Terrain analysis in forested areas: consequences of using DSM instead of DTM

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Keywords: Amazon, resolution, digital elevation model, quality, radar, landforms.

Abstract

Relief mapping through dense tropical forest is a challenge, which can be met by processing radar images. Various global digital elevation models (DEMs) are available, either free or paid, the most widely used methods for producing them at global scale being photogrammetry and short wavelength radar interferometry. However, the resulting DEMs do not directly represent the ground surface but rather the canopy or something in between. Since most users need terrain models for a variety of applications in geoscience, water management etc. but use such canopy models for lack of anything better, it was relevant to assess the consequences of this inappropriate but unavoidable choice. This paper presents a study carried out in the Brazilian Amazon, where an airborne P-band radar interferometric DEM was used as a reference based on its accuracy assessed in previous studies. A well-established DEM (SRTM) and newer ones (Copernicus and Fabdem), as well as a DEM obtained from aerial X-bands radar data, were compared to the reference according to different criteria related to elevation (accuracy and a typical application, i.e., dam filling simulation) and to slope at different scales (accuracy and a typical application, i.e., terrain classification). The results highlighted the risks of using short wavelengths to represent the terrain and emphasized the importance of slope in different resolution scales.

1. Introduction

A comprehensive understanding of the Digital Terrain Model (DTM) is crucial for applications such as urban planning and natural resource management, being essential for creating detailed and reliable topographic maps (Davidson et al., 2012; Bryan et al., 2013). The lack of accurate information on the DTM can lead to a series of problems, especially in regions like the Amazon, where obtaining cartographic data is challenging due to the vast expanse and environmental complexity (Paradella et al., 2001). Additionally, in tropical forest regions like the Amazon, the difficulty of seeing the ground through the canopy with conventional techniques makes it urgent to adopt innovative approaches to improve the quality of these data (Armenteras et al., 2006; Morton et al., 2006; Elmiro et al., 2006).

Therefore, it should be noted that the main methods of cartographic data acquisition, such as Photogrammetry and shortwave radar, often result in the creation of a Digital Surface Model (DSM) instead of a DTM (Crosetto and Aragues, 2000; Davidson et al., 2012; Dong et al., 2019; Polidori et al., 2022). This means that the models often represent the terrain elevation with tree canopies, which can lead to uncertainties in describing the relief due to elevation and slope errors (Caldeira et al., 2023). This scenario can be problematic, especially in areas with moderate relief, affecting the accuracy of important data such as watershed delineation and drainage network extraction (Polidori et al., 2022). Therefore, when considering the DSM instead of the DTM, it is crucial to carefully evaluate elevation and slope variables. The presence of trees with significant height and irregular texture can hinder the analyses of these variables, depending not only on the acquisition method but also on the resolution of the product used, as demonstrated by Polidori and Simonetto (2014).

To address this problem, among the methods to obtain global elevation models in forested areas, the use of longer wavelength radars stands out. Particularly, radar operates within a range of wavelengths between 3 cm and approximately 70 cm, showcasing itself as a significant tool in analyzing and representing terrestrial topography on a global scale. In radar, the backscattered signal can be processed through techniques such as Interferometry (InSAR) and Tomography (TomoSAR), depending on the acquisition configuration, providing the ability to model terrain even in dense forest environments (D'Alessandro and Tebaldini, 2019; El Hage et al., 2022).

Over the last two decades, various Earth observation missions have resulted in the production of global Digital Elevation Models (DEMs) with resolutions lower than 100 meters, many of which have been made freely available worldwide. These advances have represented a true revolution in geospatial sciences and have fueled a wide range of applications that rely on accurate information about Earth's topography. As a result of this progress, the demand for high-quality DEMs in various fields of knowledge has continued to grow, challenging users to understand the fundamental characteristics of these datasets and make informed choices for their specific needs. It is crucial to emphasize that, despite the effectiveness of radar in generating elevation models, it is essential to use this data appropriately to avoid significant inaccuracies in various applications. Therefore, assessing the quality of these DTMs is of paramount importance and can be evaluated using different criteria (El Hage, 2012; El Hage et al., 2022; Caldeira et al., 2023). It is also emphasized that the quality is not limited by mission characteristics, but post-processing methods can improve the product, as in the cases of TOPODATA (Valeriano, 2008) and Fabdem (Hawker et al., 2022).

As an important step in addressing this issue, this article aimed to provide relevant information to meet user demands, contributing to the community's ability to identify the most suitable

This contribution has been peer-reviewed. The double-blind peer-review was conducted on the basis of the full paper.
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dataset for their analytical needs. To achieve this goal, a qualitative and subjective comparison was conducted between the elevation and slope of the most widely used global DEMs to date (Bielski et al., 2024), including SRTM, Copernicus, and Fabdem, as well as DEMs derived from airborne radar in X and P bands. The results obtained were highly promising, allowing for an analysis of the advantages and disadvantages of each DEM and providing valuable insights for users when making decisions regarding the use of these datasets.

2. Materials and methods

2.1 Data

2.1.1 Study Area: The study area is a watershed located between north latitudes 01° 59’ 57” and 03° 29’ 52” and west longitudes 51° 59’ 57” and 53° 00’ 12” (Figure 1). It is situated in the northwest of the state of Amapá (Brazil), near the neighboring territory of French Guiana along the middle course of the Oiapoque River, which flows into the Atlantic Ocean. The region’s relief, which is a typical Pre-Cambrian geological formation of the Guiana Shield, does not exceed 500 meters in altitude, but the slopes are steep and the hydrographic network is dense. The landscape is characterized by dense forest cover, as part of the Amazon biome.

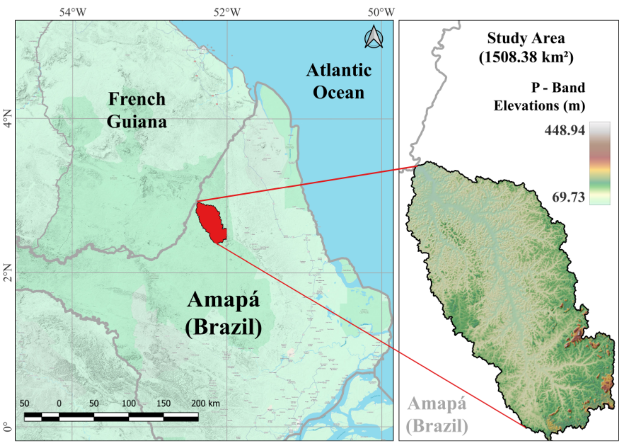

Figure 1. Study area location. On the left-hand side, the study area is highlighted in red over the Brazilian territory (State of Amapá), near the border with French Guiana. On the right, we have the hydrographic basin with greater emphasis, indicating its elevations in a color scale.

2.1.2 X- and P-band radar data: The X- and P-band radar data were collected in 2014 through a partnership between the Government of the State of Amapá (Secretary of State for Planning (SEPLAN) and Secretary of State for the Environment (SEMA)) and the Brazilian Army (Directorate of Geographic Service, Army Geographical Information and Images Center (CIGEx), and 4th Survey Division (4th DL)). This campaign extended the previous *Radiografia da Amazônia* program, encompassing other states in the Brazilian Amazon. The primary objective was to generate the *Base Cartográfica Contínua do Amapá* (BCDCA) based on airborne radar image acquisition. A DTM and a DSM were produced by P and X-band radar interferometry, respectively. The Synthetic Aperture Radar (SAR) products have a UTM projection system, zone 22 N, with SIRGAS 2000 elevation datum, and both products are in ”.TIF” format with a spatial resolution of 5 m and coded in 32 bits (Guimarães Filho and Borba, 2020).

In this work, the P band radar was used as a terrestrial reference based on studies that utilized the band P radar and showed promising results compared to altimetric and slope data (D’Alessandro and Tebaldini, 2019; Caldeira et al., 2023; El Hage et al., 2022; Caldeira et al., 2024). The average error between the altitudes of the band P radar and the LiDAR digital terrain model was below 1 meter.

2.1.3 Additional data: For additional analyses, supplementary data were used for comparison. In addition to the DTM and DSM available locally and derived from P and X-band radar, respectively, with a mesh resolution of 5 m, as described earlier, global 30-m resolution DEMs were used for this study, namely, the widely used SRTM product based on C-band radar interferometry (Farr et al., 2007) and two post-processed DEMs, namely, Copernicus and Fabdem.

The Copernicus DEM was created as part of the Copernicus program by the European Space Agency (ESA). This digital elevation model was developed using data primarily collected by the German satellite TanDEM-X, along with its counterpart TerraSAR-X (Wessel, 2018; Rizzoli et al., 2017). These satellites worked together using a technique known as SAR interferometry, which enables the generation of accurate digital elevation models. The Copernicus DEM offers high spatial resolution and global coverage, making it a valuable tool for various applications such as environmental monitoring, urban planning, natural resource management, and more. Additionally, as part of the Copernicus program, the DEM is available free of charge to users worldwide, promoting open access to geospatial data crucial for sustainable development and informed decision-making (Strobl, 2020).

The Fabdem (Forests and Buildings removed Digital Elevation Model) is part of an evolution in DEMs that are utilizing machine learning to ”improve” current global DEMs by considering additional external data. Hawker et al. (2022) were the pioneers in creating the first freely available global digital terrain model, named Fabdem, derived from the Copernicus product. The authors used machine learning to remove buildings and forests from the Copernicus DEM and produce, a global elevation map with buildings and forests removed at a grid spacing of 1 arc-second ($\tilde{3}0$ m). A correction algorithm was trained on a unique dataset of elevation data from 12 countries, covering a wide range of climatic zones and urban extents. However, even the Fabdem, in attempting to adapt the CopDEM (Copernicus Digital Elevation Model) and generate a DTM, fails to produce an accurate DTM and does not represent a universal improvement over the CopDEM (Bielski et al., 2024).

2.2 Methods

To assist in the analyses of the impacts caused by using a DSM instead of a DTM, the following sections describe how to analyze digital elevation models with respect to two variables, elevation, and slope, using P-band radar interferometry DTM as a reference. To provide a more precise description of the analyses, two case studies were also conducted, applying the variables as the basis of the study.

In this study, the same method employed by Caldeira et al. (2023) and El Hage et al. (2022) was initially adopted tocompare DEMs generated by the P-band radar with those generated by the X-band radar, Copernicus model, SRTM, and Fabdem. The accuracy of the models was assessed using a classical approach, characterizing the statistical distribution of the differences between the models, using indicators such as mean, standard deviation, and Root Mean Square Error (RMSE) (Temme et al., 2009), for both elevation and slope.

2.2.1 Elevation quality - accuracy assessment and applicative relevance: To carry out this stage, DEMs of the study area were initially downloaded. Data were obtained using the Google Earth Engine, and with the assistance of a vector shapefile, the hydrographic basin was delineated for all models. To enable pixel-to-pixel comparison among all models, ArcGIS Pro software was used to ensure compatibility of projections and to resample all DEMs to the same 30-m resolution. For statistical analyses, a Python algorithm was implemented to process raster data and calculate the mean errors, standard deviations, and RMS errors.

Concerning the use of elevation, we conducted an application involving flood scenario simulation in the case of obstruction within the hydrographic basin, such as dam construction (Domeneghetti, 2016; Salgado et al., 2017; Meadows et al., 2024). No considerations were given to factors such as flow rate or precipitation, focusing solely on the elevation defined by a dam. To this end, the Global Mapper software was used to calculate the volume of water retained in the hydrographic basin, relying solely on the elevation of each model. In the simulation, an intermediate elevation was established between the maximum and minimum elevations of the models, fixed at 100 meters for the presentation of results, as above this value, the models exhibited very similar results due to being an area with little altimetric variation of the terrain.

2.2.2 Slope quality - accuracy assessment and applicative relevance: For slope-based comparisons, since slope is a scale dependent variable (Polidori et al., 2014; Santos et al., 2017), the DEMs were initially standardized at different resolutions (30 m, 50 m, 100 m, 150 m, and 200 m), using ArcGIS Pro software to generate slope and calculate its difference between the P-band DEM and all other models at each resolution. Statistical calculations for slope difference were also performed using a Python algorithm.

Regarding the DEM application based on slope, a terrain classification into different categories was chosen. The classes are Flat, Smooth Undulating, Undulating, Strongly Undulating, Mountainous, and Steep, as suggested by Santos et al. (2018). This classification of soil based on its slope is widely used as a reference for various studies. Applications include soil characterization for land use classification, calculation of land use for flood and inundation prediction, soil loss prediction, quantification of soil erosion, among others. This classification was conducted using the ArcGIS Pro software, involving the reclassification of images according to the criteria established in Table 1, and thus, the calculation of the area for each class was performed.

Relief Classes	Slope (%)
Flat	0 – 3
Gently Undulating	3 – 8
Undulating	8 – 20
Strongly Undulating	20 – 45
Mountainous	45 – 75
Steep	>75

Table 1. Relief classes based on slope (%) according to Santos et al. (2018).

The classification process was applied to all models and at all different scales, i.e., for resolutions of 30 m, 50 m, 100 m, 150 m and 200 m, to observe the behavior of slope distribution in relation to the DEM scale.

3. Results

The results allow to quantify the consequences of using a DSM instead of a DTM.

3.1 Consequence on elevation

3.1.1 Accuracy assessment A preliminary visual analysis shows the similarity of the models compared to the one obtained from P-band radar, which is considered our reference in this study. All models have a resolution of 30 meters, and it is noticeable how the models from the X-band (aerial X-band and Copernicus), as well as the SRTM, depict a DSM describing both the upper surface of the canopy. In contrast, the models from the P-band and Fabdem represent a DTM, as observed in Figure 2.

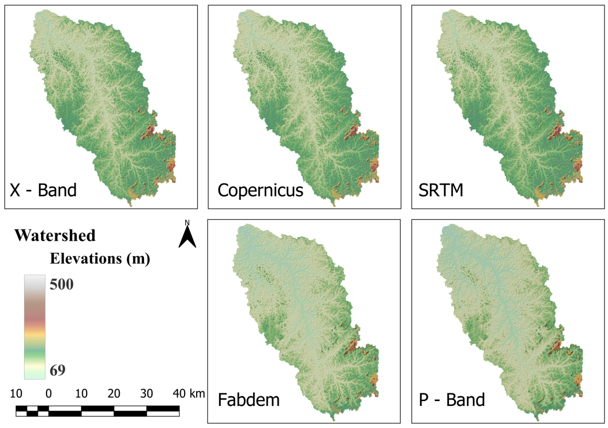

Figure 2. Hydrographic basin with a resolution of 30 m for all sensors used. There is the visual representation of the digital elevation models from aerial X-band, Copernicus model, SRTM, Fabdem, and aerial P-band, respectively. All have been adjusted to be on the same color scale for elevation representation.

To quantify the values contained in the models presented in Figure 2, Table 2 provides information about the maximum and minimum elevations, as well as the means and their standard deviations. A mean difference of 27 meters in relation to the reference model (P-band) was observed from the elevation values of all the models. As the area under consideration encompasses no built structures, it is concluded that this difference represents the average height of the vegetation within the location. Additionally, it is observed that despite the SRTM model having a longer wavelength than the X-band (aereo) and Copernicus models, it displayed a higher average elevation than the others. This outcome is justified by the original resolution of the model, which is poorer compared to the others. Even when all models are adjusted to the same resolution, it is emphasized that with a higher resolution than the one interpolated at the end, the original resolution characteristics are "carried" along with this interpolation.

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Sensor	Maximum elevation (m)	Minimum elevation (m)	Mean (m)	Standard Deviation (m)
X - Band	497.89	69.75	155.31	33.36
Copernicus	494.22	69.00	156.16	33.40
SRTM	471.00	74.00	158.85	33.14
Fabdem	477.07	69.00	133.49	32.89
P - Band	448.57	69.78	129.80	31.85

Table 2. Statistical data of elevations in meters, referring to each digital elevation model.

Figure 3 shows the statistical distribution of elevation differences between each DEM and the reference, based on three indicators - mean, standard deviation, and RMSE. The results for the SRTM, Copernicus, and airborne X-band models were quite similar, with the mean ranging between 25 and 30 m, primarily due to canopy height. It was noted that the standard deviation ranged between 5-7 m for all models, primarily due to the canopy shape with heterogeneous tree heights (even with a 30 m resolution, leading to a smoother surface model). Therefore, the behavior of these models concerning the terrestrial reference was observed, clearly indicating the representation of these models as much closer to a DSM than a DTM.

However, one of the models stood out in terms of comparison with the elevation, due to its proximity to the terrain, which was Fabdem. This model had a result of 3.74 m in its mean elevation difference compared to the reference, but it is noted that this value does not represent the real difference of this model from the terrain, as the bias of the P-band still needs to be considered. However, this value is considered low, as it has been calculated in previous studies to have a mean bias below 1 m (El Hage et al., 2022; Caldeira et al., 2023). Nevertheless, observing the standard deviation (5.63 m) and the RMSE (6.67 m), it was not far from the other DEMs, which means that the irregular canopy surface was moved down to the ground, taking along the characteristics of the X-band.

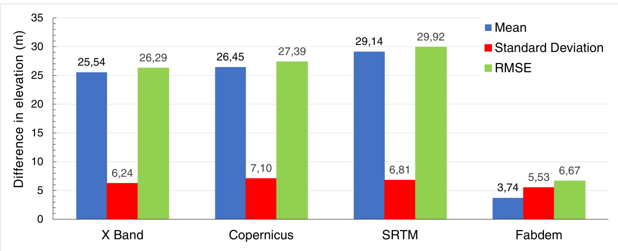

Figure 3. Statistics of elevation difference between the Digital Elevation Models and the reference Digital Elevation Model (P-band).

3.1.2 Applicative relevance:

For a case study involving the elevation variable, the basin volume of the study area was calculated each DEM. Then, a rise in water level in this region was simulated until reaching an elevation of 100 m. This elevation was adopted because the minimum elevation of the area was 69 m in all models, and the mean elevation of the reference model was 129.80 m, as shown in Table 2.

Figure 4 shows that the volume calculated from the aereo X-band, Copernicus and SRTM is greatly underestimated, with only 5.6%, 6.11%, and 2.40%, respectively, of the total water volume filled by the reference model, which was 1.89 km³. Once again, the degree of proximity of the Fabdem model is noted, which reached a percentage of 77.49% of the volume filled compared to the reference, demonstrating its excellent performance when it comes to the elevation variable.

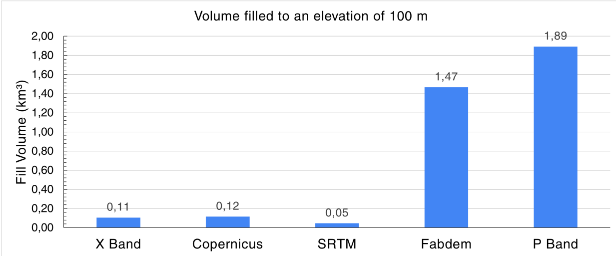

Figure 4. Volume of water filling in km³ calculated for the water level at 100 m for each DEM.

The study area has little variation in elevation, which is a common characteristic of Amazonian landscapes. Therefore, the major differences between the models are due to the vegetation present in the area.

In Figure 5, the area filled by water is presented for each DEM in cyan tone, while the reference area is represented in dark blue. The proximity of the Fabdem model to the total filled area of the reference is observed, representing 82.59% of the 213.38 km²reference value. On the contrary, the aerial X-band, Copernicus and SRTM models lead to a great underestimation of the filled area, with values of 8.07%, 7.47% and 4.34%, respectively.

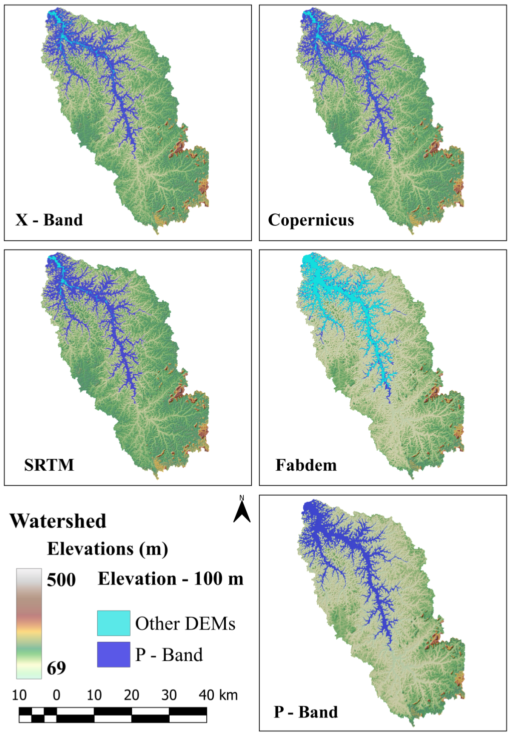

Figure 5. Representation of water filling with a quota of 100 m, in dark blue for the reference P-band DEM and in cyan for all other DEMs.

3.2 Consequence on slope

3.2.1 Accuracy assessment:

Beyond the comparisons between DEMs in terms of elevations, slope was also calculated to analyze the shape of these models. All DEMs were compared with the reference in terms of mean and standard deviation of slope. According to Polidori and Simonetto (2014), digital elevation models tend to become parallel and flat as their resolution degrades, as with sparser data, sensitivity in constructing the model’s shape is lost. Therefore, in this study, slope calculation was performed at different resolutions to consider this scale effect. Resolutions of 30 m, 50 m, 100 m, 150 m, and 200 m were chosen for the calculations.

It was concluded that as the resolution degraded, the models tended to become parallel, i.e., with similar slopes, with mean and standard deviation values becoming smaller and closer to each other. At a resolution of 30 m, for example, a mean slope value of 8.82° and a minimum value of 5.15° were obtained, related to the aerial X-band and the reference P-band models (Figure 6). However, when the same models were compared at a resolution of 200 m, these values changed to 2.76° and 2.31°, respectively. The same pattern was observed for the standard deviation, as shown in Figure 7.

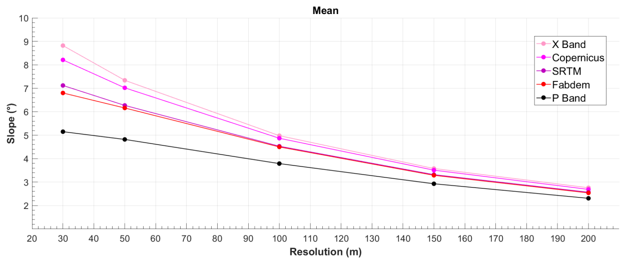

Figure 6. Average slope as a function of DEM resolution.

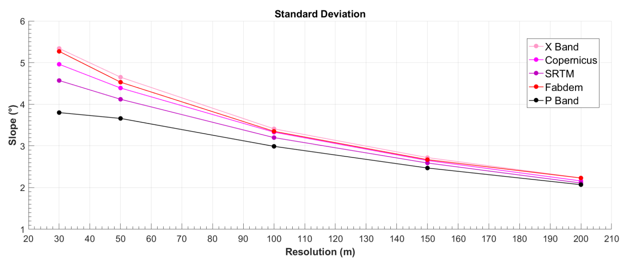

Figure 7. Slope standard deviation as a function of DEM resolution.

After extracting the results for each model and at different resolutions, the statistics of the differences between these models and the reference were also calculated. The comparison between the models and the reference further highlighted the analysis of the scale effect on slope, as evidenced in Figures 8, 9, and 10, which depicted the behavior of the mean, standard deviation, and RMSE, respectively, for each model.

In Figure 8, the mean slope varied from a maximum difference, obtained by the aerial X-band model, of 3.67° at 30 m resolution, to an average difference of 0.45° for the same model at a resolution of 200 m, highlighting the loss of terrain detail with the degradation of scale, as well as the loss of canopy details and consequently the removal of noise.

The standard deviation (Figure 9) and the RMSE (Figure 10) exhibited a distinct behavior from the mean in the model analyses, as the original resolution influenced the process. The Fabdem model, which had previously yielded the best results,

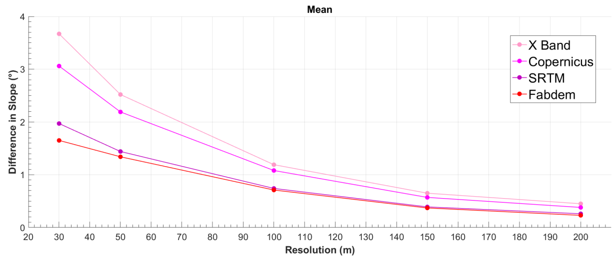

Figure 8. Average slope difference between each DEM and the reference DEM et different resolutions.

became variable, as it is derived from the Copernicus (X-band) and interpolated to resemble a digital terrain model. Despite this interpolation, a behavior similar to the aereo X-band was observed in its standard deviation and RMSE as the resolution degraded.

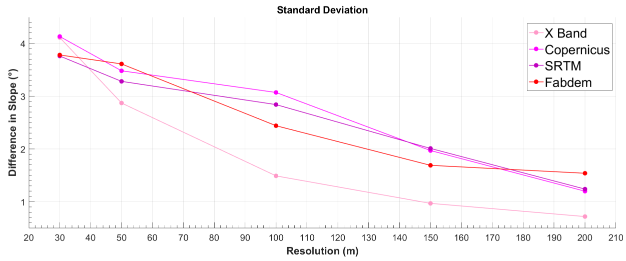

Figure 9. Standard deviation of slope difference, in degrees, between each DEM and the reference DEM at different resolutions.

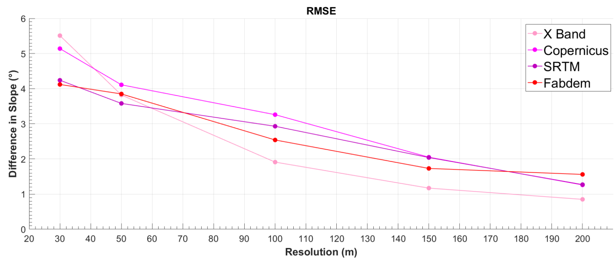

Figure 10. RMSE of slope difference, in degrees, between each DEM and the reference DEM at different resolutions.

3.2.2 Applicative relevance: Figure 11 presents the results of the case study based on DEM slope. As slope is utilized by users as a basis for various applications (erosion map, flood risk map, landslide risk map, etc.), a classification proposed by Santos et al. (2018) was employed. This classification utilizes the percentage slope of the model to categorize it into 6 classes: Flat 0 – 3%; Gentle Undulating 3 – 8%; Undulating 8 – 20%; Strongly Undulating 20 – 45%; Mountainous 45 – 75%; and Steep > 75%. Subsequently, the areas representing each class were calculated at all resolutions used (30 m, 50 m, 100 m, 150 m, and 200 m).

It was observed through the graph that all DEMs exhibited similar behaviors, predominantly classified as undulating terrain at a 30 m resolution. Although the reference obtained the same classification (undulating terrain), the Gentle Undulating and Undulating terrain classes were very close. As the resolution degraded, ranging from 30m to 200m, it was observed that the models also tended to align in their classification. In other

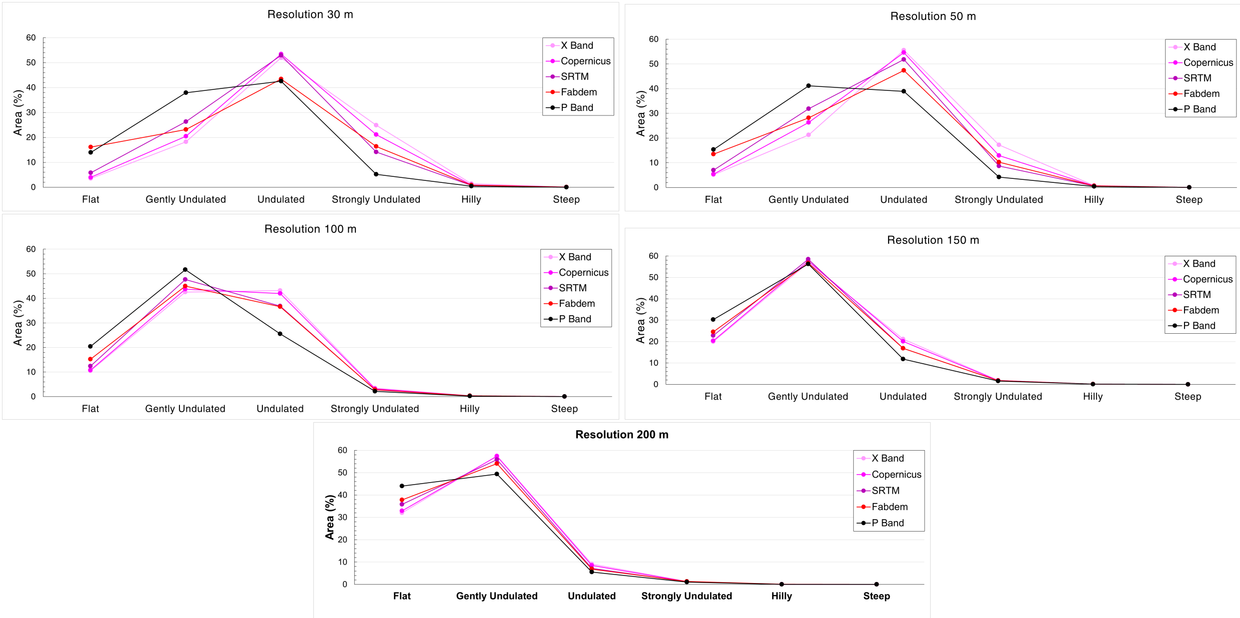

Figure 11. Relative areas of slope classes in DEM classifications for different resolutions.

words, it was noted that, for this classification, depending on the precision used by the user, resolutions larger than 100 m tend to yield similar results in their applications, regardless of the product. As the resolution degraded, the details of the terrain shape were lost, gradually becoming flatter, as evidenced in Figure 11.

These results show that the various DEMs analysed, which are influenced by the shape of the canopy resulting in higher slopes, lead to an overestimation of the risk of erosion.

4. Conclusion

Based on the analyses conducted, it becomes evident that the appropriate selection of radar bands, according to their specific wavelengths, played a crucial role in altimetric analyses. It was observed that when applying altimetry to DEMs, DSMs such as the X-band, Copernicus, and SRTM exhibited a volume filling of less than 10% compared to our terrestrial reference. In contrast, the Fabdem model achieved a 77% volume filling of the total water within the watershed, highlighting the risks associated with using DSMs to represent the Earth’s surface. Therefore, a transparent approach is recommended when using these models, emphasizing the inaccuracies resulting from altimetric usage.

Regarding terrain slope analysis, it was observed that as resolution decreases, fewer data points are used for interpolation, resulting in stabilization in slope representation among different DEMs. Although radar penetration at lower resolutions has less interference in slope analysis than in altimetry, the lack of terrain details at lower resolutions is highlighted.

Concerning the DEMs used, it is important to note that among the evaluated methods, SRTM showed inferior results compared to others, despite having a longer wavelength compared to Copernicus. On the other hand, the Fabdem model demonstrated great potential for soil representation in altimetric applications, outperforming the terrestrial reference used, which was the P-band. However, when analyzing the slope of the model, it was observed that during the processing of Copernicus to obtain Fabdem, the slope was not corrected, concluding that Fabdem behaves altimetrically similar to the P-band but in terms of slope behaves similar to the X-band.

It is then concluded that it is possible to use a DSM instead of a DTM only under specific conditions, such as using slope at resolutions above 100 meters, where this variable loses its distinctive characteristic, resulting in very similar models. However, it is crucial to emphasize that when using altimetry, it is necessary to clearly identify the model used and the expected accuracy, as DSM-related models will always have a bias compared to the actual terrain, especially in forested or urban areas with constructions, due to the height of trees or buildings.

These conclusions provide valuable insights for users when selecting the most suitable DEM for their altimetric analyses, highlighting the importance of considering not only resolution but also the characteristics of radar bands used in generating elevation models.

Acknowledgements

The authors are grateful to SEMA (Amapa state) for providing P- and X-band radar DEMs.

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