Vertical Accuracy Assessment of ALOS PALSAR, GMTED2010, SRTM and Topodata Digital Elevation Models

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Keywords: DEM, Evaluation, Precision, Altitude, Brazilian Cartographic Accuracy Standard.

Abstract: Three-dimensional data of the Earth's surface can support several types of studies, such as hydrological, geomorphological, environmental monitoring, among many others. But, due to the difficulty of acquiring these data in the field, freely available Digital Elevation Models (DEM) have been widely used, and therefore, it is increasingly necessary to check their accuracy to ensure their correct applicability according to the appropriate scale. However, there are no studies which have assessed specifically the vertical accuracy of the ALOS PALSAR, GMTED2010, SRTM and Topodata DEMs according to Brazilian Cartographic Accuracy Standard (PEC). In this sense, this paper aims to evaluate the quality of the above-mentioned DEMs by using the official high accuracy altimetric network data of the Brazilian Geodetic System. Statistical analysis of errors results demonstrated that the DEMs have applications compatible with 1:100,000 scales or smaller than this, and although the GMTED2010 presented a lower accuracy than the other DEMs, it also could be classified in the same accuracy category according to the Brazilian PEC. We conclude that DEMs assessment is very important to ensure their correct application as they can be used in many researches since these data are available for practically all areas of the planet.

1 INTRODUCTION

Digital Elevation Model (DEM) is a generic term that comprises both the Digital Terrain Model (DTM), which represents the ground surface, and the Digital Surface Model (DSM), which represents the upper surface above the ground level, including trees, buildings and other natural or artificial objects (Polidori and El Hage, 2020). DEM consists of the terrestrial surface representation supposedly free of vegetation, buildings and other non-ground objects, despite this term is often used in a generic way to refer to DSM and DTM (Liu et al., 2015).

In the last years, several DEMs elaborated using various techniques have been made freely available to the community, thereby for better use of these products, it is important to analyse their accuracy aiming to identify their possible applications (Moura et al., 2014). The assessment of DEMs quality is a subject that requires further attention, and despite the importance of DEMs applications in several fields, there are no specific standardized guidelines concerning their accuracy assessment, which represents a challenge for this kind of geospatial technology users (Mesa-Mingorance and Ariza-López, 2020).

DEMs quality has been studied frequently to assess their wide range of applications and most of these studies consist of comparing the obtained data from DEMs and a set of reference data generally called control points (Polidori et al., 2014). According to these authors, this comparison, that is based on accuracy statistical indicators such as mean difference, standard deviation or root mean square error, is very important to evaluate the DEM positional accuracy and contributes to improving the mapping methods. Moreover, to ensure the reliability of the data extracted from a DEM, it is necessary to have very clear information about its coordinate system, its cartographic projection and its datum, as

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Ferreira, Z. and Cabral, P.
Vertical Accuracy Assessment of ALOS PALSAR, GMTED2010, SRTM and Topodata Digital Elevation Models.
DOI: 10.5220/0010404001160124
In *Proceedings of the 7th International Conference on Geographical Information Systems Theory, Applications and Management (GISTAM 2021)*, pages 116-124
ISBN: 978-989-758-503-6

well it is necessary to consider that horizontal positional accuracy errors can result in relevant vertical errors in the DEM, mainly in areas of steep slopes (Yap et al., 2019).

In Brazil, the quality of the cartographic products is regulated by the Decree n° 89,817 published in the year 1984, that establishes regulatory instructions for the technical standards of national cartography. Conforming to this decree, the cartographic products must be classified observing the Cartographic Accuracy Standard (Padrão de Exatidão Cartográfica - PEC), which is a dispersion statistical indicator relative to 90% probability and corresponds to 1.6449 times the Root Mean Square Error (RMSE). Thus, 90% of the collected points errors in the cartographic product must present values equal to or less than those predicted in the PEC when compared to its coordinates surveyed in the field by a high accuracy method (Brazil, 1984; 2016).

Many studies addressed DEMs accuracy assessment (Hu et al., 2017; Jain et al., 2018; Mouratidis and Ampatzidis, 2019; Varga and Bašić, 2015; Wessel et al., 2018); however, there are no studies which assessed specifically the vertical accuracy of the ALOS PALSAR, GMTED2010, SRTM and Topodata DEMs according to Brazilian Cartographic Accuracy Standard (PEC). In this sense, this paper aims to evaluate the vertical quality of the above-mentioned DEMs by using the official high accuracy altimetric network data of the Brazilian Geodetic System. Therefore, it is expected that the obtained results from this comparison contribute to the correct applicability of the analysed DEMs according to an appropriate use scale in the country.

2 METHODOLOGY

2.1 Study Area

The Balsas River watershed is inserted in thirteen municipalities and occupies an area of 12,352.5 km², that corresponds to about 4.5% of the total area of the State of Tocantins (Figure 1) (Brazil, 2012). This watershed altitudes are approximately between 200 and 800 meters considering the average sea level, that represents more than 600 meters of altimetric amplitude as can be seen in Figure 2. Inside Balsas River watershed area were identified 105 stations of the official Brazilian altimetric network which are located along the main roads of the region (Figure 2).

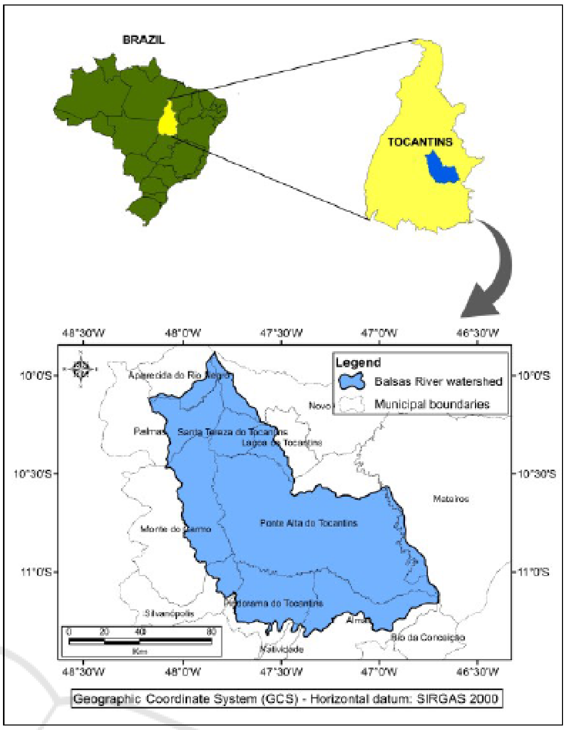

Figure 1: Geographical location of the study area.

To evaluate the DEMs, we used the official high accuracy altimetric network data of the Brazilian Geodetic System available as orthometric altitudes. Composed by altimetric geodesic stations implanted along with the road network throughout the Brazilian territory, this network was established in 1945 by using the high accuracy geometric levelling method. In order to ensure the integrity, consistency, and reliability of the Geodetic Database information, level references altitudes are recalculated periodically due to the incorporation of new levelling lines and the development of new data measurement and processing techniques. According to these altimetric data last quality assessment carried out in 2018, 87.5% of the adjusted geopotential values showed standard deviations between 6 and 10 centimeters (IBGE, 2019).

2.2 Data

The satellite observation program Advanced Land Observing Satellite (ALOS) was created to support mapping of land coverage, disaster monitoring, and resource surveying (JAXA, 2020a). In 2006, ALOS satellite was launched from the Tanegashima Space Center with three sensors onboard: Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM), Advanced Visible and Near Infrared

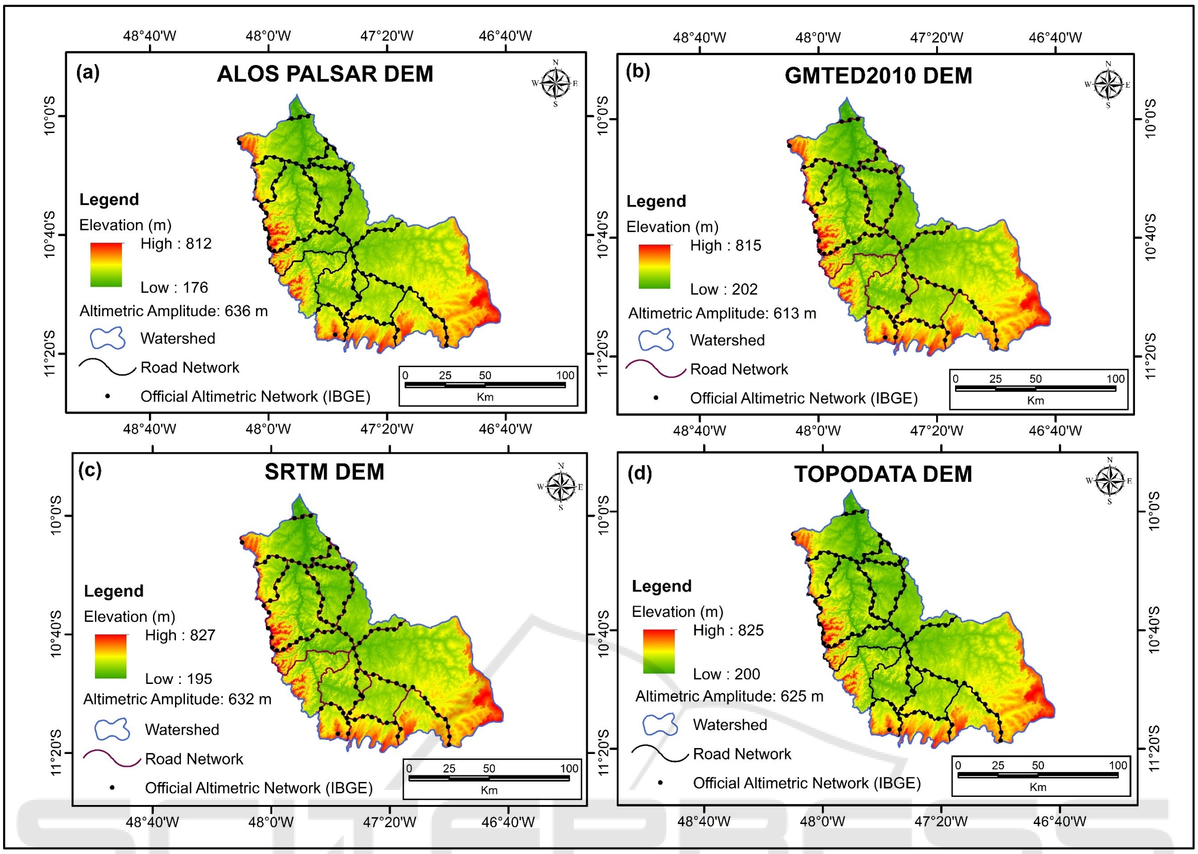

Figure 2: Hypsometric maps of Balsas River watershed elaborated from the DEMs: (a) ALOS PALSAR, (b) GMTED2010, (c) SRTM and (d) Topodata.

Radiometer type 2 (AVNIR-2), and Phased Array type L-band Synthetic Aperture Radar (PALSAR) (JAXA, 2020a). The PRISM sensor is a panchromatic radiometer with 2.5 meters spatial resolution at nadir and is composed of a set of three optical systems which produces stereoscopic images providing a high accuracy digital surface model (JAXA 2020b). AVNIR-2 sensor is a visible and near-infrared radiometer aimed at mapping land use and coverage that provides images with 10 meters spatial resolution, and PALSAR is an active microwave sensor capable of obtaining daytime and night-time terrestrial observation without cloud interference (JAXA, 2020b).

The PALSAR images acquired during the ALOS mission were corrected geometrically and radiometrically (Laurencelle et al., 2015). The geometric distortions were first corrected with the use of a DEM and, later, the radiometry adjustment was executed in the affected foreshortening and layover regions. After radiometric terrain correction, the products were distributed using two resolutions. Some products generated from high-resolution DEM (NED13) were distributed with a 12.5 meters pixel size, and others generated from mid - resolution DEMs (SRTM 30 m, NED1 and NED2) have a 30 meters pixel size (Laurencelle et al., 2015).

The Shuttle Radar Topography Mission (SRTM) was executed onboard of the Space Shuttle Endeavour during 10 days in February 2000 by using two radar antennas to collect topographic data over nearly 80 percent of Earth's land surface. The SRTM international project was developed with the partnership of the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA) providing the first-ever near-global data set of land elevations (NASA, 2020). In 2003, the SRTM data were made available for many parts of the world with an accuracy of 3 arc-seconds which corresponds to about 90 meters. But, in 2014, all global SRTM data have been released with the original measurements full resolution equivalent to 1 arc-second, or 30 meters (NASA, 2020).

The Topodata project consists of a topographic database elaborated through the refinement of the

SRTM data resolution from 3 arc seconds (90 meters) to 1 arc second (30 meters) by kriging techniques (Valeriano and Rossetti, 2012). This project was developed to provide geomorphometric data from all over the Brazilian territory due to the unavailability of cartographic products in scales suitable for some regions.

Released in 2008 and after being successively inspected and revised, the Topodata project offers local geomorphometric variables corresponding to basic elements based on techniques of interpretation and relief analysis. Thus, this project presents variables such as slope, slope orientation, horizontal curvature, vertical curvature and inputs for the design of the drainage structure resulting in the generation of an extensive database structured for free use by the scientific community (Valeriano, 2008).

The Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) is a digital terrain model developed with the collaboration between the United States Geological Survey (USGS) and the National Geospatial-Intelligence Agency (NGA) providing global coverage of all land areas from latitude 84°N to 56°S for most products (Danielson and Gesch, 2011). This model is based on data derived from 11 raster elevation sources (Table 1) and it has been generated at three different resolutions of approximately 250, 500, and 1,000 meters, that equal to 7.5, 15 and 30 arc-seconds, respectively (Danielson and Gesch, 2011). Table 2 shows the original main characteristics of each DEM evaluated in this paper.

Table 1: GMTED2010 - Input source data characteristics adapted from Danielson and Gesch (2011).

Dataset	Resolution	Horizontal unit	Horizontal datum
SRTM DTED® 2	1	Arc-second	WGS 84
DTED® 1	3	Arc-second	WGS 84
CDED1	0.75	Arc-second	NAD 83
CDED3	3	Arc-second	NAD 83
15-arc-second SPOT 5 Reference3D	0.00416666	Decimal degree	WGS 84
NED	0.00027777	Decimal degree	NAD 83
NED – Alaska	0.00055555	Decimal degree	NAD 83
GEODATA 9 second DEM version 2	0.0025	Decimal degree	GDA 94
Greenland satellite radar altimeter DEM	1,000	Meter	WGS 84
Antarctica satellite radar and laser altimeter DEM	1,000	Meter	WGS 84
GTOPO30	0.00833333	Decimal degree	WGS 84

(DTED®, Digital Terrain Elevation Data; WGS 84, World Geodetic System 1984; CDED, Canadian Digital Elevation Data; NAD 83, North American Datum of 1983; SPOT, Satellite Pour l'Observation de la Terre; NED, National Elevation Dataset; DEM, digital elevation model; GDA 94, Geocentric Datum of Australia 1994; GTOPO30, Global 30-Arc-Second Elevation Dataset).

Table 2: Original characteristics of the evaluated Digital Elevation Models.

DEM	Coordinate System	Horizontal Datum	Vertical Reference	Spatial Resolution	Radiometric Resolution
ALOS PALSAR	UTM	WGS 84	Ellipsoid*	12.5 meters	16 bits (signed integer)
GMTED2010	Geographic	WGS 84	Geoid (EGM96)	231 meters (7.5 arc-seconds)	16 bits (signed integer)
SRTM	Geographic	WGS 84	Geoid (EGM96)	30 meters (1 arc-second)	16 bits (signed integer)
Topodata	Geographic	WGS 84	Geoid (EGM96)	30 meters (1 arc-second)	32 bits (floating point)

*The orthometric heights with EGM96 vertical datum were converted to ellipsoid heights using the ASF MapReady tool named "geoid_adjust" (Laurencelle et al., 2015).

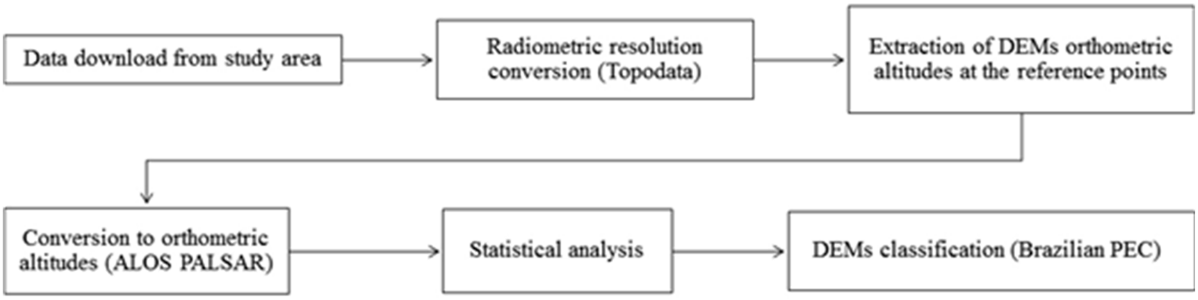

Figure 3: Flowchart of methodology.

Table 3: Statistical analysis of the altitude difference between control points and DEMs.

	ALOS PALSAR	**GMTED2010**	**SRTM**	**Topodata**
Mean Error (m)	12.70	13.31	12.82	12.87
RMSE (m)	4.95	7.48	4.76	5.38
H_E *min* (m)	-3.58	-14.22	-3.21	-6.17
H_E *max* (m)	22.04	39.78	20.93	23.60
Error Amplitude (m)	25.62	54.00	24.14	29.77

2.3 Methods

Figure 3 shows the flow chart of the methodology used in this study. The first step was to download the data from the study area, such as raster DEMs and points official Brazilian altimetric network. To standardize the data, it was necessary to convert the radiometric resolution of the Tododata DEM from 32 bits (floating point) to 16 bits (signed integer). The next step consisted of extracting the altitudes of the ALOS PALSAR, GMTED2010, SRTM and Topodata DEMs at the coordinates of the reference points (official altimetric network). But as GMTED2010, SRTM and Topodata models were available with altitudes referenced to the geoid (EGM96), then it was necessary to convert the ellipsoidal altitudes of the ALOS PALSAR DEM to orthometric altitudes (geoid) using the MAPGEO2015 software (IBGE, 2015), which is developed by Brazilian Institute of Geography and Statistics in partnership with Polytechnic School of the University of São Paulo.

Subsequently, as well as in previous studies (Jain et al., 2018; Varga and Bašić, 2015; Wessel et al., 2018), statistical analysis of the errors was performed, where were calculated some accuracy statistical indicators such as Altimetric Error (HE) (1), Mean Error (ME) (2), and Root Mean Square Error (RMSE) (3). We also used the Brazilian Cartographic Accuracy Standard (PEC) to evaluate each DEM and to identify their best application scale. It is important to highlight that this methodology has been used in several similar studies such as Moura et al. (2014) and Iorio et al. (2012).

$$\mathrm{H_E} = \mathrm{H}_{REF} - \mathrm{H}_{DEM} \tag{1}$$

$$\mathrm{ME} = \sum_{i=1}^{n} \frac{(\mathrm{H}REF \; - \; \mathrm{H}DEM)}{n} \tag{2}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (\mathrm{HE} - \mathrm{ME})^2}{n}} \tag{3}$$

Where H_E = altimetric error; H_{REF} = reference point altitude from Brazilian geodetic system official altimetric network; H_{DEM} = altitude extracted from DEM at reference point coordinates; ME = Mean Error; RMSE = Root Mean Square Error; and n = number of reference points.

3 RESULTS

Table 3 shows the main results of the statistical analysis performed in this study where it is possible to verify that regarding the mean error, the values did not differ much. ALOS PALSAR DEM was the one with the lowest RMSE (4.76 m) and GMTED2010 was the one with the worst RMSE (7.48 m). As for the amplitude of the altimetric error, given by the difference between the minimum and maximum altimetric errors, SRTM presented the smallest result (24.14 m) whilst GMTED2010 presented the largest amplitude (54.00 m). Figure 4 shows the altimetric error distribution of each DEM where it is possible to notice a positive distortion in all DEMs, as well as a higher variability of errors in the GMTED2010 product.

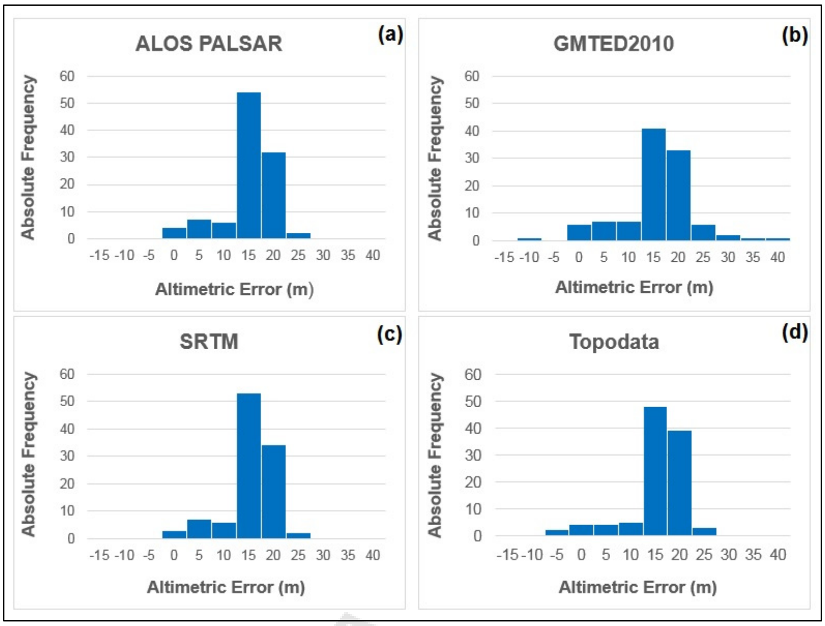

Figure 4: Histogram of the altimetric error for ALOS PALSAR (a), GMTED2010 (b), SRTM (c) and Topodata (d).

Table 4: Altimetric Cartographic Accuracy Standard of the Quoted Points and the Digital Terrain Model, Digital Elevation Model and Digital Surface Model for Digital Cartographic Products production (Brazil, 2016).

SCALE	**1:25,000**		**1:50,000**		**1:100,000**		**1:250,000**	
PEC Class	PEC* (m)	RMSE (m)	PEC* (m)	RMSE (m)	PEC* (m)	RMSE (m)	PEC* (m)	RMSE (m)
A	2.70	1.67	5.50	3.33	13.70	8.33	27.00	16.67
B	5.00	3.33	10.00	6.66	25.00	16.66	50.00	33.33
C	6.00	4.00	12.00	8.00	30.00	20.00	60.00	40.00
D	7.50	5.00	15.00	10.00	37.50	25.00	75.00	50.00

*90% of point errors collected in the cartographic product, when compared with its coordinates surveyed in the field by a high precision method, must present the same values or less than the predicted in this table.

Table 5: Extracted points from the DEMs (quantity and percentage) which showed altimetric errors below 15 and 25 meters.

DEM	H_E **< 15m**		H_E **< 25m**		
	Points	**%**	**Points**	**%**	**RSME (m)**
ALOS PALSAR	71	67.6	105	100	4.95
SRTM	69	65.7	105	100	4.76
Topodata	63	60.0	105	100	5.38
GMTED2010	62	59.0	101	96.2	6.54

Table 4 presents the altimetric cartographic accuracy standard for digital cartographic products production and Table 5 shows the quantity and percentage of extracted points from the DEMs which presented altimetric errors below 15 and 25 meters.

Analysing the obtained results, it can be observed that the DEMs assessed in this study may be included in Class B for the 1:100,000 scale and in Class A for the 1:250,000 scale (Table 6), since more than 90% of the extracted points from DEMs assessed showed altimetric errors less than 25 meters when compared to the reference points. In this sense, these DEMs can satisfactorily support studies that need a level of detail compatible with scales 1:100,000 or smaller than this considering the national cartographic standard specifications.

Table 6: DEMs classification according to Altimetric Cartographic Accuracy Standard for Digital Cartographic Products.

Scale	ALOS PALSAR	GMTED2010	SRTM	Topodata
1:100,000	B	B	B	B
1:250,000	A	A	A	A

4 DISCUSSION

This study assessed the vertical accuracy of the ALOS PALSAR, GMTED2010, SRTM and Topodata DEMs according to Brazilian Cartographic Accuracy Standard aiming to contribute to the correct applicability of the analysed DEMs in the study area and in similar areas. It was possible to verify that all DEMs analysed here presented satisfactory accuracy to supply mappings in 1:100,000 scales or smaller than this, and although the GMTED2010 presented a lower accuracy than the other DEMs, it also could be classified in the same accuracy category according to the Brazilian PEC, but it should be emphasized that studies carried out in other areas may present different results.

Previous studies have shown that ALOS PALSAR DEM performed better when compared to other DEMs, such as SRTM and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (Arabameri et al., 2019; Rabby et al., 2020). However, Andrades Filho and Rossetti (2012) stated that SRTM products have a higher potential for delineating morpho-structural lineaments when compared to ALOS PALSAR. Thomas et al. (2014) also attested a relatively higher accuracy of SRTM when compared to ASTER and GMTED2010, where it was also found that GMTED2010 showed the worst results due to its larger pixel size (Thomas et al., 2015). Nonetheless, the results presented by Mantelli et al. (2011) demonstrated a better quality of the Topodata product in relation to SRTM and ASTER in the characterization of drainage networks and watershed vectors due to its refined resolution.

Regarding the Brazilian cartographic accuracy standard, the results presented by Moura et al. (2014) showed compatibility with the scale of 1:50,000 for the Topodata, SRTM, ASTER and HydroSHEDS DEMs for watersheds with little rugged relief, but for watersheds with higher slopes and higher drainage density, the results showed compatibility with scales of 1:100,000 and smaller than this.

The present study demonstrated that the evaluated DEMs have applications compatible with 1:100,000 scales since more than 90% of the extracted points from them showed differences less than 25 meters in the altitudes when compared to the reference points extracted from the high accuracy altimetric network of the Brazilian Geodetic System. In fact, ALOS PALSAR, SRTM and Topodata DEMs presented 100% of altimetric errors less than 25 meters and only GMTED2010 DEM presented 3.8% of altimetric errors higher than 25 meters.

5 CONCLUSIONS

After analysing several DEMs comparative studies, we conclude that this kind of assessment is very important to ensure their correct applicability regarding the appropriate scale since these data are available for practically all areas of the planet. Although, there are often no precise data available for free that can make these comparisons possible, such as, for instance, the control points of the high accuracy altimetric network used in this study, thus making fieldwork indispensable.

Indeed, one of the limitations in this research was the small number of points located within the area of the Balsas River watershed which were not evenly distributed as they were implanted linearly along the banks of the Brazilian highways. But it is worth mentioning that the availability of these data from the Brazilian altimetric network facilitates the DEMs assessment since it enables an accurate data analysis without the need for fieldwork.

Particularly in this study, we found that all four assessed DEMs can support several types of researches provided they do not require a high level of detail and can be represented in scales up to 1: 100,000. However, future DEMs assessments should be based on the accuracy of a specific application, such as hydrodynamics modelling as well as they should investigate the correlation between altimetric error and slope (or altitude) in the study area.

ACKNOWLEDGEMENTS

This study was supported by national funds through FCT *(Fundação para a Ciência e a Tecnologia)* under the project UIDB/04152/2020 - *Centro de Investigação em Gestão de Informação* (MagIC) and the *Instituto Federal de Educação, Ciência e Tecnologia do Tocantins (Campus Palmas)*.

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