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Evaluation of altimetry from the COP-30 DEM in central-western Brazil

Avaliação da altimetria do MDE COP-30 no Centro-Oeste do Brasil

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Abstract: This study analyzes the Brazilian Cartographic Accuracy Standard for Digital Cartographic Products (PEC-PCD) of the digital elevation model (DEM) from Copernicus DEM program, denominated COP-30, with the ellipsoidal altitudes provided by 317 reference stations of the Brazilian Geodetic System located in federative units of Goiás and Distrito Federal (Brazil). The PEC-PCD defines error tolerances according to eight different scales (from 1:1000 to 1:250,000) and four quality classes (ranging from A to D). Considering class A, the DEM COP-30 meets the 1:50,000 scale and lower scales, while for class B, the DEM COP-30 meets the 1:25,000 scale and lower scales. DEM COP-30 presented lower values of root mean square error (RMSE=1.98 m), indicating that it presents higher accuracy compared to other global free DEM.
Keywords: Altimetric accuracy. Digital elevation model. PEC-PCD.

Resumo: Este estudo analisa a acurácia posicional vertical dos dados coletados do modelo digital de elevação (MDE) do programa Copernicus DEM, denominado COP-30, baseado no Padrão Brasileiro de Exatidão Cartográfica para Produtos Cartográficos Digitais (PEC-PCD), com as altitudes elipsoidais fornecidas por 317 estações de referência do Sistema Geodésico Brasileiro localizadas no estado de Goiás e Distrito Federal. O PEC-PCD definiu tolerâncias de erro de acordo com oito escalas diferentes (de 1:1000 a 1:250.000) e quatro classes de qualidade (variando de A a D). Com os dados em sistemas de coordenadas compatíveis e considerando o PEC-PCD classe A, o MDE COP-30 atende a escala 1:50.000 e escalas inferiores, enquanto para a classe B, o MDE COP-30 atende a escala 1:25.000 e escalas inferiores. O MDE COP-30 apresentou para o estado de Goiás e Distrito Federal raiz de erro quadrático médio de 1,98 m, indicando apresentar maior acurácia em relação a outros MDEs globais gratuitos.
Palavras-chave: Acurácia altimétrica. modelo digital de elevação. PEC-PCD.

1 INTRODUCTION

Digital Elevation Models (DEM) have become essential for research in areas such as geomorphology, hydrology, climatology, agricultural sciences, soil science, biodiversity, and cartography. As an input for different applications, the vertical errors of the DEMs can propagate itself throughout the data processing in which they are used and can negatively affect the results (WECHSLER, 2007). Therefore, it is important to understand the quality of the DEM to be used in light of the diversity of applications (RAO et al., 2014). Currently, there are different global or near-global free DEMs, whose global accuracy of these products may not represent the quality in the local area, since the quality of the DEM varies at regional scale (HAN et al., 2021).The Shuttle Radar Topography Mission (SRTM) data, which was acquired in 2000, have provided with

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the first set of free near-global DEM between latitudes of 60°N and 56°S (RODRIGUES; PARADELLA; OLIVEIRA, 2011; FRAN et al., 2018; ORLANDI et al., 2019), being widely used until today, despite limitations such as the presence of voids due to radar shadows and lack of coverage in high latitudes. Besides the SRTM DEM, it is possible to highlight the ASTER GDEM and the AW3D30 data elaborated from photogrammetric processing of optical orbital images from ASTER and PRISM sensors, on board the Terra and ALOS satellites, respectively. Another free near-global DEM is NASADEM which consists of reprocessing the original SRTM data. Some scientific studies have reported the quality of these DEMs in some regions of Brazil (such as the works from RODRIGUES; PARADELLA; OLIVEIRA, 2011; FRANCE; ALMEIDA; PENHA, 2018; FRANCE; PENHA; CARVALHO, 2019; ORLANDI et al., 2019; BETTIOL et al., 2021). Generally, the evaluation of the altimetric accuracy of DEMs has been performed by applying guidelines based on the sampling of reference points and the DEM to be evaluated (e.g. MORAIS et al., 2017; JAIN et al., 2017).

In Brazil, the vertical positional accuracy of the DEMs is presented in terms of the Standard of Cartographic Accuracy for Digital Cartographic Products, according to metrics of error between a reference data and the DEM, evaluated for different scales (e.g.: 1:25,000, 1:50,000, 1:100,000 and 1:250,000), and classes A, B, C and D (see item 2.3) (DSG, 2011; 2016a). Different works have been using the Brazilian regulation to evaluate the vertical positional accuracy of DEMs in national territory (e.g. FRANÇA; PENHA; CARVALHO, 2019; ORLANDI et al., 2019; BETTIOL et al., 2021).

In December 2020, a new global and freely accessible DEM was launched by the European Space Agency (ESA), the DEM COP-30 (also named GLO-30). Therefore, regional evaluations on the positional accuracy of the altitude of this DEM are needed in order to include a wider range of landscape conditions. In this work, the first evaluation of the absolute vertical positional accuracy of the COP-30 over the Brazilian territory is presented through a comparison with altimetric data from the Brazilian Geodetic System (SGB) covering the federation units of Goiás and Distrito Federal, in central-western Brazil.

2 METHODOLOGY

In order to asses the altimetric positional accuracy of the COP-30 DEM by the PEC-PCD, the data from IBGE (Brazilian Institute of Geography and Statistics) regarding the altitudes described in subsection 2.1 were used as reference (Figure 1). The COP-30 DEM evaluated in this study has been described in subsection 2.2. Finally, in subsection 2.3, the procedure adopted to evaluate the vertical positional accuracy of the DEM by the PEC-PCD was presented.

2.1 Reference altimetric data

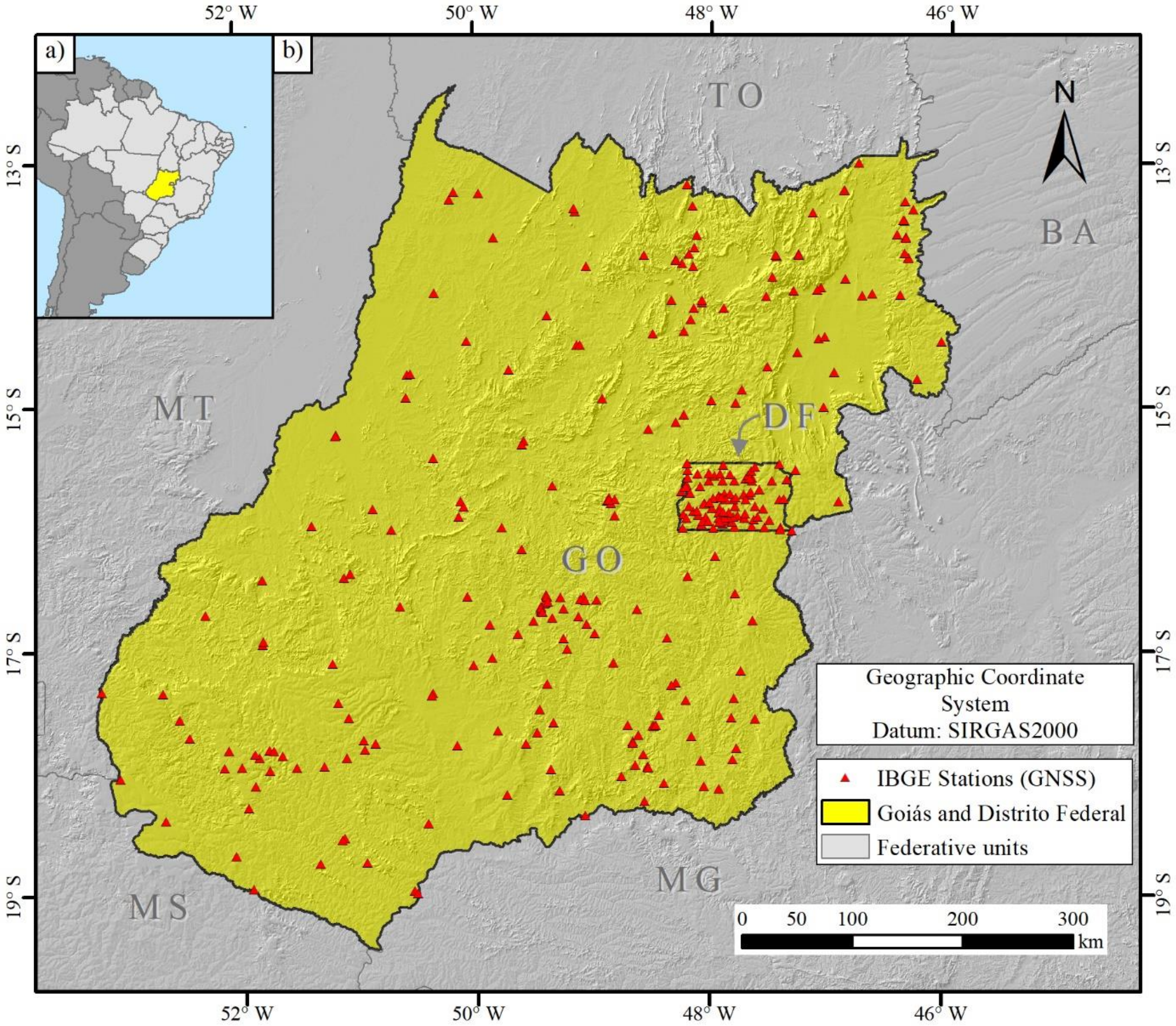
The SGB, maintained by IBGE, is characterized as the fundamental geodetic infrastructure for positioning, mapping and national registry. A set of networks with vertices materialized in the terrain are part of the SGB, among them planimetric, altimetric and planialtimetric, which have a set of stations with known geodesic coordinates (latitude, longitude and altitude). The data from the geodesic stations can be obtained through the service called Geodesic Database (BDG) (IBGE, 2021).

The SGB's High-Precision Altimetric Network (RAAP) is composed by a set of Level References (RN), established since 1945 by means of high precision geometric leveling. Originally, the RAAP provided orthometric altitudes, obtained from the gradients between the stations of the network. In 2018, a new calculation methodology was established and the network was readjusted, with the incorporation of gravimetric information to the leveled gradients (IBGE, 2019). From then on, RAAP started to provide information of the geopotential number and normal altitudes of the geodetic stations. However, the planimetric values of RN stations have diverse sources such as topographic charts of different scales and navigation Global Navigation Satellite System (GNSS) whose standard deviation values for latitude and longitude are unknown. Thus, while the altimetric quality of these data is known, the planimetric quality is unknown. Even though the planimetry is not evaluated in this work, the planimetric positioning accuracy of the reference stations is important for a better comparison between these stations and the pixels with altimetric values corresponding to the same location.

The SBG also has a planialtimetric network composed of a set of geodetic stations based on surveys by the GNSS, classified as "GPS or Doppler", besides polygonal stations and the triangulation vertices, the latter one based on conventional geodetic surveys (IBGE, 2021). The satellite-based stations have altitudes associated with the ellipsoid of the Geodetic Reference System 1980 (GRS80) and planimetric coordinates with standard deviation values of the observations known for latitude and longitude less than 1 cm. For this work, satellite-based stations with altitudes acquired from GNSS were selected as reference data for comparison with the COP-30 DEM data, with average sigma altitude values of 1.8 cm according to the data obtained by BDG for the study area.

From the planialtimetric network, it was possible to find 330 points in the state of Goiás and the Federal District with known ellipsoidal altitude from GNSS survey. From the total of 330 stations, thirteen were discarded since they were located in buildings of high altitude in relation to the surroundings, thus not reflecting the characteristic of an DEM with pixel size of approximately 30 m (see item 2.2), thus leaving 317 points for validation (Figure 1).

Figure 1 - Location of the study area. a) context of the state of Goiás and the Federal District in Brazil and South America; b) IBGE GNSS planialtimetric stations in Goiás and the Federal District.



Source: The authors (2022).

2.2 COP-30

COP-30 DEM is one of the open access and global coverage versions of the Copernicus DEM program. It consists on a digital surface model (DSM) representing the Earth's surface including buildings, infrastructure and vegetation. This DEM is derived from X-band synthetic aperture radar (InSAR) interferometry from the

TanDEM-X and TerraSAR-X mission between the years 2011 and 2015, and is funded by a public-private partnership between the German government, represented by the German Aerospace Agency (DLR) and Airbus Defence and Space.

The InSAR processing, calibration and mosaics were done by DLR forming the TanDEM-X DEM with pixel size of 0.4 arc-seconds (approximately 12 m at the Equator) with an altitude relative to the GRS80 ellipsoid (WGS84-G1150). Based on this DEM, Airbus Defence and Space reprocesses it to orthometric altitude based on the EGM2008 geoidal model, which is then called WorldDEMCore. This DEM is later edited with voids filling, editing the coastlines, flattening areas of water bodies and making the DEM hydrologically consistent, this edited MDS is commercial and called WorldDEMTM keeping the same pixel size of 0.4 arc-seconds (AIRBUS, 2019). The WorldDEMTM data were resampled and passed on to ESA to make up the Copernicus DEM program (AIRBUS, 2020).

Currently, thes Copernicus DEM comes in 3 free versions and two global coverage versions called COP-30 and COP-90, also named GLO-30 and GLO-90 respectively. These versions vary in pixel size, COP-30 is a resampling of the WorldDEMTM by aggregation of 0.4 to the 1 arc-second (approximately 30 m in metric coordinate system at the equator), while COP-90 is the resampling of the pixel to 3 arc-seconds (approximately 90 m) (AIRBUS, 2020). Copernicus DEM is also available with pixel size of 0.4 arc-seconds (approximately 10 m) with a restricted coverage for Europe (AIRBUS, 2020).

In Table 1, it was presented some parameters and specifications of the COP-30 DEM.

Table 1 – Parameters and specifications of the COP-30 DEM.

Format	GeoTIFF and DTED
Type of data	32 bits, floating point (DGED format), i.e. altitude is given in decimal numbers. 16 bits, integer (DTED format), i.e. altitude is given in integer numbers (meter in meter).
Squares	1° x 1° latitude/longitude
Coordinate Reference System	Geographic Coordinates
Horizontal datum	WGS84 (EPSG 4326)
Vertical datum	EGM2008 (EPSG 3855)
Pixel size	1 arc-second
Vertical unity	Meters

Source: AIRBUS (2020).

Technical specifications of the Copernicus DEM products provide a relative vertical accuracy of <2 m for areas with surface slope less than 20% and <4 m for slopes greater than 20% (AIRBUS, 2020). The hydrological consistency of the WorldDEMTM cannot be assured for the COP-30 due to the resampling process in its preparation. The COP-30 DEM data can be acquired from ESA's PANDA data repository (ESA, 2022) or from the OpenTopography repository (ESA, 2021).

2.3 Evaluation method of PEC-PCD

The Decree No. 89,817, of June 20, 1984, established the regulatory guidelines for the Brazilian cartographic technical standards, establishing the Brazilian Cartographic Accuracy Standard (PEC) in which parameters that constitute them are used as a reference for three categories of quality varying in classes A, B and C for different scales of work (BRASIL, 1984). The advent of new technologies with digital cartography led to a review of the standards established by Decree No. 89,817 and a more restrictive standard was determined to meet Brazilian Cartographic Accuracy Standard for Digital Cartographic Products (PEC-PCD), now with 4 classes where class A of the decree became class B, class B became C, class C became D and class A of the PEC-PCD has more restrictive criteria than previously proposed (DSG, 2011, 2016a).

In this work, the altitude evaluation of COP-30 DEM (DGED format) followed the PEC-PCD, published in the 2nd edition of the Technical Specification for the Acquisition of Geospatial Vector Data (ET-

ADGV) version 2.1.3 (DSG, 2011) and in the Technical Specification for Quality Control of Geospatial Data Set Products (ET-CQDG) (DSG, 2016a).

The PEC-PCD for vertical positional accuracy is based on metrics associated with the error (e_z) (Eq. 1) between the cartographic product to be evaluated, in this case the altimetry of the DEM (Z_i), and a reference data (Z_{ref}) with accuracy at least three times higher than the evaluated product (DSG, 2016a), being used: the root mean square error (RMSE) and the linear error with 90% probability (LE90). LE90 corresponds to 1.6449 times the value of RMSE (Eq. 3).

$$e_z = Z_i - Z_{ref} \tag{1}$$

$$RMSE = \sqrt{\sum_{i=n}^{n} \frac{(Z_i - Z_{ref})^2}{n}} \tag{2}$$

$$LE90 = 1.6449 \times RMSE \tag{3}$$

Every scale (1:1,000; 1:2,000; 1:5,000;1:10,000; 1:25,000; 1:50,000; 1:100,000 and 1:250,000) has its Standard of Cartographic Accuracy (PEC) and a standard error (SE) which are classified into levels of product quality varying on the classes A, B, C and D. In Table 2, it was presented the ME and SE values for the smaller scales.

Table 2 – Brazilian Cartographic Accuracy Standard for Digital Cartographic Products in relation to the altimetric accuracy of DEMs. Values for scales 1:25,000, 1:50,000, 1:100,000 and 1:250,000.

PEC - PCD	1:25.000		1:50.000		1:100.000		1:250.000	
	PEC (m)	SE (m)	PEC (m)	SE (m)	PEC (m)	SE (m)	PEC (m)	SE (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

Source: DSG (2011).

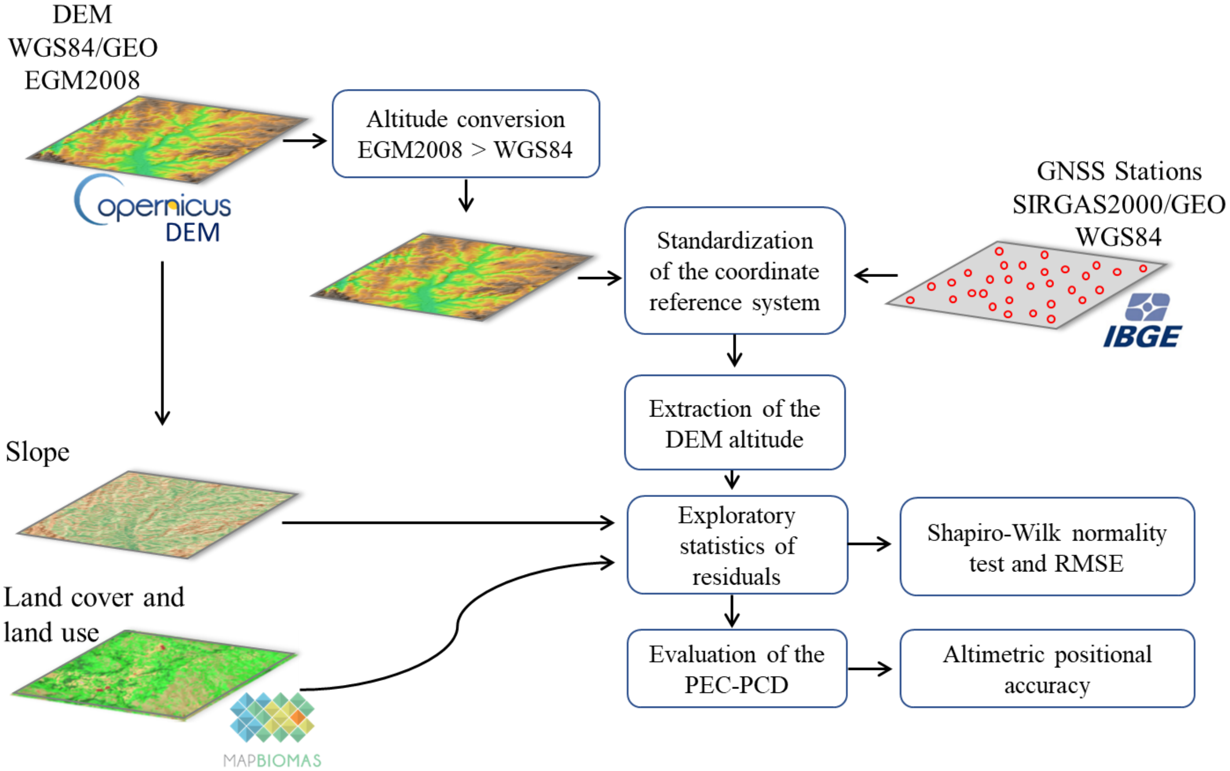
By the PEC-PCD, the DEM to be classified in a certain scale and class needs to consider the following conditions:

a) Ninety percent of the validation points of an DEM must present error values equal to or less than the PEC tolerance value of the scale and class tested, when compared to the data corresponding to the reference data; and
b) The RMSE of the altimetric discrepancies must be equal to or less than the SE tolerance defined for each scale and class.

The COP-30 DEM is referenced to WGS84 geographic coordinates (horizontal data) and orthometric altitude referenced to the EGM2008 geoidal model (vertical data). The EGM2008 model has 5-10 cm accuracy, a 3-6 times improvement over the EGM96 model (PAVLIS et al, 2012) and which is used in the SRTM, ASTER GDEM, AW3D30 and NASADEM DEMs. In order to make the coordinate reference system between the COP-30 DEM and the IBGE GNSS stations compatible, it was necessary to convert the COP-30 data from orthometric altitude to ellipsoidal altitude by adding the DEM raster data to the EGM2008 geoidal model raster (AGISOFT, 2022) with the same pixel size as the DEM (1 arc-second) by bilinear interpolation (GROHMANN, 2018; BETTIOL et al, 2021). As for the SIRGAS2000 and WGS84 data, there is a planimetric compatibility considering the pixel size of the analyzed DEM (~30 m), the conversion was not performed.

With the compatible data between the horizontal and vertical data, for each point with reference altitude was extracted the pixel value of the ellipsoidal altitude of the DEM COP-30 (Figure 2).

Figure 2 – Methodological flowchart used in the research.



Source: The authors (2022).

It is important to highlight that many works that evaluated the vertical accuracy of global DEMs did not perform the compatibility between the orthometric altitude of the DEMs (provided by the geoidal models EGM96 or EGM2008) with the altitude of the reference data. Rodrigues, Paradella and Oliveira (2011), Grohmann (2018) and Bettiol et al. (2021) are examples of works that performed this compatibility between the orthometric altitude of the DEMs and the reference data in the evaluation of their analyses.

The altimetric quality of the COP-30 DEM was estimated by comparing the altitudes from the reference stations based on RMSE values and LE90 values. Then each e_z value was compared with the ME from the PEC-PCD table for each class (Table 2). The product fits when it has at least 90% of points with error less than the ME and the RMSE value less than or equal to the EP for the scale and class identified in Table 2.

Additionally, it was evaluated if the errors meet a normal statistical distribution by the Shapiro-Wilk test, as well as by the exploratory analysis of the data with histogram and quantile-quantile plots. The correlation between the COP-30 DEM and the reference data was also evaluated, as well as the relationship of the errors as a function of the DEM slope, as well as the land use and land cover classes (Figure 2) referring to the year 2015 (last collection year for data generation), from the base of the MapBiomas project - collection 5 (SOUZA et al., 2020). These steps were processed by GeoPEC 3.5.1 (SANTOS et al., 2016) and R (R CORE TEAM, 2021) software.

3 RESULTS AND DISCUSSIONS

The evaluation of the PEC-PCD was conducted in two steps. First, the RMSE was calculated for the COP-30 DEM, in order to compare it with the PEC accordingly to the scale and class. Secondly, it was conducted the comparison with the SE, which is also as a function of scale and each class (Table 2). The RMSE of the model was 1.98 m. To reach class A at scale 1:25,000, it would be necessary that 90% of the 317 points analyzed had an error lower than 2.70 m. However, 86.75% of the points (275 stations) were below this error value. By this criterion, the COP-30 DEM does not meet this class and scale. The ME for the 1:25,000 scale

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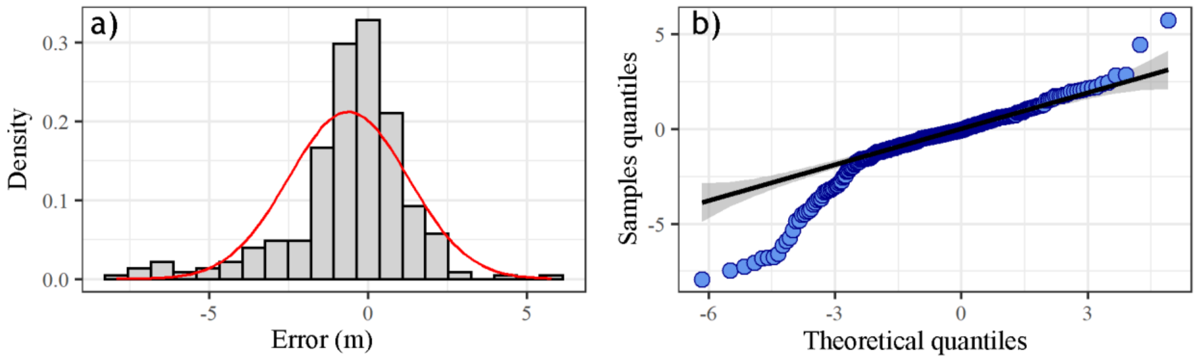
class B is 5 m. By this criterion, 95.5 % of the points (304 stations) meet this criterion and the RMSE is below the EP. Thus, for the state of Goiás and the Federal District it is possible to point out that the COP-30 meets the 1:25,000 class B scale, the 1:50,000 class A scale, and the lower scales.

The Shapiro-Wilks statistical test of the error data has suggested that its distribution is significantly different from the normal distribution (p-value < 0.001), that is, it is possible to assume the non-normality of the data. Such a finding is reinforced by the statistical distribution of the data that although it approaches near-normality by the histogram distribution (Figure 3-a), it is still notable that by the quantile-quantile plot the distribution is not normal (Figure 3-b). The issue of non-normality of the data in the altimetric evaluation is common, and it has even been the object of criticism for improvement of the PEC-PCD in Brazil (CARVALHO; SILVA, 2018).

The evaluation between the altimetric data of the COP-30 DEM and the altimetric reference data from IBGE, has a strong correlation with a coefficient of determination (R^2) equal to 0.99 (Figure 4-a). The distribution of the module errors between the COP-30 DEM and the reference data has shown that the largest errors were not associated with higher slope values, since it is possible to observe higher error values both in flatter areas and in steeper areas. This finding differs from other works where the errors of the analyzed DEMs tended to increase with increasing slope (for example in the works of MORAIS et al., 2017 and JAIR et al., 2017).

Figure 3 - Visualization of the statistical error distribution between the COP-30 DEM and the IBGE reference data. a) density histogram with the normal distribution curve (red line); and b) quantile-quantile plot.



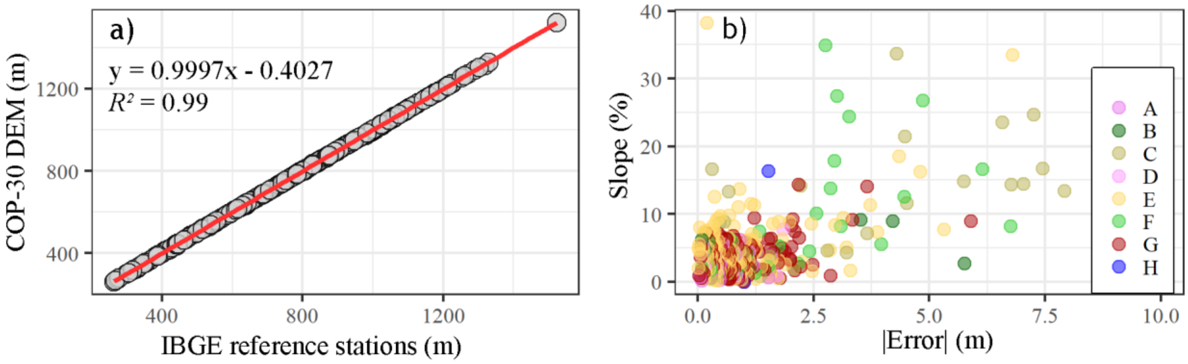
Source: The authors (2022).

There has been also observed no relationship of higher errors occurring as a function of land use and land cover class (Figure 4-b). Higher errors have occurred in different classes such as grassland, savanna, pasture, and urban infrastructure, but there is no pattern as lower errors also occurred in these classes. Unlike Jain et al. (2017), which on their work, when comparing different DEMs in India, have found higher errors in urban areas compared to agricultural or forested areas.

Results obtained in this work, for the central-western of Brazil, are corroborated with the work from Guth and Geoffroy (2021), which have evaluated the COP-30 and other global DEMs in relation to LiDAR (Light Detection and Ranging) data and have shown that the vertical accuracy of the COP-30 has little effect in relation to slope and for different land cover classes. In areas with sparse vegetation, the COP-30 appears to be just above ground level as measured by LiDAR, and in areas with more dense tree vegetation the COP-30 appears to be a model that falls between the MDS and the digital terrain model (DTM) (GUTH; GEOFFROY, 2021).

The presented results have shown that, for the study area, the COP-30 DEM has the PEC-PCD better than the SRTM data for other areas of Brazil (RODRIGUES; PARADELLA; OLIVEIRA, 2011; MORAIS et al., 2017; FRAN et al., 2018; FRANCE; ALMEIDA; PENHA, 2018; ORLANDI et al., 2019) and better than the NASADEM and AW3D30 data (BETTIOL et al., 2021). The results obtained are in accordance with the global technical specification of the COP-30 DEM (AIRBUS, 2020).

Figure 4 - a) Relationship between the data from the COP-30 DEM and the IBGE reference stations. b) Graph between the errors of the DEM validation, slope and land use and land cover classes, being: A - Agriculture, B - Forest Formation, C - Countryside Formation, D - Other non-vegetated areas, E - Pastureland, F - Savanna Formation, G - Urban infrastructure, and H - Water).



Source: The authors (2022).

Gesch (2018), Grohmann (2018) and Guth and Geoffroy (2021) have concluded that both the TanDEM-X or the COP-30 are better to all other global DEMs with 1 arc-second. For Guth and Geoffroy (2021) and Purinton and Bookhagen (2021) the improvements are so marked over the other DEMs that COP-30 should become the "gold standard" for free globalDEMs, to be used for landscape representation and statistical analysis in areas without sufficient coverage of better quality local DEMs.

Although the pixel size of the COP-30 DEM is 1 arc-second (approximately 30 m in metric coordinate systems) is not the typical size for an DEM at the 1:25,000 scale, this size still reaches the minimum required size accordingly to the Technical Specification for Geospatial Data Set Products (DSG, 2016b). Given the little difference of stations to reach class A at scale 1:25,000, it is possible that for other regions, or even with another reference dataset, this product may present better performance and reach this class and scale of PEC-PCD, and may be useful for mappings that involve altimetric information at scales 1:25,000 and 1:50,000, in which the central-western region has a large cartographic void.

The PEC-PCD is based on normatives that involve the traditional comparison between reference point samples and the DEM to be evaluated. For Ariza-López and Reinoso-Gordo (2021), this approach has two disadvantages: 1) the points used in the evaluations are few compared to the total area of an DEM and, therefore, leave much of the model without evaluation; and 2) the evaluation of a surface feature is done by comparison of point features, when it seems more appropriate to evaluate by comparison of surfaces. Purinton and Bookhagen (2021) further point out as a disadvantage of this approach the fact that it does not capture the spatial variability of the DEM, in which point-based metrics do not measure inter-pixel consistency of the DEM on a matrix data, due to high elevation variability in adjacent pixels in an DEM impacting geomorphometric derivations (for example, slope, slope orientation, and curvatures) or determination of flow direction for drainage network extraction.

In this sense, Ariza-López and Reinoso-Gordo (2021) have proposed an alternative method to evaluate the vertical accuracy of DEMs based on orthogonal surfaces in which it is possible to detect outliers and biases when evaluating the DEM and enable the elaboration of distribution functions eliminating the need to consider the assumptions of normality on the residuals (ARIZA-LÓPEZ; REINOSO-GORDO, 2021). Such a method has not yet been evaluated and is a possibility to be explored in future studies.

Some works have been concerned with the evaluation of the landforms, geomorphometric derivations (such as. slope and slope orientation), drainage network and inter-pixel consistency obtained by the DEM and not only the vertical accuracy of the data (POLIDORI; EL HAGE; VALERIANO, 2014; TOLENTINO, SILVA, SANTIL, 2017; MOZAS-CALVACHE, UREÑA-CÁMARA; ARIZA-LÓPEZ, 2017; ALBA-FERNÁNDEZ, 2021; PURINTON; BOOKHAGEN, 2021). In this sense, further studies can be explored in order to evaluate the quality of the derivations possible to extract with COP-30.

4 CONCLUSION

This study supports the conclusion that, for the State of Goiás and for the Federal District in Brazil, the altimetric quality of the COP-30 DEM data met the requirements of the Brazilian PEC-PCD standards for 1:25,000 Class B and 1:50:000 Class A topographic maps. Bias effects were detected for the product, expressed by the non-normal distribution of errors for the COP-30 DEM. Given the cartographic void in the central-western region of Brazil and for other regions, altimetric data derived from the COP-30 DEM are shown to be an alternative for semi-detailed topographic mapping programs in large sectors of the country, where altimetric information is rarely available or of poor quality.

Author’s contribution

Conceptualization, E.H.C.; methodology, E.H.C., G.M.B, J.P.M.J. and F.C.M.; software, E.H.C., J.P.M.J. and M.W.O.R.; validation, E.H.C, J.P.M.J. and F.C.M.; formal analysis, E.H.C.; investigation, E.H.C.; data curation, E.H.C.; writing—original draft preparation, E.H.C.; visualization, E.H.C. and M.W.O.R.; writing—review and editing, E.H.C., G.M.B, J.P.M.J., F.C.M. and M.W.O.R. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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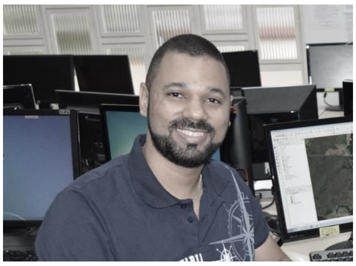
Biography



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