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ORIGINAL ARTICLE

VERTICAL ACCURACY ASSESSMENT OF THE PROCESSED SRTM DATA FOR THE BRAZILIAN TERRITORY

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Abstract:

This research aims to determine the vertical accuracy of the Interferometric Digital Elevation Model (DEM) obtained from the processed Shuttle Radar Topographic Mission (SRTM) data. The research compared the SRTM-GL1 (Shuttle Radar Topographic Mission-Global 1) with 30-meter resolution and the following 90-meter resolution models: (a) EMBRAPA; (b) Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales (HydroSHEDS) (HydroSHEDS), provided by the United States Geological Survey (USGS); (c) Consultative Group for International Agricultural Research-Consortium for Spatial Information (CGIAR-CSI); and (d) Jonathan de Ferranti. The accuracy analysis considered the diverse Brazilian regions, adopting 1,087 field points from the Global Navigation Satellite System (GNSS) trackers or topography methods. The Jonathan de Ferranti model achieved the best accuracy with RMSE of 9.61m among the 90-meter resolution models. Most SRTM models at 1:100,000 scale reached Grade A of the Cartographic Accuracy Standard. However, the accuracy at the 1: 50,000 scale did not achieve the same performance. SRTM errors are linearly related to slope and the most significant errors always occur in forest areas. The 30-meter resolution SRTM showed an accuracy of around 10% better (RMSE of 8.52m) than the model of Jonathan de Ferranti with 90-meter resolution (RMSE of 9.61m).

Keywords: SRTM mission, vertical accuracy, interferometry, digital elevation model.

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1. Introduction

The Shuttle Radar Topography Mission (SRTM) is one of the most widely used altimetric data sources in the world, due to its quality and global coverage (Reuter et al. 2007). The SRTM mission, developed by the National Aeronautics and Space and Administration (NASA) and National Geospatial-Intelligence Agency (NGA), obtained topographic data on 80% of the Earth's surface between parallels 60° N and 56° S during 11 days (Lehner et al. 2006). The SRTM data has spatial resolutions of 90m or 30m, but the latter was only available from the end of September 2014 (Brochado 2015) and is not the object of this study. The 90-meter SRTM is superior to the Global 30 Arc-Second Elevation (GTOPO30) model, previously available at 1-km resolution (Azizian et al. 2015). Several institutions have processed SRTM data with the purpose of improving their quality, such as National Center for Satellite Monitoring Research of the Brazilian Company of Agricultural Research (EMBRAPA) (Miranda 2005) and TOPODATA data provided by the National Institute for Space Research (INPE) (Valeriano 2008). The free availability of processed SRTM data by government agencies expands its use (Bias et al. 2010; Iorio et al. 2012). Therefore, SRTM data has been used in different applications such as flood areas (e.g., Suwandana et al. 2012), glacier inventories (e.g., Frey and Paul 2012), karst depression detection (e.g., Siart et al. 2009; de Carvalho Júnior et al. 2014), and geomorphological mapping (e.g., Vasconcelos et al. 2014; Sena-Souza et al. 2016), among others.

Several scientific studies have evaluated the SRTM accuracies in several regions of the world, using different methods such as topographic measurements, GNSS tracking, and cartographic bases (e.g., 1:10,000 or 1:25,000) obtained by photogrammetric, laser or satellite data (Figure 1 and Table 1). However, most of the SRTM mission data accuracy assessments considered small regions, with few works at a global or regional scale. Besides, few papers compare the models provided by research institutions. Therefore, the primary motivation of this research is the lack of comparative studies on the accuracy of the various models of digital terrain based on the SRTM data considering the extension of the Brazilian territory.

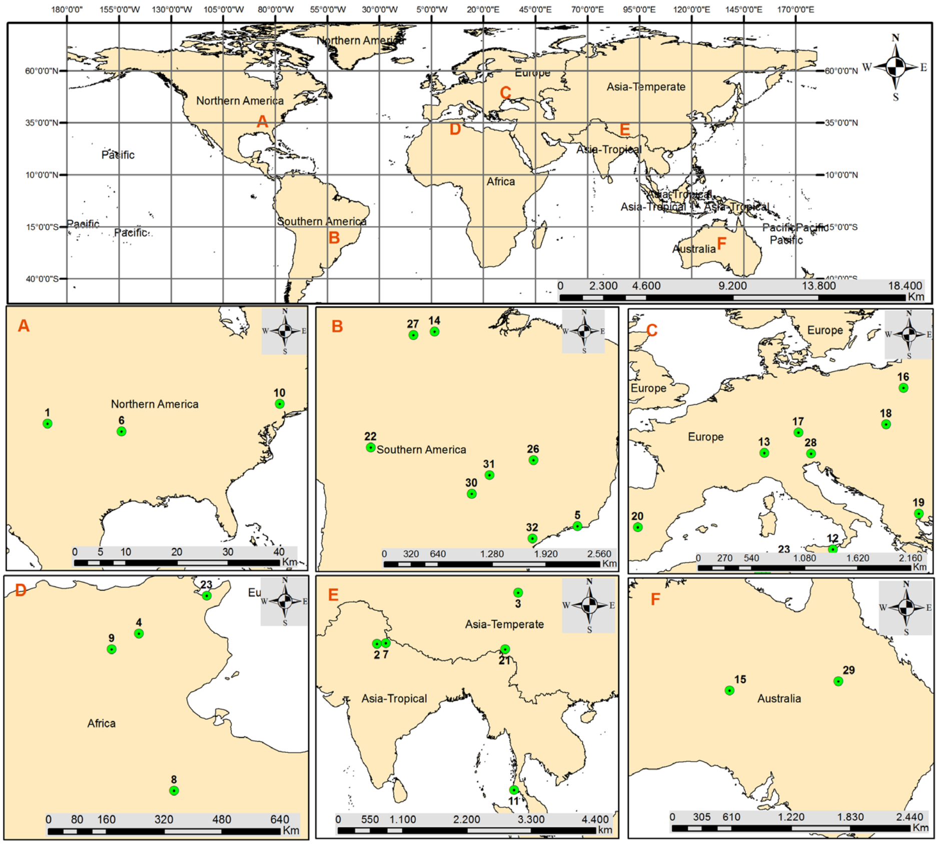

Figure 1: Study sites on SRTM accuracy. ●– location of the studies described in Table 1.

The present article aims to identify and compare the vertical accuracy of the SRTM model from different sources for the Brazilian territory according to the National Standard for Cartographic Accuracy (Padrão de Exatidão Cartográfica - PEC) described in Decree 89.817/84, which establishes the general norms of Brazilian cartography (Brasil 1984). Specifically, the research intends: (1) adoption of 1,087 field measurements distributed in Brazil to obtain a spatial representation of the altimetric accuracy; (2) comparison of different treated SRTM data; (3) PEC classification considering a spatial distribution by four degrees of latitude; and (4) evaluation of the slope and vegetation influence in model accuracy.

Table 1: Summary of SRTM data accuracy studies in Figure 1. SD - standard deviation, ME – mean error, and RMSE - root-mean-square error.

	Referência	**Local**	**Modelo**	**Insumo**	Resultados
0	Berry et al. (2007).	Global	SRTM V2	Satélite ERS-1.	ME: 3.60m; SD: 16.16m.
1	Shortridge and Messina (2011).	EUA	SRTM-V2	National Elevation Dataset (NED)	ME: 2.0 m; SD: 8.3 m.
2	Mukherjee et al. (2013).	Shiwalik Himalaya	CGIAR-CSI SRTM v4.1	Ground Control Points (GCPs)	ME: −2.94 m RMSE: 9.20m.
3	Liu (2008).	China	NASA SRTM3	Topographic map 1:25.000	ME: -6.635m; SD: 29.16 m.
4	Chaieb et al. (2016)	Kasserini, Tunisia	SRTM v4.1	Ground Control Points (GCPs)	ME: -1.85 m; SD: 9.41m.
5	Miceli et al. (2011).	Rio de janeiro, Brazil	SRTM 1	Topographic map 1:10.000.	90% less than 15m; RMSE de 8.86m.
6	Robinson et al. (2014).	EUA	CGIAR-CSI SRTM v4.1	Ground Control Points (GCPs)	ME: 1.66 m; RMSE 4.15m.
7	Datta and Kirchner (2010)	India	SRTM University of Maryland.	Ground Control Points (GCPs)	ME: -12.56m; SD: 51.37m.
8	Athmania and Achour (2014).	Anaguid, Tunisia	CGIAR-CSI SRTM v4.1	RTK-DGPS	ME: 2.9 m; SD: 4.6m.
9	Athmania and Achour (2014).	Tebessa, Tunisia	CGIAR-CSI SRTM v4.1	RTK-DGPS	ME: 0.48 m; SD: 8.4m.
10	Gorokhovich and Voustianiouck (2006).	Catskill Mountains, EUA	CGIAR-CSI SRTM	Ground Control Points (GCPs)	ME: 7.58 m; SD: 8.09m.
11	Gorokhovich and Voustianiouck (2006).	Phuket, Thailand.	CGIAR-CSI SRTM	Ground Control Points (GCPs)	ME: 4.07 m; SD: 4.01m.
12	Tarquini et al. (2012).	Italy	SRTM-JPL-NASA	LIDAR	RMSE: 7.78m
13	Frey and Paul (2012).	Switzerland	SRTM3	DHM25 (swisstopo).	ME: 2.23 m; SD: 21.64m.
14	Miceli et al. (2011).	Amazon, Brazil	SRTM 1	Ground Control Points (GCPs)	90% less than 25.00m; RMSE: 11.70m.
15	Rexer and Hirt (2014)	Australia	CGIAR-CSI SRTM v4.1	Ground Control Points (GCPs)	ME: 3.04 m; SD: 3.22m.
16	Karwel and Ewiak (2008)	Poland	SRTM	Ground Control Points (GCPs)	RMSE: 2.9m (plan); RMSE= 5.4m (mountain)
17	Jörn and Diana (2008)	Southern Germany	SRTM-JPL-NGA	Ground Control Points (GCPs)	SD: 3.90m.

Continue...

Table 1: Continuation.

	Referência	**Local**	**Modelo**	**Insumo**	Resultados
18	Natalia and Jacek (2014)	Poland	SRTM -v4	DEM-Cartographic Inventory	ME: 4.31 m; SD: 14.09m.
19	Antonios et al. (2010)	Greece	SRTM v4	KGPS coletados com veículo (GPS).	ME: 0.30 m; SD: 6.40m.
20	Alvaro et al. (2011)	Spain	SRTM v4.1	Topographic map 1:10.000	RMSE: 6.10m
21	Wang et al. (2012)	Tibet	CIGIAR_ SRTM	Topographic map 1:50.000	ME: 5.3 m; SD: 12.2m.
22	Mukul et al. (2015)	South America	SRTM v4.1	Ground Control Points (GCPs)	ME: 5.2m; RMSE:11.2m.
23	Ouerghi et al. (2015)	Grombalia, Tunisia	SRTM v4.1	Topographic map 1:25.000	ME: 0.76 m; SD: 47.46m.
24	Suwandana et al. (2012).	Indonesia	SRTM v4.1	RTK-DGPS	RMSE: 3.250m
25	Mukul et al. (2015)	Global	SRTM v4.1	Ground Control Points (GCPs)	ME: 8.0 m; SD: 8.3m.
26	Moura et al. (2014)	Federal District, Brazil	SRTM v4	Topographic map 1:10.000	ME: 3.14 m; SD: 4.06m.
27	Santos et al. (2006)	Amazon, Brazil	SRTM-3	Ground Control Points (GCPs)	SD: 11.06m.
28	Ludwig and Schneider (2006)	Germany	SRTM	Topographic map 1:25.000	ME: 11.98 m; RMSE: 36.21m.
29	Jarihani et al. (2015)	Australia	SRTM (30/90m)	Ground Control Points (GCPs)	SD: 1.84m
30	Iorio et al. (2011)	Pantanal, Brazil	SRTM v4	Ground Control Points (GCPs)	RMSE: 16.69m
31	Medeiros et al. (2009)	Goiás, Brazil	SRTM-EMBRAPA	Ground Control Points (GCPs)	ME: -3.0m; SD:10.0m.
32	Nobrega et al. (2005)	São Paulo Brazil	SRTM	Photogrammetry 1:8.000	ME: 14.23m; SD:13.73m.

2. Materials and Methods

2.1 Acquisition and Distribution of Field Data

The Brazilian territory was divided into intervals of four-degree latitudes to obtain a homogeneous distribution of the field data and to minimize the occurrence of vast areas without data, making it similar to the division achieved in the Brazilian systematic mapping at 1:1,000,000 scale (IBGE 2016). The selection included the maximum UTM zones that cover the Brazilian territory: 20, 21, 22, 23 and 24 (Figure 2). The selected regions sought to include different levels of altitudes. The highest measured point was in the height of 829.09 meters and the lowest at the elevation of 0.74 meters.

The data used were obtained from the Documentation Center of the Brazilian Electricity Regulatory Agency (ANEEL), where the projects of hydroelectric plants or hydroelectric inventories approved are archived (ANEEL 2009).

The measured points in the field came from GNSS (Global Navigation Satellite System) trackers to support photogrammetric restitutions or topographic survey. The data selection considered zones with 4 degrees of latitude for Brazil. The field points were converted to a single reference system, SIRGAS2000. The SRTM evaluation adopted at least 50 field points for each latitude zone.

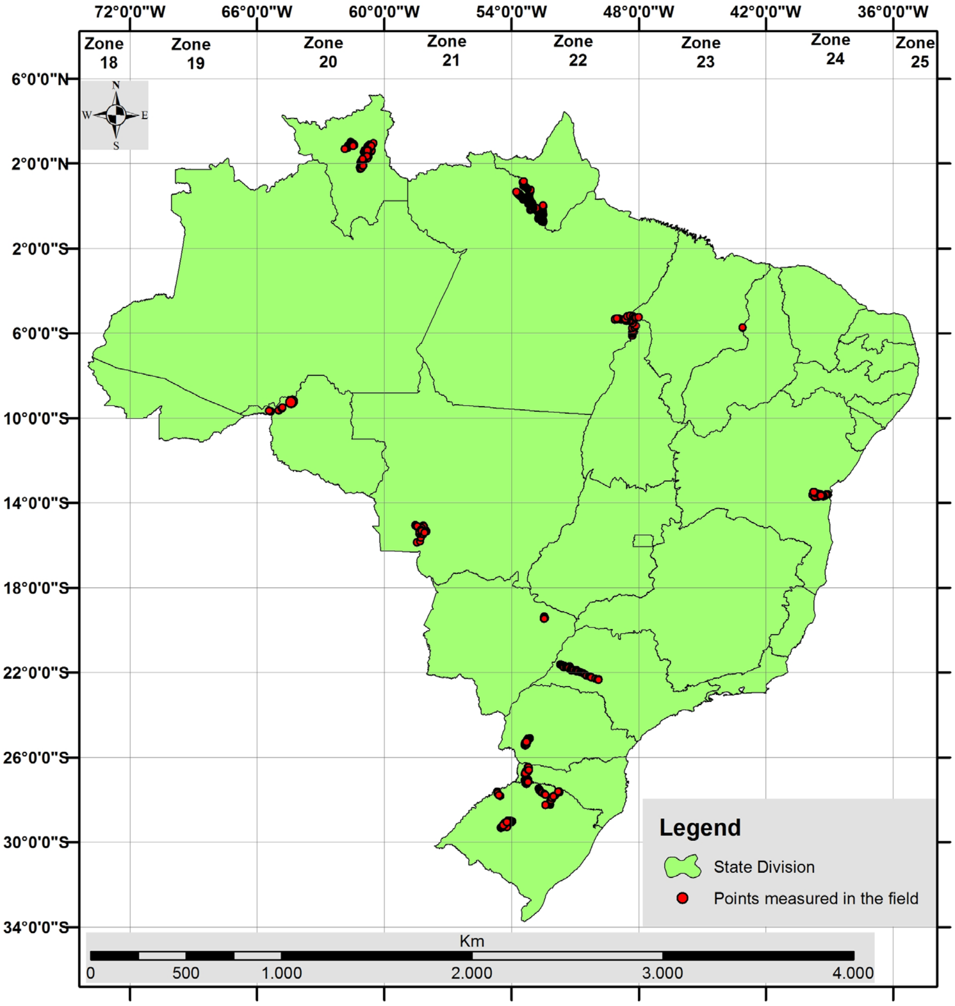

Figure 2: Division of Brazil in zones with 4 degrees of latitude (SIRGAS2000, UTM), containing location of the points measured in the field.

2.2 Digital Elevation Models Evaluated and Data Processing

The present research used the SRTM-GL1 with 30-meter resolution and the following processed SRTM models with 90-meter resolution: (a) EMBRAPA (Miranda 2005); (b) Shuttle Elevation Derivatives at multiple Scales (HydroSHEDS) (Lehner et al. 2006); (c) Consultative Group for International Agricultural Research-Consortium for Spatial Information (CGIAR-CSI) version 4.1 (CGIAR-CSI 2016); and (d) Jonathan de Ferranti (Ferranti 2016). The SRTM from the National Center for Satellite Monitoring Research of EMBRAPA has a GeoTIFF format that covers an area of 1º (latitude) by 1º30 ‘(longitude), containing correction of spurious depressions, anomalous peaks and lack of data. The HydroSHEDS model is a hydrologically conditioned DEM, providing data such as drainage lines, river basin boundaries, and stream topology (Lehner et al. 2006; Dasgupta 2011; Lehner 2012). HydroSHEDS data is available in raster format in grids of 5x5 degree. The CGIAR-CSI Model (version 4.1) is available in GeoTIFF format in regions with equal grid size (5x5 degrees), having a void-filling procedure and applications for the slope calculation, flood modeling and obtaining elevations of mountains (Wang et al. 2012; Kolecka and Kozak 2014; Rexer and Hirt 2014). The Jonathan de Ferranti model is available in the HGT file, containing 1x1 degree data titles and void filling mainly in mountainous regions (Tait 2010). The SRTM-GL1 at a global scale is available in the HGT file (1x1 degree grid), comprising an improved spatial resolution of 30 meters (NASA JPL 2013; Watkins 2018).

The different SRTM models were reprojected for the same SIRGAS2000 Reference System. A Triangulated Irregular Network (TIN) was generated from the SRTM model (raster format) to calculate the altitude of the measured in the field. The option by the TIN method was its suitability to represent altimetry variations (Fernandes and Menezes 2005). With the two orthometric altitudes, the error is the simple difference between the SRTM and the respective field values and the root mean squared error (RMSE) is the standard deviation of the errors.

The RMSEs of the SRTM models are compared with the tabulated values of the PEC to establish the accuracy class. The PEC (Decree nº 89.817/1984; Brazil 1984) establishes three accuracy classes according to the scale of the map: "A", "B", and "C"; where "A" is the most accurate product. Table 2 lists the PEC classification for the 1: 50,000 and 1: 100,000 scales. This approach enables a comparison with other studies (Santos et al. 2006; Miceli et al. 2011).

Besides, we evaluated the elevation errors from slope and vegetation type, considering the best SRTM model (90m) among the four tested. The slope analysis considered the mean absolute error within the following slope intervals (<1%, 1-5%, 5-10%, 10-20% and> 20%). A regression analysis between the mean absolute errors and mean slope within each interval sought to define a rate of slope-induced error from SRTM altimetry (Gorokhovich and Voustianiouk 2006; Rexer and Hirt 2014). The SRTM C- and X- bands have limitations to reach the bare ground in the presence of a forest canopy (Walter et al. 2007). Therefore, the SRTM vertical accuracy depends on vegetation characteristics (tree height, density, branching angle, among others) (Brown et al. 2010; Pinel et al. 2015). In this research, we evaluated the type of vegetation for the points of greatest errors.

Table 2: PEC values for classes "A", "B" and "C" at 1:100,000 and 1:50,000 scales. Data source: decree nº 89.817 / 84 (Chai and Draxler 2014; Santos 2010).

	1:50,000		1:100,000	
	Tolerance	RMSE	Tolerance	RMSE
A	90% of points <10.0m	6.6m	90% of points <25.0m	16,6m
B	90% of points <12.0m	8.0m	90% of points <30.0m	20,0m
C	90% of points <15.0m	10.0m	90% of points <37.5m	25,0m

3. Results

3.1 Statistical Analysis of Errors and PEC Classification

SRTM vertical accuracy varied considerably among the models evaluated, with a significant difference of the RMSE in the 14ºS-10ºS range between the CGIAR-CSI model (18.43m) and Jonathan de Ferranti (9.61m) (Table 3). The RMSE of HydroSHEDS (12.68 m) showed a little different to values found by Santos et al. (2006) of 11.066m in the Amazon Region (between 02ºS and 02ºN). The SRTM model, regardless of data source, did not show a constant variation in the field measurements. The Jonathan de Ferranti's model presented the lowest values of the RMSE in 7 of the 9 latitude intervals. Compared with the researches developed in South America, the result has a higher similarity with the Mukul et al., (2015) (RMSE of 11.2m). These results may have been influenced by the type of data used. Mukul et al., (2015) compared with field points (GCPs) like the present study.

The PEC classification considered two types of analysis: one local (Latitude bands) and another general (all Brazil) (Table 4). The models at a scale of 1:100,000 showed a PEC classification of “A” predominantly in the local analysis (with few exceptions acquiring “B”) and obtained “A” class in general analysis. The 1: 50,000 scale models had different classifications in the local analysis (“A”, “B”, or “C”) and were not classifiable considering general approach (Table 4). The Jonathan de Ferranti’s model presents considerably better results for models with 90m, with smaller errors for 90% of the points and standard deviation (Table 4).

Table 3: Summary of SRTM statistics obtained at latitude intervals. Where the models show the following numeration: 1-CGIAR-CSI; 2- EMBRAPA; 3-HydroSheds; 4- Jonathan de Ferranti; 5- SRTM-GL1.

		Mean Error (meter)					Standard deviation				
Interval	Points	1	2	3	4	5	1	2	3	4	5
02ºN-06ºN	76	-0.4	-0.07	-11.94	-0.61	-0.48	4.36	5.46	8.03	3.79	3.41
02ºS-02ºN	159	13.17	15.25	1.97	12.15	10.83	10.16	9.47	12.56	8.28	8.54
06ºS-02ºS	51	4.44	4.31	-14.91	4.01	4.30	3.38	8.99	8.82	2.84	3.34
10ºS-06ºS	134	1.21	2.26	-5.68	0.3	-0.14	6.72	8.88	8.76	5.37	5.07
14ºS-10ºS	132	13.51	11.15	9.04	7.7	5.75	12.57	10.29	12.75	5.77	5.07
18ºS-14ºS	149	8.07	9.47	5.39	7.79	6.88	6.15	6.69	7.02	4.91	4.14
22ºS-18ºS	69	6.72	8.18	-4.77	6.91	7.48	3.25	5.50	5.46	3.07	4.22
26ºS-22ºS	127	10.77	14.11	5.33	9.19	7.57	11.18	9.66	10.18	5.64	4.58
30ºS-26ºS	190	6.03	7.74	0.07	4.91	3.86	10.75	14.23	14.78	7.88	6.91
Total (Brazil)	1087	9.78	8.89	0.24	6.33	5.35	8.16	11.20	12.70	7.22	6.64
		Minimum error – Maximum error (absolute values-meter)					Root Mean Square Error				
Interval	Points	1	2	3	4	5	1	2	3	4	5
02ºN-06ºN	76	0.06 15.27	0.05 16.45	0.28 34.66	0.04 14.81	0.01 11.10	4.35	5.42	14.11	3.82	3,42
02ºS-02ºN	159	0.28 43.62	1.16 44.51	0.11 32.64	0.41 32.77	0.21 34.45	16.62	17.94	12.68	14.69	13,78
06ºS-02ºS	51	0.11 12.02	0.30 35.57	0.20 34.33	0.21 9.98	0.41 14.77	5.57	9.89	17.01	4.90	5,43
10ºS-06ºS	134	0.02 22.47	0.02 42.64	0.16 37.68	0.04 18.84	0.02 18.22	6.80	9.13	10.42	5.36	5,04
14ºS-10ºS	132	0.82 54.75	0.15 71.30	0.18 49.02	0.22 23.71	0.22 19.19	18.43	17.53	15.60	9.61	7,65
18ºS-14ºS	149	0.06 26.02	0.48 26.57	0.12 25.28	0.01 20.74	0.24 20.96	10.13	11.58	8.83	9.21	8,02
22ºS-18ºS	69	0.02 13.23	0.95 19.69	0.33 15.66	2.17 15.47	1.35 17.86	7.46	9.84	7.23	7.55	8,56
26ºS-22ºS	127	1.10 39.79	0.13 54.43	0.16 34.16	0.59 24.52	0.13 19.44	15.49	17.08	11.45	10.78	8,84
30ºS-26ºS	190	0.08 49.25	0.06 76.98	0.03 63.68	0.02 36.64	0.01 27.68	12.31	16.16	14.74	9.27	7,89
Total (Brazil)	1087	0.02 54.75	0.02 76.98	0.03 63.68	0.01 36.64	0.01 34.45	12.74	14.34	12.70	9.61	8,52

Table 4: PEC Classification by latitude interval (RMSE and Tolerance of Table 2). Where the models show the following numeration: 1- CGIAR-CSI; 2-EMBRAPA; 3-HydroSheds; 4- Jonathan de Ferranti; 5- SRTM 30m of resolution. The symbol X represent the model does not classify into any PEC class (Santos 2010).

Interval	1	2	3	4	5
	90% of the points < / PEC 1:100,000 / PEC 1:50,000				
02oN-06oN	5.81 /A /A	9.74 /A /A	21.65 /A /X	5.29 /A /A	5.16 /A /A
02oS-02oN	24.38 /A /X	27.16 /B /X	18.5 /A /X	21.44 /A /X	21.69 /A /X
06oS-02oS	7.99 /A /A	11.1 /A /C	23.3 /B /X	7.52 /A /A	7.88 /A /A
10oS-06oS	12.52 /A /C	13.84 /A /C	16.59 /A /X	9.26 /A /A	7.90 /A /A
14oS-10oS	29.01 /B /X	26.19 /B /X	24.26 /A /X	14.13 /A /C	11.79 A /B
18oS-14oS	15.77 /A /X	19.07 /A /X	13.12 /A /C	14.33 /A /C	12.11 /A /C
22oS-18oS	10.47 /A /B	14.43 /A /C	9.86 /A /B	10.83 /A /B	12,49 /A /C
26oS-22oS	23.78 /A /X	26.85 /B /X	16.66 /A /X	15.8 /A /X	13.41 /A /C
30oS-26oS	17.59 /A /X	25.68 /B /X	23.94 /A /X	14.4 /A /C	11.27 /A /B
Total	19.71 /A /X	22.55 /A /X	20.36 /A /X	15.52 /A /X	14.19 /A /C

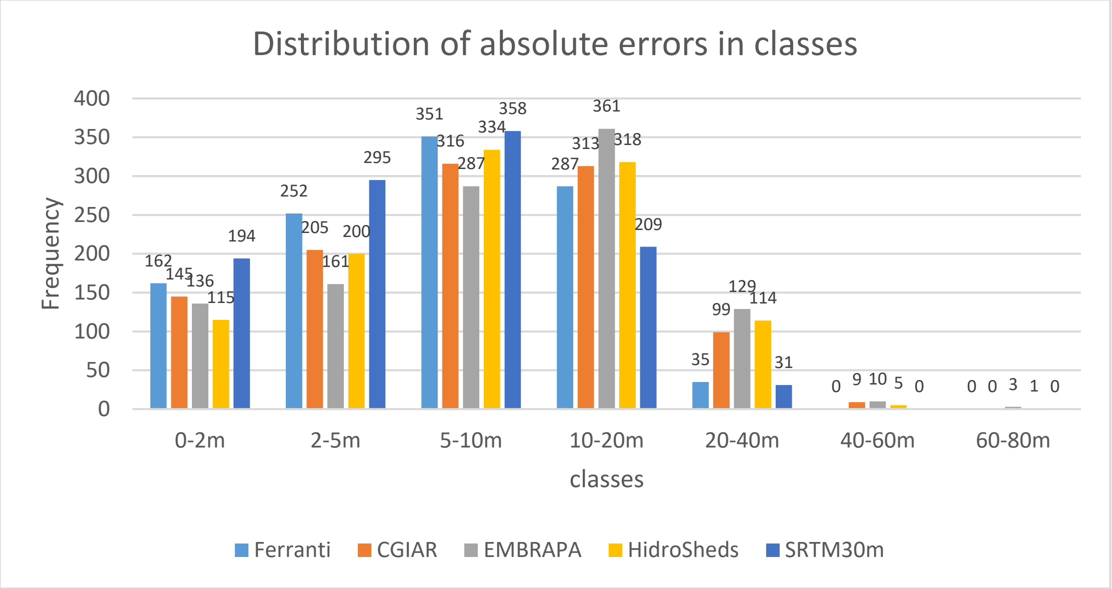

Figure 3: Histogram of distribution of absolute errors in classes.

Predictably, the 30-meter resolution model showed higher accuracy than the 90-meter resolution models. However, although the resolution is three times better, the accuracy is approximately 10% higher. For example, the RMSE of Jonathan de Ferranti's model for all Brazil is of 9.61m, while for the SRTM-GL1 is of 8.52m. The obtained RMSE result for SRTM GL1 was compatible with that found for the South American Andean Plateau (RMSE = 9.7) (Satge et al. 2016).

3.2. Analysis of Slope and Vegetation in the Altimetric Accuracy

In the slope analyzes, we used only the 90-meter resolution model with the best accuracy (Jonathan de

Ferranti's SRTM). The absolute values of the average error varied linearly with the mean slope within each slope range, obtaining a significant coefficient of determination (R2) of 0,907 (Figure 4). Complementarily, the second-order polynomial function obtains an extremely accurate adjustment of the data, achieving an R2 of 0.999. The average magnitude of errors in slope terrains (>20%) is approximately twice higher than flat terrain (<1%). The regression obtained serves as a basis to estimate the expected errors in the different types of relief. The results were consistent with other surveys, which demonstrated that the highest errors occur preferentially in mountainous regions than in flat areas (Sun et al. 2003; Gorokhovich and Voustianiouk 2006; Rexer and Hirt 2014).

Shortridge and Messina (2011) emphasize the importance of evaluating vegetation interference in the most significant errors found in SRTM altimetry. In the present study, the highest errors within each analyzed latitude zone occurred in densely vegetated areas (Figure 5). Thus, this simple qualitative analysis evidenced the vegetation influence on the SRTM model accuracy. This expected behavior is because the SRTM is a digital surface model (MDS) and not originally a digital terrain model (MDT). The electromagnetic waves of the C- and X- radar bands interact with elements larger than their respective wavelengths such as dense vegetation, causing significant altimetric differences in SRTM data (Sun et al. 2003; Brochado 2015; Pinel et al. 2015). The present study did not evaluate in depth the role of vegetation in the altimetric errors, not considering in detail the type of canopy and height of the trees. However, the research showed that vegetation interference was the main source of error encountered, confirming the results of other surveys (Ludwig and Schneider 2006; Pinel et al. 2015).

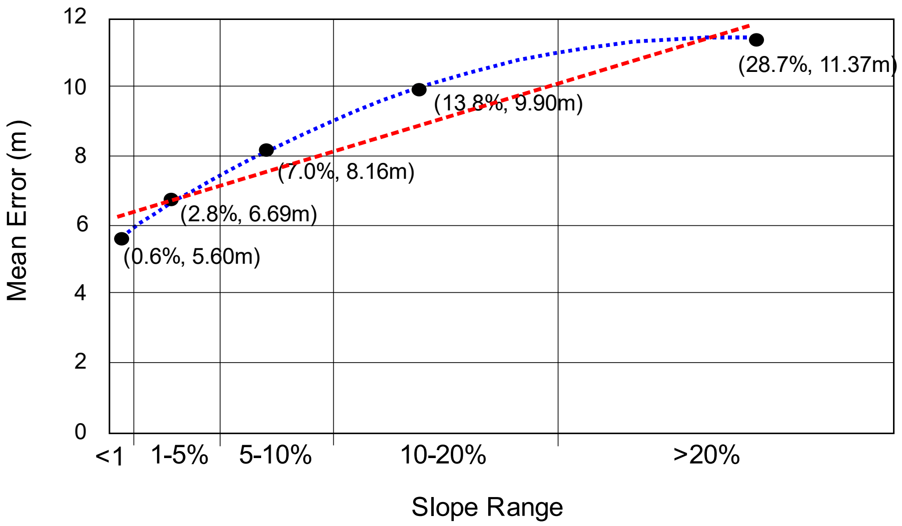

Figure 4: Regression functions between the Mean Absolute Error (MAE) of the Jonathan de Ferranti's SRTM and mean slope within each slope ranges (<1%, 1-5%, 5-10%, 10-20%, and >20). Red line is the linear best fit line (y = 0.1965x + 6.2603) with the coefficient of determination (R^2) of 0.907, while the blue line is the polynomial best fit line (y = $-0.0081x^2 + 0.4397x + 5.4284$) with R^2 of 0.999.

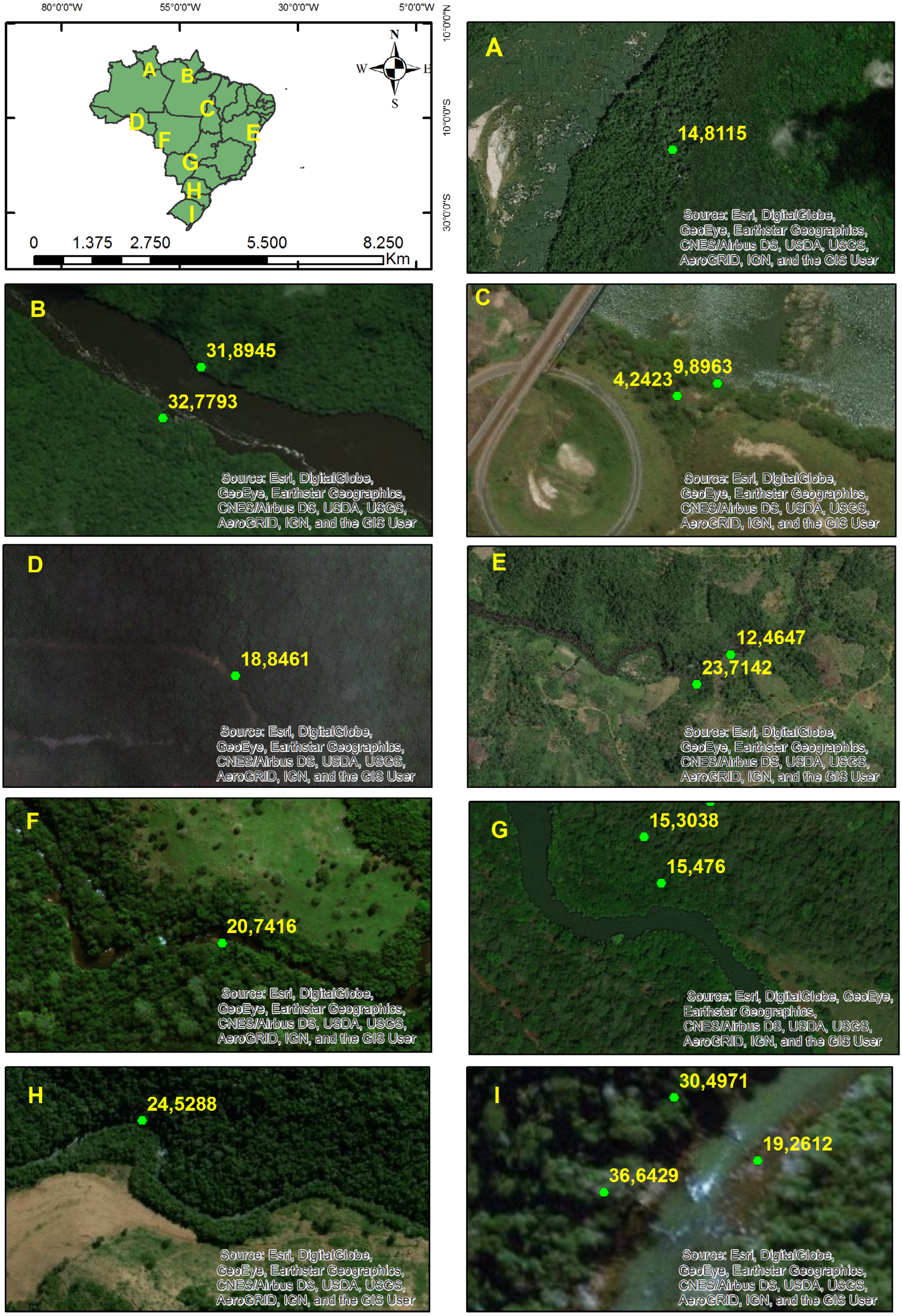

Figure 5. Position of the largest errors by latitude range from Jonathan de Ferranti´s SRTM and its incidence in forested regions. Image Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographicas, CNES / Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, Swisstopo, the GISUser Community.

4. Conclusion

The results show a variation of the vertical accuracy within the Brazilian territory according to SRTM type: EMBRAPA (RMSE of 14.74m); HydroSHEDS (RMSE of 12.70m); CGIAR-CSI (RMSE of 12.74m); Jonathan de Ferranti (RMSE of 9.61m); and SRTM-GL1 (RMSE of 8.52m). Therefore, several SRTM models demonstrate significant differences, whereas Jonathan de Ferranti's model presents the most consistent behavior and the best altimetry accuracy for the 90-meter resolution models. The classification of models corresponds to "PEC-A" at 1:100,000 scale for all 1087 points. The SRTM-GL1 model with a resolution of 30 meters provided an improvement in the altimetric accuracy by approximately 10%, reaching the PEC "C" at 1: 50,000 scale for the total data set evaluated in research. However, Jonathan de Ferranti's model is not much more imprecise than SRTM-GL1. The SRTM height bias has a direct correlation with the slope, having a perfect fit with the second-order polynomial function (R2 = 0.99). The highest errors occur in forested areas.

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AUTHOR´S CONTRIBUTION

Alex Gois Orlandi, Osmar Abílio de Carvalho Júnior and Renato Fontes Guimarães wrote the manuscript and was responsible for the research design, mathematical model, data preparation, and analysis. Alex Gois Orlandi and Douglas Corbari Corrêa provided some of the data, conducted the field-works, and gave technical support. Edilson de Souza Bias and Roberto Arnaldo Trancoso Gomes provided significant input to the numerical analysis. All the authors contributed to the editing and reviewing of the manuscript.

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