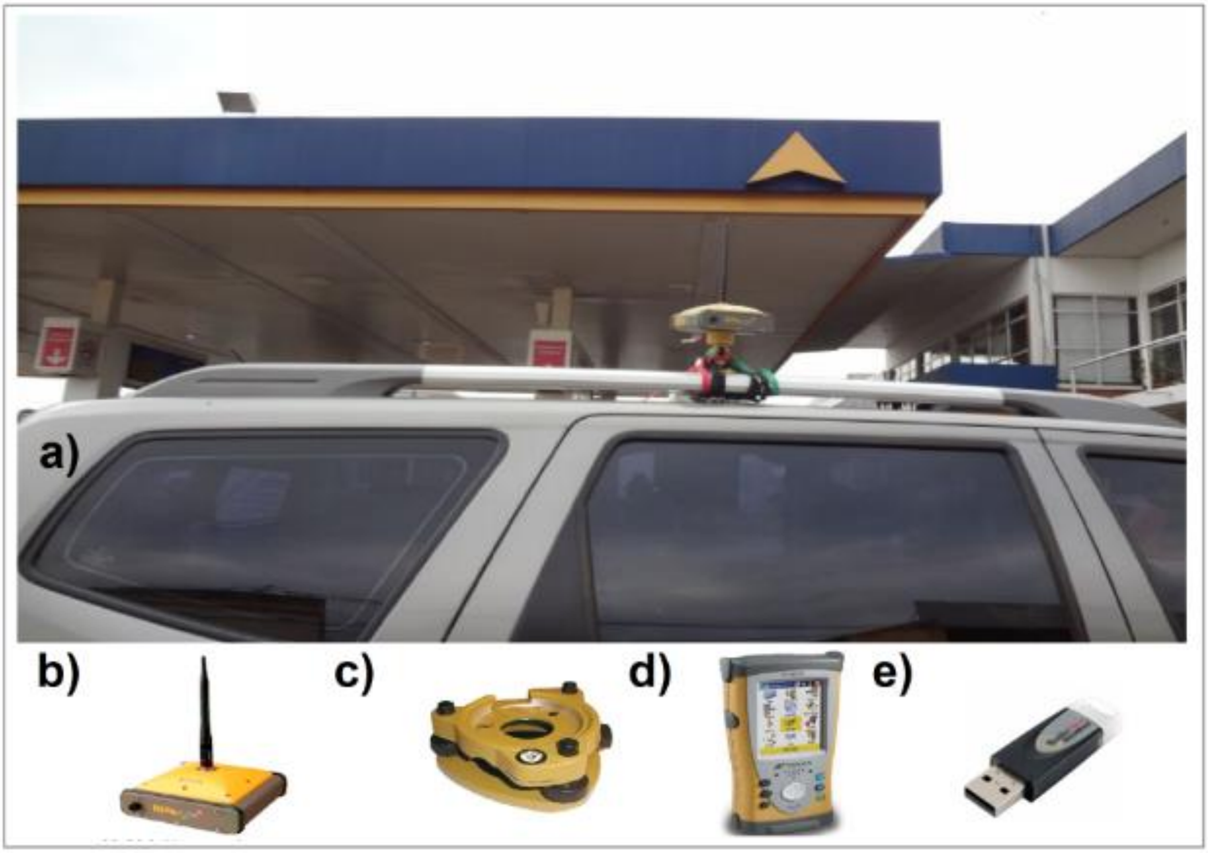

Figure 3: Kia Mohave vehicle (a), GNSS receiver (b) and accessories (c, d and e) used during the kinematic GNSS survey.

A total of 275916 points with 3D coordinates were collected in Mirim Lagoon Hydrographic Basin. Figure 4 shows the result of the kinematic GNSS survey.

The files corresponding to the GNSS survey were transferred from the receiver to the computer using a USB cable and the software Topcon Tools® version 8.2.3. The archive format of the native data of the receiver Topcon Hiper Lite+ is the TPS. After importing those files, the configuration was defined as GPS+ because it uses data from the GPS (Global Positioning System) constellation and GLONASS (Globalnaya Navigatsionnaya Sputnikovaya Sistema). The height and brand of the antenna, the geodetic reference system WGS84 and the mask of elevation of 15° were supplied. That information is essential, considering that the post-processing service will correct and reduce the data to the antenna phase center. In GNSS precise positioning its necessary to have the accurate antenna phase center offsets values and its variation. The use of the manufacturer's recommended offset values may not match the precise values determined by the calibration process. Also important is the phase center correction factors during data processing. Both values are necessary to avoid errors in the resulting coordinates, especially the height component (El-Hattab 2013 and Seeber 2003).

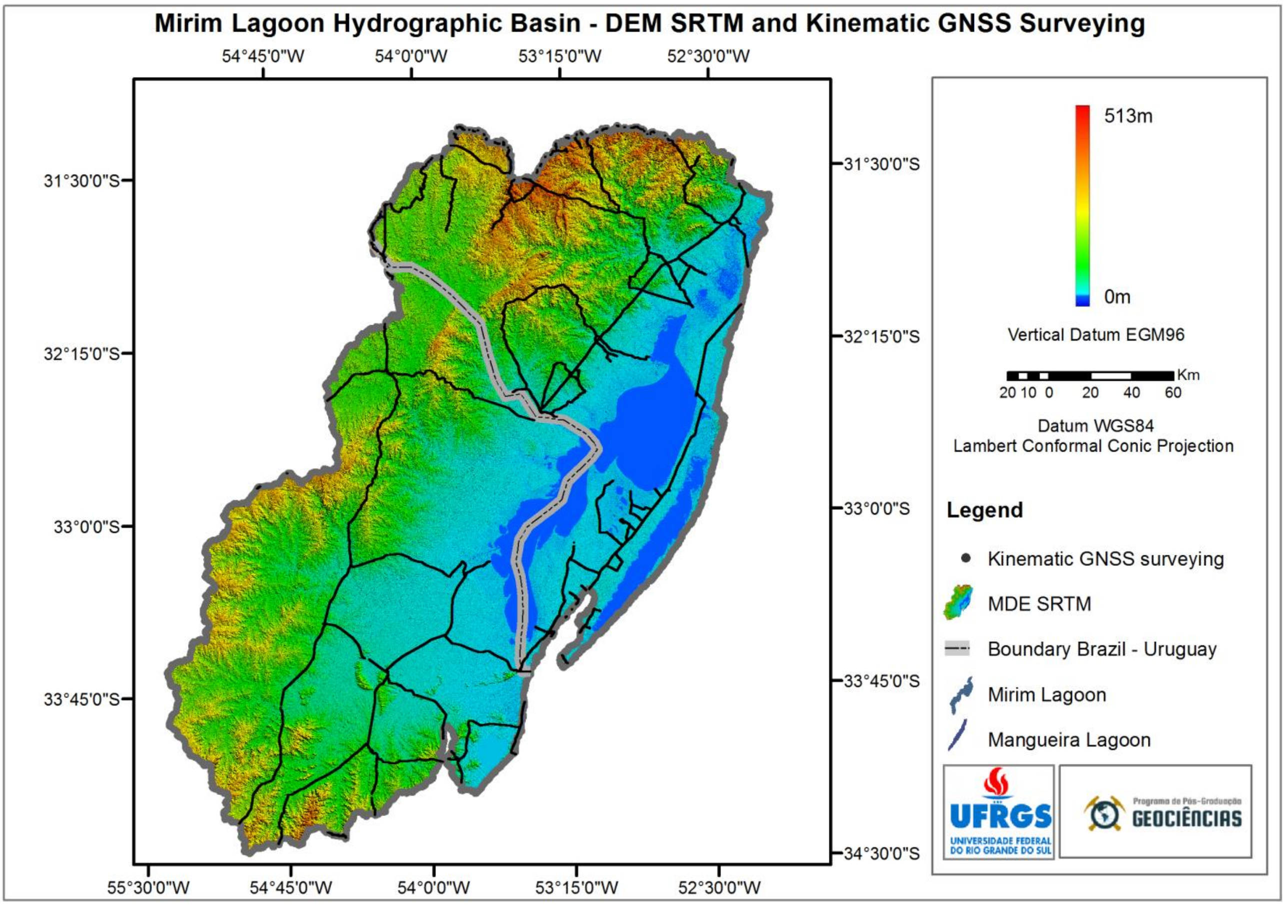

Figure 4: Kinematic GNSS surveying in the Mirim Lagoon Hydrographic Basin.

After this procedure, the files were exported to the RINEX (Receiver Independent Exchange) format and post-processed individually through the PPP method with the Canadian Spatial Reference System – Precise Point Positioning (CSRS-PPP). CSRS-PPP is a free of charge online service developed by the Geodetic Survey Division of the Natural Resources of Canada (NRCAN), applied for the post-processing of GNSS data (NRCAN 2017), and it is available online (https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php?locale=en). In Brazil, there is a similar service for the online post-processing of GNSS data, the IBGE-PPP, which could not be used because the study area spreads along two countries, demanding the use of a global service.

When accessing the online service, the user chooses the survey method (either static or cinematic) and the reference system (either ITRF or NAD83). In this work, the kinematic positioning and the reference system ITRF (International Terrestrial Reference Frame) used is compatible with WGS84. The North American Datum of 1983 (NAD83) is used everywhere in North America except Mexico (Sickle 2017). The resulting files from the post-processing are sent to the user by e-mail. These four files have the following information: one file (CSV) with the corrected base station position for each time stamp during the survey; one file (pdf) with a processing report; one file (pos) with the estimated parameters for each observed period, the estimated coordinates and the respective standard deviation; and a file (sum) with the complete description of the processing.

3.2 Height Conversion

GNSS receivers provide geometric heights (ellipsoidal heights). The determination of orthometric heights can be done using classic leveling techniques or by the association of data obtained with GNSS receivers and geoid models. The geoid models are gravitational models of the Earth and can be global (e.g., the Earth Gravitational Model 96 - EGM96), regional (e.g., the Brazilian model MAPGEO 2015) or local, determined for states or municipalities. In this work, the global geopotential model EGM96 (Lemoine et al. 1998) was used as a reference model, because the heights of the DEM SRTM are originally referenced in EGM96.

Geoid undulation was computed using the INTPT geoid calculator (NGA 2015) after adding the file with GNSS points coordinates (latitude and longitude). This geoid height calculator is an online tool that calculates the geoid undulation correction at a specified location on Earth using EGM96 gravity models. The error for EGM96 geoidal undulation is in the range ±0.5 to ±1.0m (Lemoine et al. 1998). With the geoid undulation of each point, the following relationship (1) was used to transform elevation from ellipsoidal height to orthometric height (Bomford 1980):

$$H = h - N \tag{1}$$

where
H = orthometric height;
h = ellipsoidal height;
N = geoid undulation.

3.3 DEM SRTM Development

Fifteen images SRTM, version 3, band C, with a spatial resolution of 1 arcsecond (approximately 30 m) were used to develop the DEM SRTM of the Mirim Lagoon Hydrographic Basin. This information of the relief was processed and distributed by the U.S. Geological Survey – USGS (http://earthexplorer.usgs.gov/).

These images were individually processed to obtain the Digital Elevation Model Hydrologically Consistent (DEMHC) and to treat the inconsistencies. Afterward, a mosaic with the 15 images of the basin region was created. These procedures were executed in the software ArcGIS, version 10.2.2. Figure 5 illustrates the DEM SRTM of the Mirim Lagoon Hydrographic Basin, representing orthometric heights referred to EGM96.

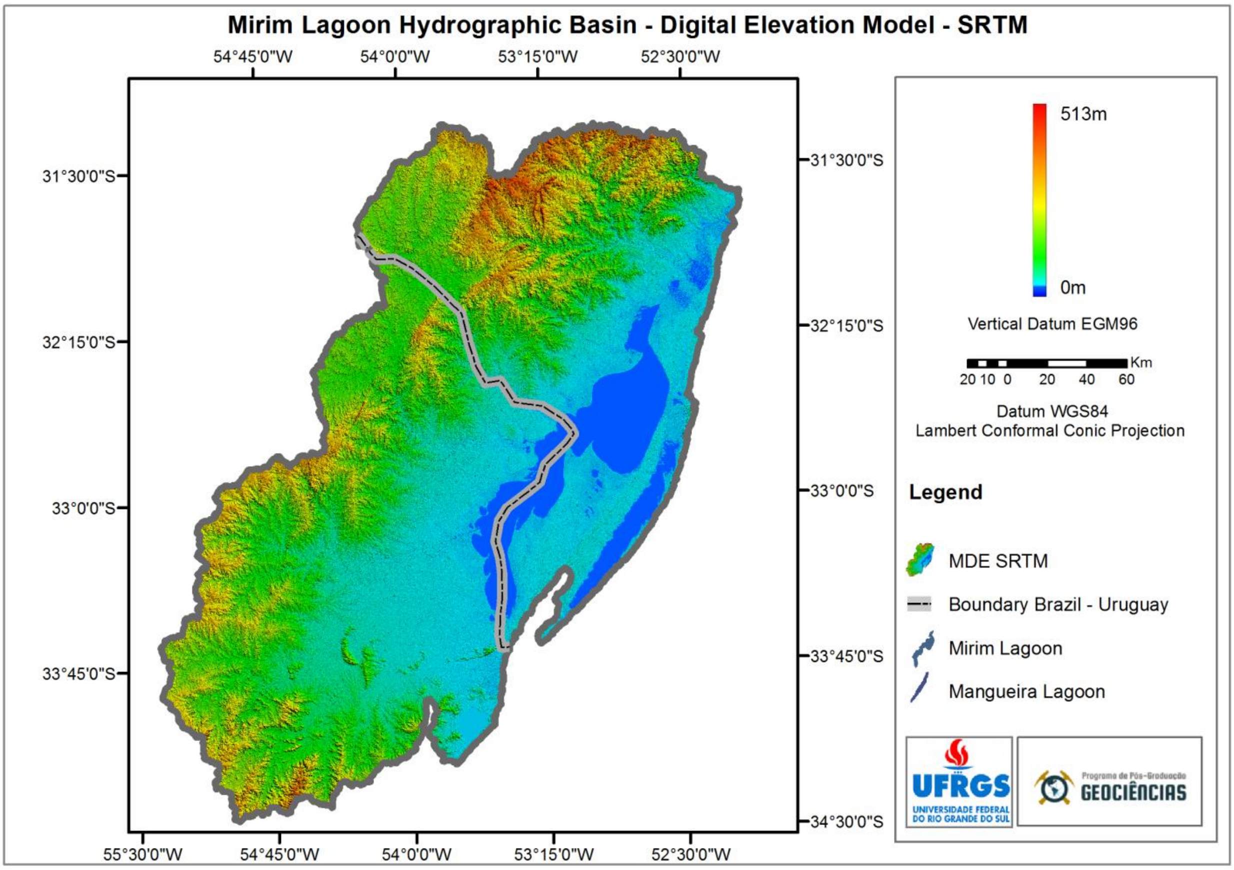

Figure 5: DEM SRTM of Mirim Lagoon Hydrographic Basin.

3.4 Integration of the GNSS survey data with the DEM SRTM

After the post-processing of the GNSS survey data and the conversion of the ellipsoid heights in orthometric heights, the data was imported into the ArcGIS software, version 10.2.2. For the vertical accuracy analysis and, consequently, validation of the DEM SRTM, it is necessary to compare the model with elevation data with higher precision. In this research, the comparison was made using the GNSS survey data.

The extraction of the homologous points (corresponding points) of the GNSS survey and the DEM SRTM was performed through the Extract Values to Point tool, of the software ArcGIS ArcToolBox. After getting the homologous points, the differences between the orthometric height of each point of the GNSS survey and the DEM SRTM were determined. These differences were used in the statistical analyses.

3.5 Statistic's analysis

Usually, vertical accuracy is computed by Root-Mean-Square-Error (RMSE). RMSE (2) measures the difference between the DEM heights and the GNSS reference heights (Congalton and Green

2009). These individual point differences are called residuals (3), and the RMSE serves to aggregate them into a single measure of predictive power:

$$RMSE = \sqrt{\sum_{i}^{n} (e_i)^2 / n} \tag{2}$$

where

$$e_i = e_{ri} - e_{mi} \tag{3}$$

and

e_{ri} = reference GNSS elevation at the i_{th} point;

e_{mi} = DEM SRTM elevation at the i_{th} point;

n = number of points.

The statistic analysis was performed in the software ArcGIS 10.2.2, through the extension Geostatistical Analyst, and in the software Statistica version 12. It was examined the magnitude of absolute errors in the SRTM data. These errors were named discrepancies between the SRTM height and the GNSS survey points. After the post-processing and the conversion of the ellipsoid heights into orthometric heights, the GNSS survey points were considered accurate and used as a reference for DEM SRTM validation. The goal of the statistic analysis was to verify if the absolute vertical precision of the DEM data exceeds 16 m, according to the precision specifications of the DEM SRTM.

4. RESULTS

The 275916 control points collected with 3D coordinates in the Mirim Lagoon Hydrographic Basin were post-processed with the PPP method. The resulting files have the information of the corrected base station position for each time stamp during this survey (CSV), the shortened report of the processing (pdf), the estimated parameters for each period observed, the estimated coordinates at each moment and the individual standard deviation (pos), and the complete report of the processing (sum). Table 1 presents an example of 3D coordinates, with the related standard deviation, generated during the post-processing step. Table 2 shows the mean and the standard deviation for the set of 3D coordinates (275916 points) post-processed by the PPP method. The results confirm that the vertical accuracy of GNSS survey observations is suitable to validate DEM SRTM.

The statistical analysis of the acquired data was carried out in the software ArcGIS, version 10.2.2, using the Geostatistical Analyst extension and in the software Statistica, version 12. Initially, it was created two samples with 4000 and 500 points from the GNSS survey and DEM SRTM. These samples were defined considering the software limitations. Whenever possible, it was used all the points, and when the software tool did not allow that, it was used one of the samples. Figure 6 represents the DEM SRTM of the Mirim Lagoon Hydrographic Basin and the GNSS survey points, with all survey data (N=275916 points) and two samples (N=4000 and N=500 points). And figure 7 shows the orthometric heights resulting from the GNSS surveying and the orthometric heights of the DEM SRTM, from the samples N=275,916, N=4000 and N=500 points.

Table 1: Example of 3D coordinates and standard deviations obtained in the Mirim Lagoon Hydrographic Basin

3D Coordinates			Standard Deviations		
Latitude (° ' ")	Longitude (° ' ")	Ellipsoidal Height(m)	Lat(m)	Long(m)	Height (m)
-32 35 54.62967	-53 24 56.42174	-34.873	2.069	3.613	0.00357
-32 35 54.62712	-53 24 56.4133	-35.017	2.031	3.533	0.00371
-32 35 54.62692	-53 24 56.41474	-35.030	2.035	3.535	0.00242
-32 35 54.62734	-53 24 56.41289	-34.917	2.036	3.536	0.00301

Table 2: Mean and standard deviation of 3D coordinates obtained in the GNSS survey

	Latitude(m)	Longitude(m)	Ellipsoidal Height(m)
Mean	0.071	0.1135	0.00367
Standard Deviation	0.213	0.3752	0.00073

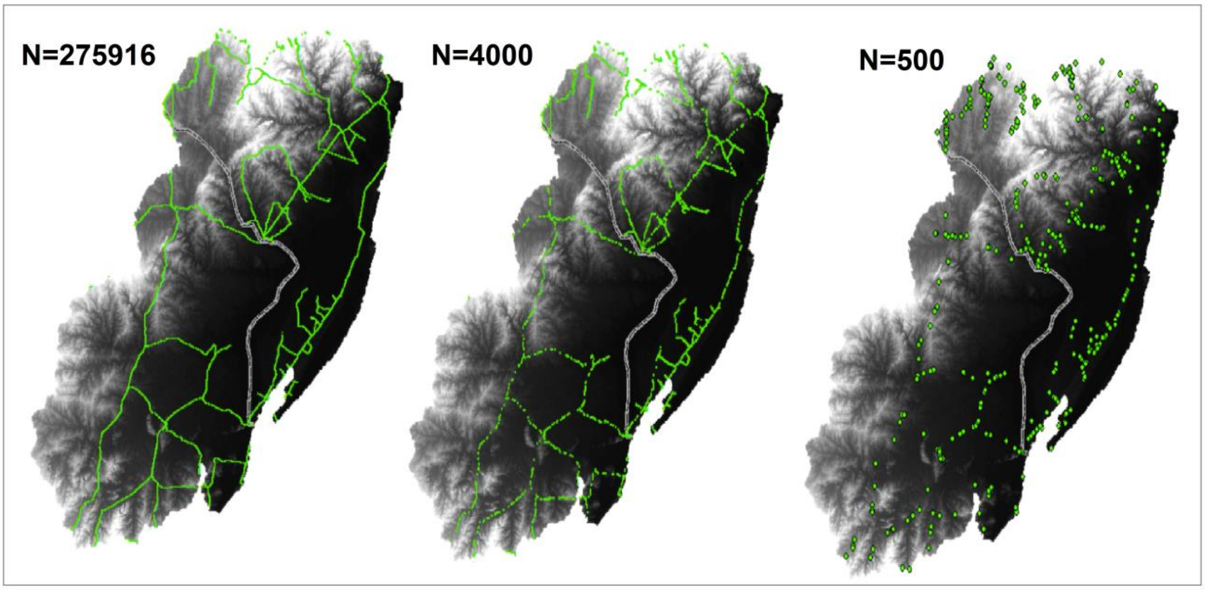

Figure 6: DEM SRTM of the Mirim Lagoon Hydrographic Basin and GNSS surveying with different sizes of data samples.

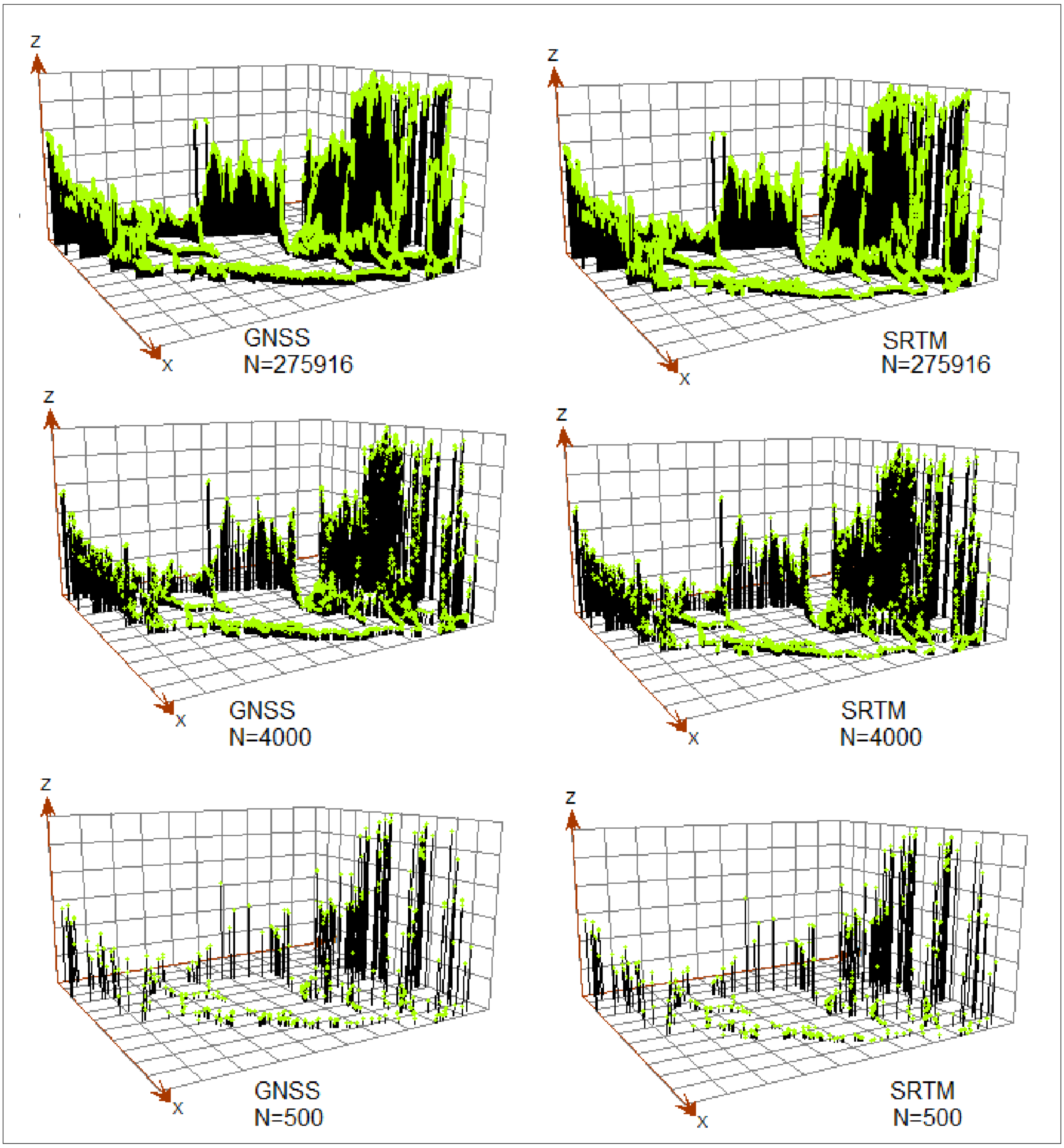

Figure 7: DEM orthometric height of the GNSS surveying versus orthometric height in the DEM SRTM, for the samples: N=275916 points, N=4000 points and N=500 points.

In ArcGIS software, the analysis was achieved using all data available (N=275916 points). Figure 8 gives a graphic with the distribution of differences between the orthometric heights DEM SRTM and GNSS surveying. The number of points in the samples is 275916. The results demonstrate that differences in heights have a minimum value of -9.9998m and maximum of 9.9994m. The minimum difference in module is 0.000185m, and the mean is -0.2817m. The values of the first and third quarters are -2.9549m and 2.3028m, respectively, and the median is -0.33377m. It can be seen that the histogram gives symmetric distribution pattern. The asymmetry statistics (skewness=0.066466) assess that the asymmetry level in the observations is close to zero, which confirms the symmetry of the data. The small values are higher than zero, which means that the distribution is more concentrated than the normal distribution.

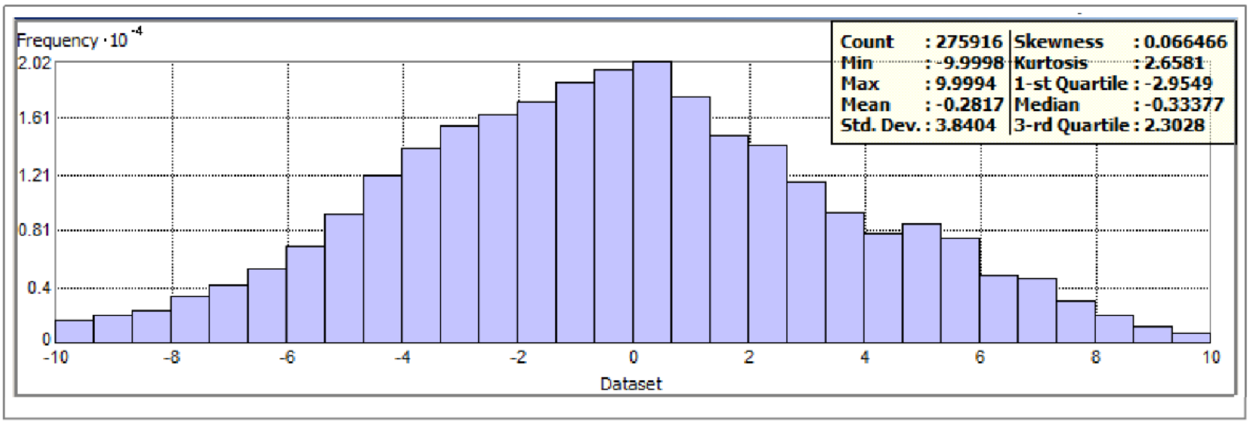

Figure 8: Graphic demonstrating the distribution of differences between the orthometric heights of the DEM SRTM and the GNSS surveying.

Figure 9 presents the Normal QQ Plot with the distribution of differences between the orthometric heights of the DEM SRTM and the GNSS surveying respecting the normal distribution. The frequency distribution of heights is compared to the normal distribution. As the straight line represents the normal distribution, the graphic shows that the sample points follow the normal distribution. Figure 10 displays a two-dimensional (2D) scatterplot, showing the correlation between the GNSS surveying and the DEM SRTM. The correlation coefficient of 0.999528 indicates that the data are highly correlated.

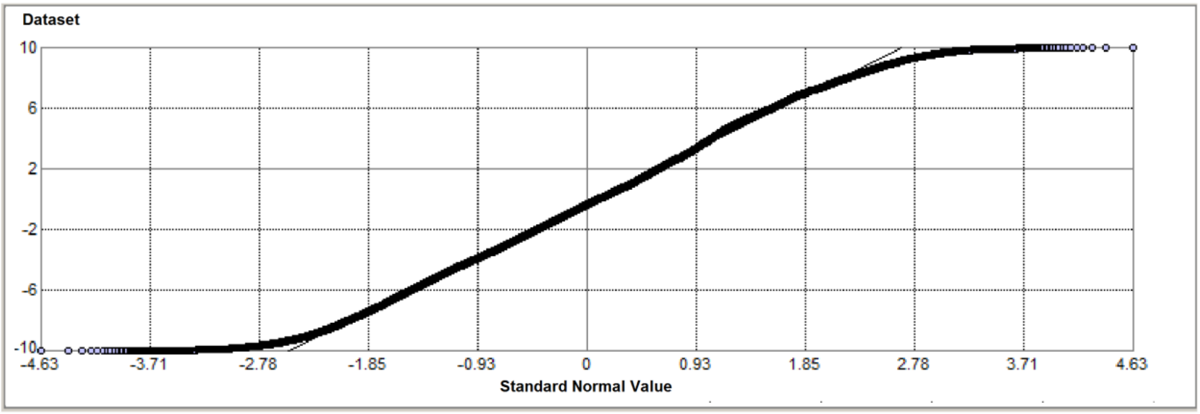

Figure 9: Normal QQ Plot shows the distribution of the orthometric heights of the DEM SRTM and the GNSS surveying concerning the normal distribution.

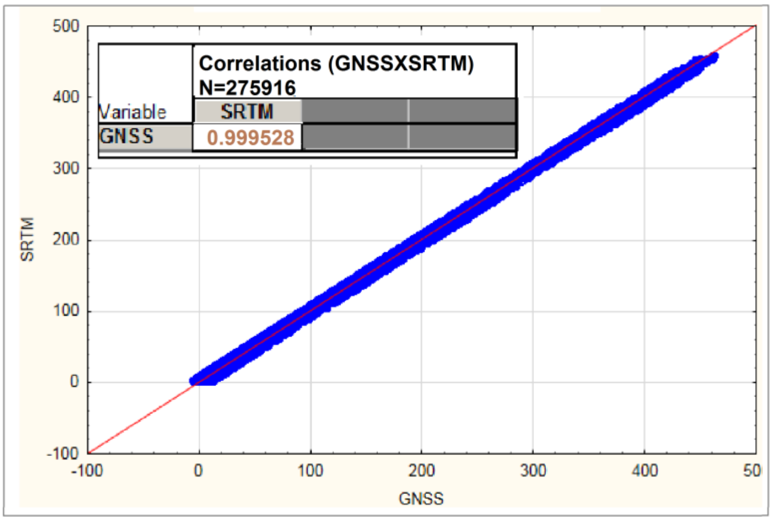

Figure 10: 2D scatterplot showing the correlation between the DEM SRTM and the GNSS surveying.

Figure 11 compares statistical analysis results performed in the software Statistica, where 4000 points versus the statistical analysis in the software ArcGIS, for 275.916 points. In this analysis, the mean is -0.187m, the minimum and maximum values are -9.907m and 9.819m, respectively. The variance 14.43m and the standard deviation is 3.799m. In the ArcGIS software, instead, the mean is -0.281699m and the minimum and maximum values are -9.9999823m and 9.999424m, respectively. The standard deviation is 3.840385m.

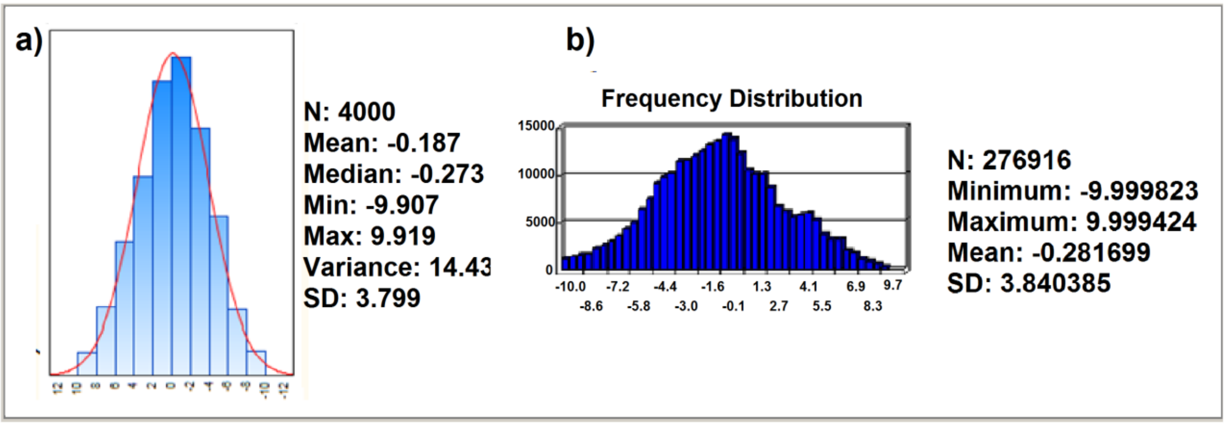

Figure 11: Statistics in the software Statistica (N=4000) versus software ArcGIS (N=275916).

The statistical computation for the absolute vertical accuracy of SRTM elevation data gave the values fluctuate from ± 0.7m to ±9.9m and correlation between DEM SRTM and GNSS data equal to 0.999528. This value indicates that the data are highly correlated, i.e., DEM SRTM and GNSS elevation data values are very similar and DEM SRTM validation is confirmed. For this study area, the 30m SRTM elevation data featured a greater absolute vertical accuracy compared to absolute vertical accuracy value of ±16m published in the SRTM data specification.

The height in Mirim Lagoon Hydrographic Basin ranges from 0 to 513m. Besides that, the lowest heights are located to the east and the highest ones to the north and northwest. Also, the slope ranges from 0 to 45%. However, values below 8% predominate, and the relief can be classified as flat to soft wavy (Scalco 2017).

Figure 12 shows the differences in heights between DEM SRTM and GNSS surveying in two sub-basins, considering different slopes and different heights. In the higher area, with a high slope, the differences mean is -2.803619m, and the standard deviation is 3.67703m (Figure 12A). In the lower and flat area (Figure 12B) the differences mean is 1.01889m and the standard deviation is 2.401044m. Although the results for lower and flat area were more accurate than the ones for the higher area, with a high slope, in both regions, the statistics show that DEM SRTM can be validated.

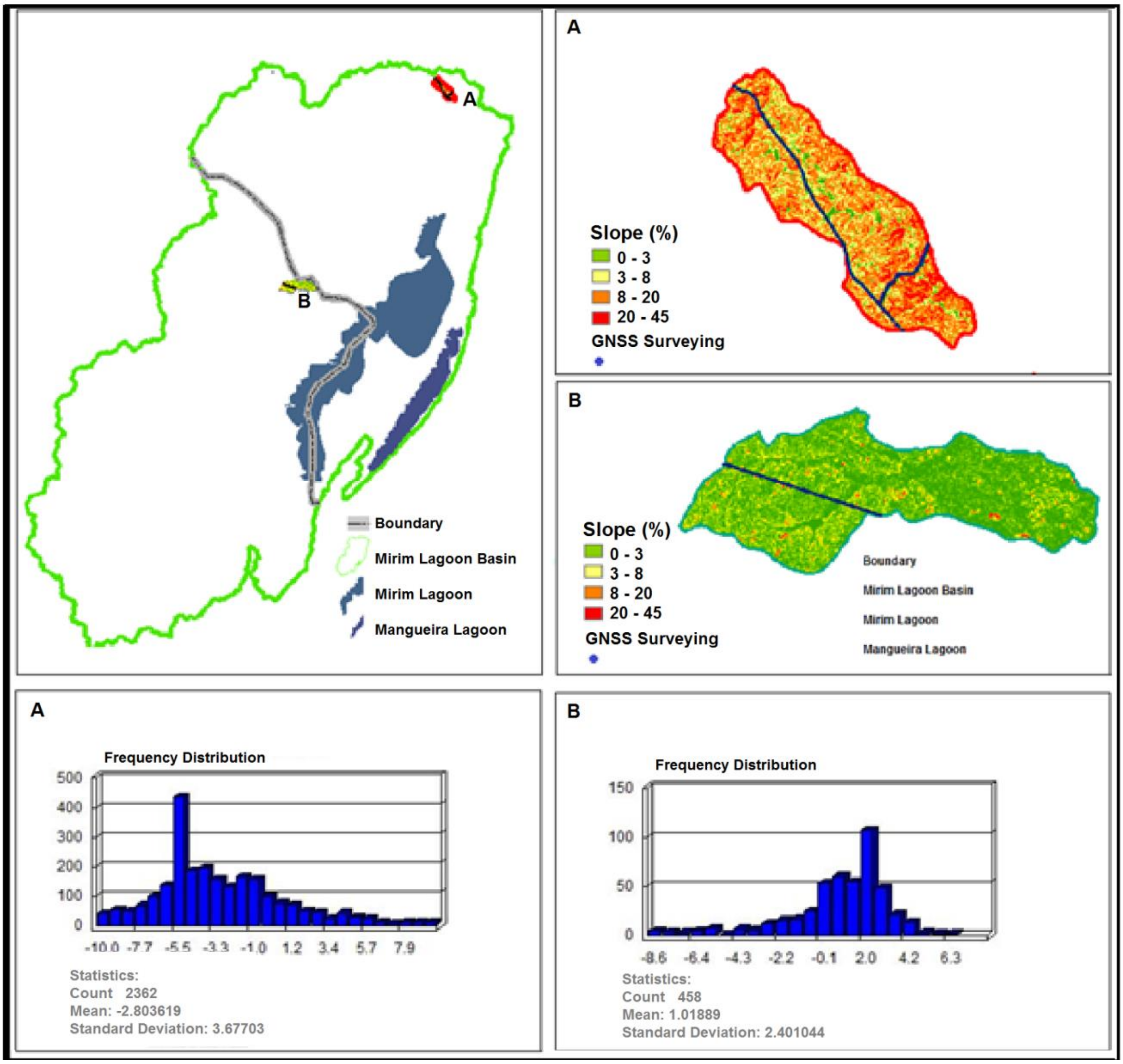

Figure 12: Difference of heights (DEM SRTM and GNSS Surveying) in regions of higher/high slope (A) and lower/flat area (B).

5. CONCLUSIONS

This paper shows the methodology adopted and the results of the analyses for validation of the vertical accuracy of the DEM SRTM through the kinematic positioning method based on GNSS in the region of Mirim Lagoon Hydrographic Basin. The objective of the research was reached using methodologies for GNSS data acquisition, post-processing of these data, the transformation of the geometric heights in orthometric heights, generation of DEM SRTM, extraction of the corresponding points in the DEM SRTM and, lastly, statistical analyses for results validation.

The vertical accuracy obtained for the 275916 control points coordinates, covering an area of 8407.78km^2, confirmed their suitability to validate the DEM SRTM. This accuracy was achieved using the kinematic relative positioning method, with a recording rate of 1 second and without reference stations for post-processing with the PPP method. It is important to mention that this methodology can be applied to cover large areas, when the reference stations are too far from the surveyed area or when different geodetic reference systems are involved (two or more countries for example).

The differences between the orthometric heights of the DEM SRTM and the GNSS survey have a minimum value of -9.9998m, the maximum value of 9.9994m and mean value equal to -0.2817m. Also, the correlation between DEM SRTM and GNSS data equal to 0.9995281 indicates that the data are highly correlated.

Considering that the main objective of the statistical analyzes was to verify if the absolute vertical accuracy of the DEM SRTM would exceed ±16m and the results showed that this vertical accuracy ranges from ± 0.7m to ±9.9m, one can affirm the model's validation. Besides that, even considering different slopes and different heights the statistics showed that DEM SRTM could be validated, in spite of the results for lower and flat area were more accurate than the ones for a higher area with high slope.

For the study area, the 30m DEM SRTM featured a much greater absolute vertical accuracy than the absolute vertical accuracy value of ±16m published in the SRTM data specification. Therefore, the results demonstrate that the methodology is suitable for the validation of the DEM SRTM of the Mirim Lagoon Hydrographic Basin.

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