VERTICAL ACCURACY ASSESSMENT OF DIGITAL ELEVATION MODELS FROM AMAZON FOREST

Eduardo José da Silva Junior [1], *Daniel Rodrigues dos Santos*[2], *Leonardo Assumpção Moreira*[3]

[1]Defense Engineering Program, Military Institute of Engineering, Rio de Janeiro, RJ, eduardo.junior@ime.eb.br
[2]Defense Engineering Program, Military Institute of Engineering, Rio de Janeiro, RJ, daniel.rodrigues@ime.eb.br
[3]Cartographic Section, Military Institute of Engineering, Rio de Janeiro, leonardo.moreira@ime.eb.br

ABSTRACT

The Amazon forest is critical in global climate change and biodiversity preservation. However, acquiring accurate terrain data for this region is still challenging due to dense vegetation and high density of cloud cover. Digital Elevation Models (DEMs) such as ANADEM, Copernicus GLO-30, FABDEM, and SRTM V3 are employed to represent such surfaces but are impacted by vegetation bias. This study evaluates the vertical accuracy of these DEMs in Amazonian deforested and first-growth areas, using the Amazon Radiography (RAM) data as a reference for metric estimations. The statistical analysis results demonstrated FABDEM and ANADEM's superior accuracy in dense forest regions. Findings suggest that region-specific terrain variations affect DEM precision, offering insights to enhance future topographic data for the Amazon.

Key words – *Accuracy, Assessment, DEM, Amazon.*

1. INTRODUCTION

The precise quantification of ecosystem services that Amazon Forest provides is essential for global change mitigation. However, the lack of accurate and up-to-date cartographic data in the Amazon forest, [1], makes it difficult to derive consistent information about structural attributes predictive of carbon stock and biodiversity. The Digital Elevation Model (DEM) is critical to understanding variations in forest structure. Despite its importance, substantial work remains, particularly for large areas with high cloud cover intensity, such as tropical forests. Most current studies rely on optical imagery [2], still, its results are limited by the constant cloud cover, whether from rain, during the rainy season, or smoke from fires, during the dry months, and by the dense vegetation cover [1].

Light Detection and Ranging (LiDAR) represents an optimal alternative for topographic data acquisition [3] since they can penetrate vegetation canopies and obtain 3D ground information accurately. The increasing availability of airborne and satellite LiDAR data enables measuring the errors these free global DEMs face, specifically the vegetation height above the terrain called vegetation bias. Despite accurately measuring terrain height, orbital LiDAR data often suffers from sparse data capture, making it challenging to remove vegetation bias from an entire DEM [4]. To fully correct for vegetation bias, a statistical model is necessary to correlate the errors introduced by vegetation with its characteristics, leveraging advanced computational power and the rich array of available Earth observation data [4, 5].

ANADEM [4] and FABDEM [6] are products of an innovative approach to creating DEMs that correct for vegetation bias. While they are based on different methodologies and have distinct objectives, both aim to enhance the accuracy of scientific studies. ANADEM addresses vegetation bias specifically for the continent of South America, whereas FABDEM offers a global DEM that incorporates elements to correct for biases related to vegetation and urban construction. FABDEM has already been validated in various applications, demonstrating its superiority over other global DEMs [5–7]. In contrast, ANADEM was launched in 2024 and still requires validation for different applications.

2. MATERIALS AND METHOD

2.1. Dataset description

This section briefly describes the DEMs used in the present study: ANADEM, Copernicus GLO-30, FABDEM, SRTM V3 and DTM from RAM. The main differences between the DEMs used are summarized in Table 1.

Dataset	Aquisition Time	Mapping Technique	Vertical Datum
ANADEM	2011-2015	InSAR X-Band	EGM2008
Copernicus GLO-30	2011-2015	InSAR X-Band	EGM2008
FABDEM	2011-2015	InSAR X-Band	EGM2008
SRTM V3	2001	InSAR C-Band	EGM96
RAM DTM	2009-2011	InSAR P-Band	MAPGEO 2010

Table 1: Main differences in the datasets

2.1.1. ANADEM

ANADEM is a DTM produced to reduce the vegetation bias [4]. It was developed by the National Water Agency (ANA) and the Federal University of Rio Grande do Sul (UFRGS) based on the Copernicus DEM GLO-30. The proposed methodology uses multispectral images, Copernicus DEM GLO-30, Global Ecosystem Dynamics Investigation (GEDI) elevation data as inputs for training a machine learning model. The results are validated with independent data using the Ice, Cloud, and Land Elevation Satellite-2 (IceSat-2) elevation data.

2.1.2. *Copernicus DEM GLO-30*

TanDEM-X satellites aimed to produce a high precision DSM, WorldDEM, with global coverage based on SAR interferometry with 0.4 arc second spatial resolution [8]. The Copernicus DEM GLO-30 is a DSM resampled (with 30 m spatial resolution) from the WorldDEM and was made available for general use in 2019 and scheduled to be maintained through 2026 [9]. Research has shown that Copernicus DEM GLO-30 is the most accurate freely available global DSM [3, 4].

2.1.3. *FABDEM*

The Forest and Building removed Copernicus DEM (FABDEM) was proposed in 2022 and is the first open global DEM with buildings and forests removed at 1.0 arc-second ($\sim$ 30 m) [6]. It is based on the Copernicus DEM GLO-30, GEDI, and IceSat-2 and references LiDAR data from 12 countries to train and validate the machine learning algorithm. Forests were cleared in areas where the forest height exceeded 3 m, and tree cover was more significant than 10%. Recent studies have shown that FABDEM is the most suitable global DEM for different applications [3, 5].

2.1.4. *SRTM V3*

The Shuttle Radar Topography Mission (SRTM) was a joint effort between the American, Italian, and German space agencies [10]. The mission covered the globe between latitudes 60 S and 60 N(about 80% of Earth), and the data acquisition occurred 11 days in February 2001. The Land Processes Distributed Active Archive Center (LP DAAC), a laboratory affiliated with NASA, reprocessed SRTM data and populated void regions based on data interpolation with the best DEM available for each area at the time, and this is called the SRTM V3 [11].

2.1.5. *RAM*

The Project Amazon Radiography (RAM) used interferometry techniques with X and P bands. Radar was chosen because of the region's constant cloud cover and dense forest. While the X band reflects on the tree canopy cover, the P band penetrates the canopy cover and reflects on the soil, allowing it to be mapped [12]. The products from this project are suitable with a 1:50 000 scale, [13], and have a spatial resolution of 5 m. The project generated different products, such as SAR orthoimages from the X and P bands, a Digital Surface Model (based on the X band), a Digital Terrain Model (based on the P band), and a Digital Vegetation Height Model. In the present study, we will use only the Digital Terrain Model from the P band.

2.2. Study Area

The study area comprises 150 1/50k scale maps (equivalent to a 15'x 15' square) spread across the Brazilian Amazon rainforest region, which has a total area of 116,175 km². These study regions are spread across three states and have regions of first-growth forest (75 regions) and regions with deforestation (75 areas) proven by PRODES up to 2016. Care was taken to choose both flat and mountainous regions of the Brazilian Amazon.

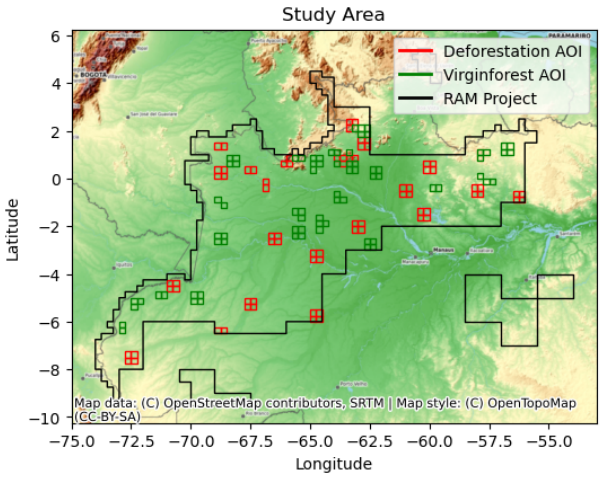


Figure 1: Areas of interest with and without deforestation.

2.3. Methods

This study evaluates the vertical accuracy and classification compliance of global DEM's in areas of deforestation and regions with primary vegetation, following the ET-CQDG standards. For each Area of Interest (AOI) altimetric accuracy is quantified through RMSE (Root Mean Square Error) and E90 (90th percentile) value, as ET-CQDG requests, as well as other common metrics used to evaluate DEM's, like MAE (Mean Absolute Error), NMAD (Normalized Median Absolute Deviation) and Median like [3], to ensure a comprehensive analysis of the datasets' vertical precision.

Additionally, statistical tests such as the t-student test for bias and the chi-square test for precision are applied to determine the significance of observed biases and deviations as [14]. Through this approach, the study aims to classify each dataset according to PEC-PCD standards, yielding valuable insights into the data's suitability for environmental monitoring and cartographic applications.

2.3.1. *Data preparation*

The areas with deforestation up to 2016 in the RAM project region were determined based on PRODES. Thus, 150 areas of interest (AOI) were possible: 75 with some degree of deforestation and 75 with first-growth vegetation. For each of the 150 chosen AOIs, images from each evaluated dataset were generated, resampling the pixel to 5 m with the nearest neighbor algorithm, the exact spatial resolution as the RAM project. This algorithm was selected to match the RAM project spatial resolution without creating new values in the evaluated datasets, 1 pixel, with a spatial resolution of 30m, will be split into 36 pixels, with a spatial resolution of 5m, but the pixel value will be copied to the new ones, without changing.

According to the ET-CQDG [15], the product to be measured for quality should be divided into 4 cm squares on

the product scale. Depending on the number of squares and some criteria, the number of points that should be sampled will depend, ensuring that each square receives only one point. Each of the 150 AOIs chosen corresponds to a region of 0.15' x 0.15' which is approximately 27 km. Bearing in mind that a 4 cm square on a 1:50k scale is equivalent to a square with a side of 2 km, a grid of 169 points (13 x 13) was generated for each of the 150 AOIs to resemble the number of points predicted by the ET-CQDG and all the points were considered in the vertical precision evaluation. For each of these generated points, the altitude value considered is the arithmetic mean of the values of a 5x5 pixel kernel centered on the pixel closest to the point and when necessary, Table 1, orthometric altitudes were converted to EGM2008. This approach was adopted to reduce the error caused by the planimetric displacement of features on the ground since it is not possible to register the images.

2.3.2. Metrics

The altimetric error (ε) in a reference point (x,y) is calculated as the difference of Z_{obs} (arithmetic mean of the values of a 5x5 pixel kernel centered on the pixel closest to the point on the evaluated dataset) and Z_{ref}(arithmetic mean of the values of a 5x5 pixel kernel centered on the pixel closest to the point on the RAM dataset). As described in [16], the Root Mean Square Error (RMSE) and E90 (90th percentile) of errors were calculated to perform the PEC-PCD classification according to ET-CQDG and following [3] the Normalized Median Absolute Deviation (NMAD) and median of errors were estimated to reduce the effect of the outliers in the analyses.

Table 2 shows the limits values of EP and EM and according to ET-CQDG, for a product to be classified within the classes established in each scale, this product must meet the specifications of two tests, which are RMSE lower than EP and Maximum Error in 90% (E90) of the evaluated points lower than EM.

PEC PCD	1:25k		1:50k		1:100k		1:250k	
	EP	EM	EP	EM	EP	EM	EP	EM
A	2,7	1,67	5,5	3,33	13,7	8,33	27	16,67
B	5,0	3,33	10	6,67	25	16,67	50	33,33
C	6,0	4,0	12	8,0	30	20	60	40
D	7,5	5,0	15	10	37,5	25	75	50

Table 2: Altimetric PEC-PCD [15].

In addition to the PEC-PCD, the t-student test was performed for bias analysis and the chi-square test for precision analysis according to [14].

3. RESULTS

Table 3 shows the general metrics (Root Mean Square Error (RMSE), 90th percentile (E90), Mean Absolute Error (MAE), and Normalized Median Absolute Deviation (NMAD) and median of vertical errors) considering all AOI, only AOI with deforestation, and only AOI without deforestation.

As seen in Table 3, two groups of similar results can be observed in all situations, that is, GLO-30-SRTM and ANADEM-FABDEM. While GLO-30-SRTM showed a general classification compatible with a 1:100k scale (class "D" or "R"), ANADEM-FABDEM group was classified in a 1:50k scale (class "B"). For both cases, the classification was not better due to the E90. The GLO-30 had better results in RMSE, MAE, and median, while SRTM showed lower values of E90 and NMAD. A PEC classification cannot be found for GLO-30 in the investigated scales because its E90 was above 25 m. According to Table 2, the maximum limit for class D, although GLO-30, had a slightly lower RMSE than SRTM in both scenarios. Focusing on the ANADEM-FABDEM group, FABDEM had better results in all metrics except the median in regions with and without deforestation. It is important to note that all datasets failed in the bias (t-student) test but reached the expected precision (chi-square) test.

Figure 2 exhibits the PEC class and scale for each AOI with and without deforestation for all analyzed datasets.

By comparing the results of ANADEM and FABDEM in both situations and analyzing Figure 2, we noted that ANADEM has better results (class A for scale 1:50k) but also has worse results (class B, C and D for scale 1:100k). In comparison, FABDEM has more results in the expected average (class B and C for scale 1:50k). Focusing on GLO-30 and SRTM the results are very similar.

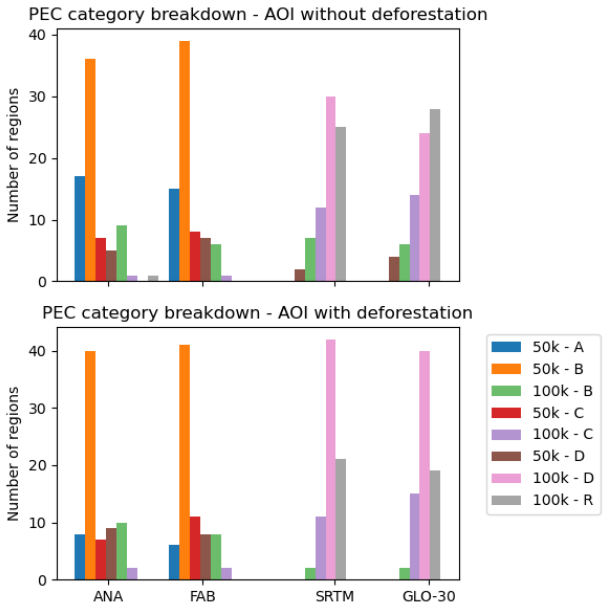


Figure 2: PEC classification breakdown for all analyzed datasets

4. DISCUSSION

GLO-30 and SRTM had similar results with GLO-30 a little worse in terms of E90 and NMAD, metrics related to error dispersion, and this was crucial to the worst GLO-30 PEC-PCD classification. This result is consistent with the findings of [3] who showed that GLO-30 and SRTM have similar results in dense forest regions, despite GLO-30 being derived from a modern sensor.

Both FABDEM and ANADEM were successful in improving the accuracy of GLO-30 in dense forest regions,

Case	Dataset	PEC	Scale	RMSE	E90	MAE	NMAD	Median	t-student	bias	Chi-square
	ANADEM	C	50	5.733	7.781	4.098	4.320	1.365	False	1.607	True
overall	FABDEM	C	50	5.242	7.286	3.717	3.681	1.685	False	1.849	True
results	GLO-30	R	100	18.433	25.575	16.698	6.734	17.693	False	16.521	-
(150 AOI)	SRTM	D	100	18.567	24.970	16.951	6.334	17.873	False	16.674	True
	ANADEM	C	50	6.119	8.522	4.456	4.844	1.569	False	1.684	True
with	FABDEM	C	50	5.592	7.616	3.910	3.869	1.888	False	2.068	True
deforestation	GLO-30	R	100	18.462	25.441	16.812	6.504	17.729	False	16.561	-
(75 AOI)	SRTM	D	100	18.622	24.820	17.035	6.069	17.866	False	16.649	True
	ANADEM	C	50	5.319	6.981	3.741	3.828	1.205	False	1.529	True
without	FABDEM	C	50	4.868	6.900	3.525	3.468	1.509	False	1.629	True
deforestation	GLO-30	R	100	18.404	25.676	16.585	6.933	17.653	False	16.482	-
(75 AOI)	SRTM	R	100	18.512	25.124	16.867	6.581	17.876	False	16.699	True

Table 3: overall result considering all AOI(150), only the deforestation AOI (75) and only without deforestation AOI(75)

in all metrics evaluated, with a reduction of approximately 70%, but FABDEM had better results in all metrics except the median. When analyzing the results in Table 3 and Figure 2, it is observed that although FABDEM's overall result was better, ANADEM was better in specific regions (looking at the amount of PEC-PCD AOI with class "A" for the 1:50k scale), which suggests that although FABDEM is more accurate in general terms, ANADEM maybe even better depending on the region of study.

5. CONCLUSIONS

This paper presents an investigation to assess the vertical accuracy of DEMs from the Amazon forest. The RAM data covering a vast study area of over 116,000 km² for this study is an innovation. As highlighted, the FABDEM demonstrated the most consistent accuracy across varied regions, while ANADEM may offer better precision in specific areas. P-band radar data showed that it provides a unique baseline to address vegetation bias, a standard limitation in tropical DEMs. Future research should focus on analyzing the landscape properties such as slope, aspect, and river network consistency of FABDEM and ANADEM to evaluate the best available free digital elevation model in Amazon Forest.

6. REFERENCES

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