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Comparison between Digital Terrain Models generated by P-Band Radar and LiDAR in the Amazon, a case study in Amapá (Brazil).

Comparação entre os Modelos Digitais de Terreno gerados por Radar em Banda P e LiDAR na Amazônia, um estudo de caso no Amapá (Brasil).

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Abstract: The Digital Terrain Model (DTM) is an important product used in geosciences, but its extraction in dense forest areas is still a challenge. One of the major difficulties in extracting a DTM via remote sensors is in dense forest areas, as the generated information becomes degraded due to the fact that the most commonly used techniques can only measure canopy elevation and not terrain elevation, limiting cartography in areas such as the Amazon. The most appropriate technique for extracting a DTM is airborne LiDAR (Light Detection And Ranging), but there are limitations of time and cost for large areas. P-band radar waves have a great capacity for penetrating through dense vegetation, making it a promising tool for digital terrain modeling in forested areas. This technique was used for the latest update of the cartography of the Amapá state (Brazil). This article aims to evaluate the overall quality of a DTM produced using airborne P-band radar interferometry in relation to LiDAR data (used as a reference) in 4 regions of the Amapá state, using various criteria. In addition to the visual comparison confirming the general similarity of the two products, the difference in terms of elevation and slope was evaluated, with an average error in elevation of -0.52 m, while having a standard deviation and average RMSE below 3 meters, with a difference in slope of approximately -4° and a standard deviation and average RMSE of 4.74° and 6.14°, respectively. This study provides an estimate of the accuracy of P-band radar DTM, both in terms of elevation and slope, which are essential variables for characterizing landforms.

Keywords: Digital Elevation Models; Quality; Precision; Radar; LiDAR.

Resumo: O Modelo Digital de Terreno (MDT) é um importante produto usado em geociências, mas sua extração em áreas florestais densas ainda é um desafio. Uma das grandes dificuldades na extração de um MDT via sensores remotos é em áreas florestais densas, pois nestas áreas as informações geradas ficam degradadas, já que as técnicas mais utilizadas só conseguem medir a elevação do dossel e não do terreno, limitando a cartografia em áreas como a Amazônia. A técnica mais adequada para extração de um MDT é o LiDAR (*Light Detection And Ranging*) aerotransportado, porém há limitações de prazo e custo para grandes áreas. As ondas de radar de Banda P têm uma grande capacidade de penetração através da vegetação densa, tornando-a uma ferramenta promissora para modelagem digital do terreno em áreas florestais. Essa técnica foi usada para a última atualização da cartografia do estado do Amapá (Brasil). Este artigo tem como objetivo avaliar a qualidade geral de um MDT produzido usando interferometria radar de Banda P aerotransportado em relação a dados LiDAR (usados como referência) em 4 regiões do estado do Amapá, utilizando vários critérios. Além da comparação visual que confirma a semelhança geral dos dois produtos, foi avaliada a diferença em termos de elevação e declividade, com um erro médio em sua elevação de -0,52 m, enquanto possui um desvio padrão e RMSE médio abaixo de 3 metros, com uma diferença na declividade de aproximadamente -4° e um desvio padrão e RMSE médio de 4,74° e 6,14°, respectivamente. Este estudo fornece uma estimativa da precisão do MDT radar de Banda P, tanto em termos de elevação quanto de declividade, que são variáveis essenciais para caracterizar as formas do relevo.

Palavras-chave: Modelos Digitais de Elevação; Qualidade; Precisão; Radar; LiDAR.

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1. Introduction

The mapping of terrain surfaces in forested areas is a necessity for geosciences. Obtaining accurate digital terrain models is crucial for understanding the impact of natural events, planning transportation routes, and identifying suitable areas for infrastructure construction. This becomes even more relevant in complex tropical forest regions. In addition to housing major repositories of plant diversity (FOODY, 2003 and THOMAS et al., 2004) and playing a significant role in the global carbon cycle and climate change (DIAZ et al., 2009), tropical forests are also essential sources of natural resources for local populations.

In the Amazon, there is limited availability of large-scale maps, and the existing ones require updating. Remote sensing and photogrammetry are alternatives for obtaining information in these environments. According to Crosseto and Aragues (2000), photogrammetry has well-established techniques widely used in various mapping applications. However, for mapping dense forest areas like in the Amazon, such techniques become less effective because the targets imaged on the Earth's surface must be directly within the aerial camera's field of view, without interference from surface obstacles such as atmospheric disturbances, cloud cover, or vegetation cover. Many countries in the equatorial region, including the Amazon, have a low information index regarding natural resources, with almost perennial cloud cover throughout the year. In the Amazon, the presence of smoke further limits the availability of additional optical data (PARADELLA et al., 2001).

RADAR (RAdio Detection And Ranging) images, both airborne and orbital, can overcome problems such as atmospheric limitations in optical images. Both help analyze vegetation through its structural components, as they are not affected by the atmosphere (WOODHOUSE, 2005). Within the microwave spectrum, radar's different wavelengths are categorized into bands represented by letters K, X, C, S, L, and P, with average variations ranging from 1 to 75 cm (LOPES; LIMA, 2009). The most commonly used sensors for extracting Digital Elevation Models (DEM) use a short wavelength and are sensitive to the canopy rather than the terrain, similar to photogrammetry. According to Polidori et al. (2022), the major issue with these data is that most DEMs are actually Digital Surface Models (DSM), representing the canopies as clusters of trees, and in most applications of these models, authors use them as if they were DEMs.

One of the most accurate techniques for extracting a DEM is LiDAR (Light Detection And Ranging), especially in forested areas where ground access is challenging. However, this technique still faces logistical challenges in covering extensive areas, resulting in high costs and lengthy timelines. Another alternative is the P-band radar interferometry technology (HOFMANN et al., 1999). The long wavelength of the P-band can penetrate both clouds and a significant amount of vegetation, reaching the forest floor (DUTRA et al., 2002). Currently, there are only airborne radar data available in the P-band, with no orbital data. It is projected that a P-band radar sensor will be launched with the European Space Agency's (ESA) Biomass mission in 2024. The mission will consist of a low Earth orbit (LEO) satellite platform with the goal of providing global maps of carbon stored in the world's forests (LE TOAN et al., 2011).

Like any other product, the capability of a DEM to meet user requirements is characterized by various quality criteria. Once the general characteristics of the DEM are determined (resolution, spatial coverage, etc.), the main requirements concern the quality of the data itself, often defined in terms of absolute or relative elevation accuracy (VIEL and MENDES JUNIOR, 2020; SIM ÕES et al., 2021; CAPOANE, 2022; GOMES et al., 2022; MALINDI and ODERA, 2022)). Furthermore, digital models are expected to accurately represent the geomorphology, including elevation-derived features such as slope, aspect, curvature, among others (POLIDORI and EL HAGE, 2020; CAPOANE, 2022; COLARES et al., 2022; EL HAGE et al., 2022). The quality criteria indicate that the model should closely match the actual terrain position and resemble the real terrain as much as possible.

In this context, the objective of this study is to compare the elevation and slope of Digital Terrain Models extracted from P-band RADAR and LiDAR data in four regions of the Amapá state, in northern Brazil.

2. Materials and Methods

Study area

The study area consists of four samples representing the North, South, West, and Central regions of Amapá state in northern Brazil (Figure 1). These samples were chosen to represent the diverse landscapes of Amapá state within the Guiana Shield region. Each sample covers an approximate area of 6 km². In these areas, analyses and measurements were conducted on the altimetric data produced by LiDAR sensors (considered as the reference) and P-band radar. It is a typical Amazonian landscape with rugged terrain, dense hydrographic networks, and dense forest cover.

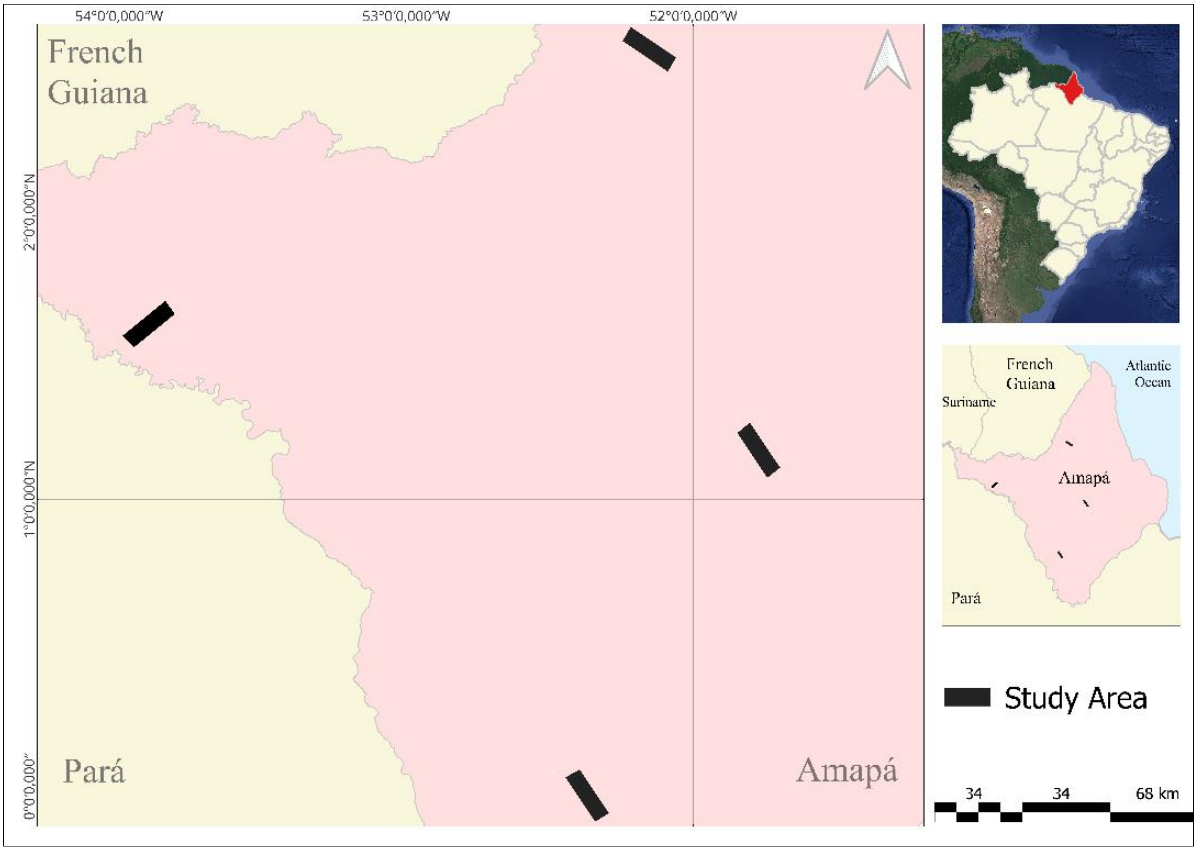


Figure 1 – Study Area
Source: Authors (2022)

MDT LiDAR

The LiDAR DTMs, used as reference, were collected between 2016 and 2018 through aerial missions of the Amazon Biomass Estimation (EBA) project, conducted by the National Institute for Space Research (INPE) and funded by the Amazon Fund. The LiDAR campaign was carried out using a Trimble Harrier 68i sensor (Trimble; Sunnyvale, CA) on board a Cessna aircraft. Horizontal and vertical accuracies were controlled to ensure values below 1 m and 0.5 m, respectively. In total, 906 transects were collected, some of which were intentionally overlapped with known field plots for model calibration (GORGENS et al., 2019 and GORGENS et al., 2020).

Point clouds were generated with a minimum density of 4 points/m², a field of view of 45°, a flight altitude of 600 m, and a ground transect width of approximately 494 m. The Universal Transverse Mercator (UTM) projection system was used, with zone 22 N and SIRGAS 2000 datum (GORGENS et al., 2019 and GORGENS et al., 2020). Points representing the ground, with a much lower density than 4 points/m² due to dense vegetation cover, were classified and interpolated into a Triangular Irregular Network (TIN) (Figure 2). The final DTM was resampled to a 5 m raster grid to be compatible with radar data.

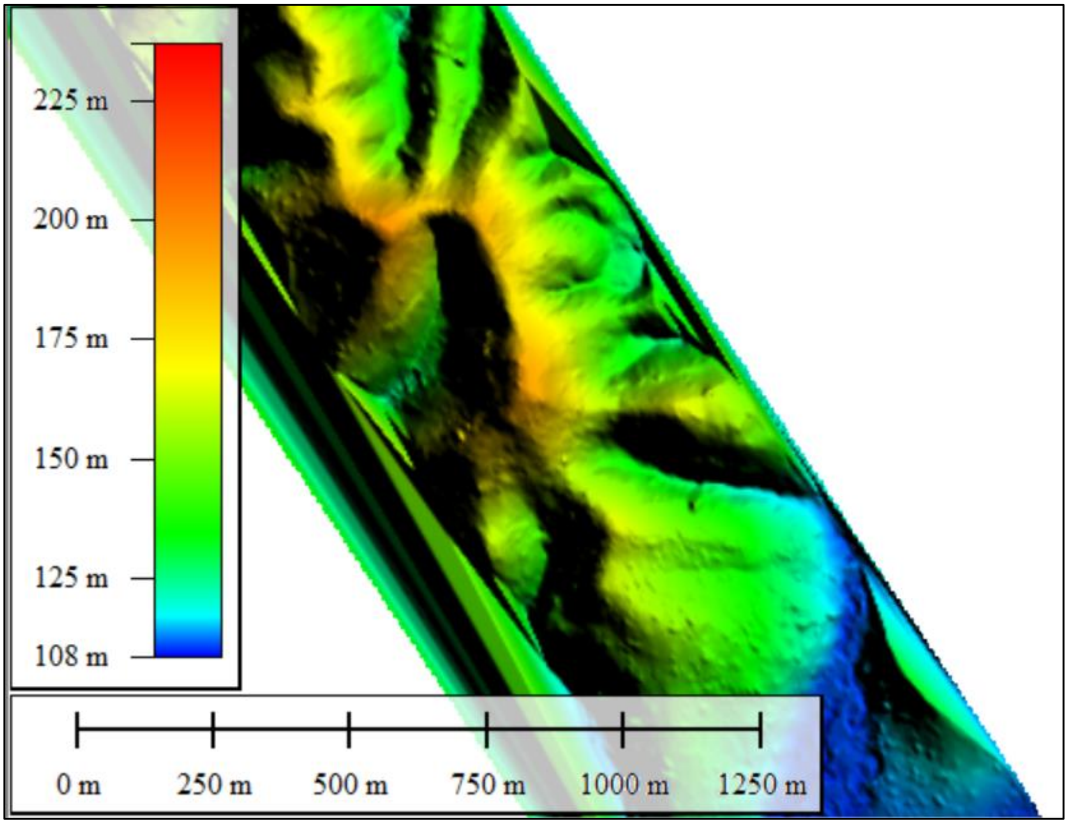


Figure 2 – Example of visualization of a LiDAR DTM, interpolated by a TIN in the Central study area.
Source: Authors (2022)

The process of creating a DTM from LiDAR data involves two sequential processes of filtering and interpolation. The filtering process can be influenced by factors such as point density, area slope, scanning angle, flight altitude, and the algorithm itself. The interpolation process, on the other hand, is especially impacted by the density of filtered returns classified as belonging to the terrain. Thus, in forested areas, positional error increases slightly, and shape errors are created due to the interpolation effect at greater distances, as shown in Figure 2 in the case of TIN interpolation, which can influence the results of slope accuracy evaluation (EL HAGE et al., 2022). Despite these artifacts, the overall high precision of the LiDAR DTM allows us to consider it as a reference for validating the DTM generated by the P-band radar. The radar and LiDAR campaigns took place on different dates, but there were no changes in the landscape relief.

P-Band DTM

The radar data was collected through a partnership between the Government of the State of Amapá (State Planning Secretariat (SEPLAN) and State Environmental Secretariat (SEMA)) and the Brazilian Army (Geographic Service Directorate, Army Geographic Images and Information Center (CIGEx), and 4th Survey Division (4th DL)). The main objective was to generate the Continuous Digital Cartographic Base of Amapá (BCDCA), acquired through airborne Synthetic Aperture Radar interferometric systems.

In this campaign, data for P-band and X-band interferometry were generated, resulting in Digital Terrain Models (DTMs) and Digital Surface Models (DSMs), respectively. Prior to the flights, corner reflectors were installed at various points to ensure proper correction of the DTMs. The SAR images are in the UTM projection system, zone 22 N, with the SIRGAS 2000 datum. Both images are in ".TIF" format with a spatial resolution of 5 m and a radiometric resolution of 32 bits. The flight was conducted with a twin-engine aircraft, at a flying altitude between 5,790 and 7,620 m and an average speed of 360 km/h.

Comparison between the DTMs

To assess the quality of a DTM, there are many possible criteria (POLIDORI and EL HAGE, 2020), but in this work, criteria related to altitude accuracy (position evaluation) and slope accuracy (shape evaluation) were considered, known as the external validation method (EL HAGE et al., 2022). External reference data were used to evaluate the position of the modeled terrain and the accuracy of the shape. The accuracy of a DTM is typically evaluated by characterizing the statistical distribution of the difference between the elevations of the DTM generated by Band P and the DTM generated by LiDAR, using indicators such as mean, standard deviation, and root mean square error (RMSE). The elevation error is a combination of gross, systematic, and random errors and is generally considered normally distributed. To characterize this distribution, histograms were generated for each DTM and each study area.

Subsequently, the elevation difference and slope difference between the DTMs were calculated to perform point-wise analyses based on these differences. For slope generation, ArcGIS 10.5 software in the ArcMap module was used with the Slope tool, calculated in decimal degrees. In any analysis between different objects, there is a certain percentage considered as outliers, which are points with significantly high errors. These errors are based on other similar studies by other authors using the same technique. In this work, a threshold of 10% of outliers with the largest errors in elevation and slope differences was used, meaning that the largest errors in our model, both positive and negative, were removed from the sample.

After calculating the elevation and slope differences between the DTMs and removing the sample with the largest errors, the mean, standard deviation, and RMSE were calculated for both variables in each study area. Finally, the mean and standard deviation of all areas were generated, representing the average error for the study region. The obtained value characterizes the elevation quality but does not necessarily reveal the uncertainty of the shape. Further analyses can determine if the altimetric data produced require corrections before being used in other applications that derive DTM data.

3. Results and Discussion

The analyses generated by comparing the MDTs (P Band and LiDAR) provided estimates of quality regarding the elevation and slope of the terrain in all study areas. Visually, it is possible to observe that the digital terrain model obtained by LiDAR was very similar to the model obtained by radar (Figure 4). This similarity is confirmed by comparing the elevation histograms (Figure 5).

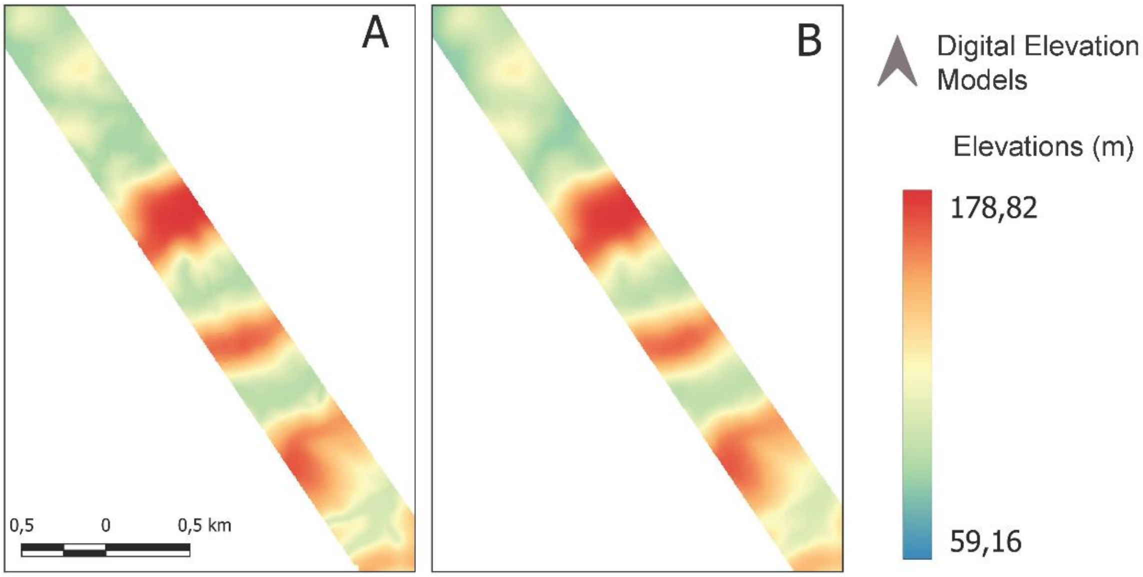


Figure 4 - Example of visualization of a LiDAR MDT (a) and a P Band MDT (b).
Source: Authors (2022).

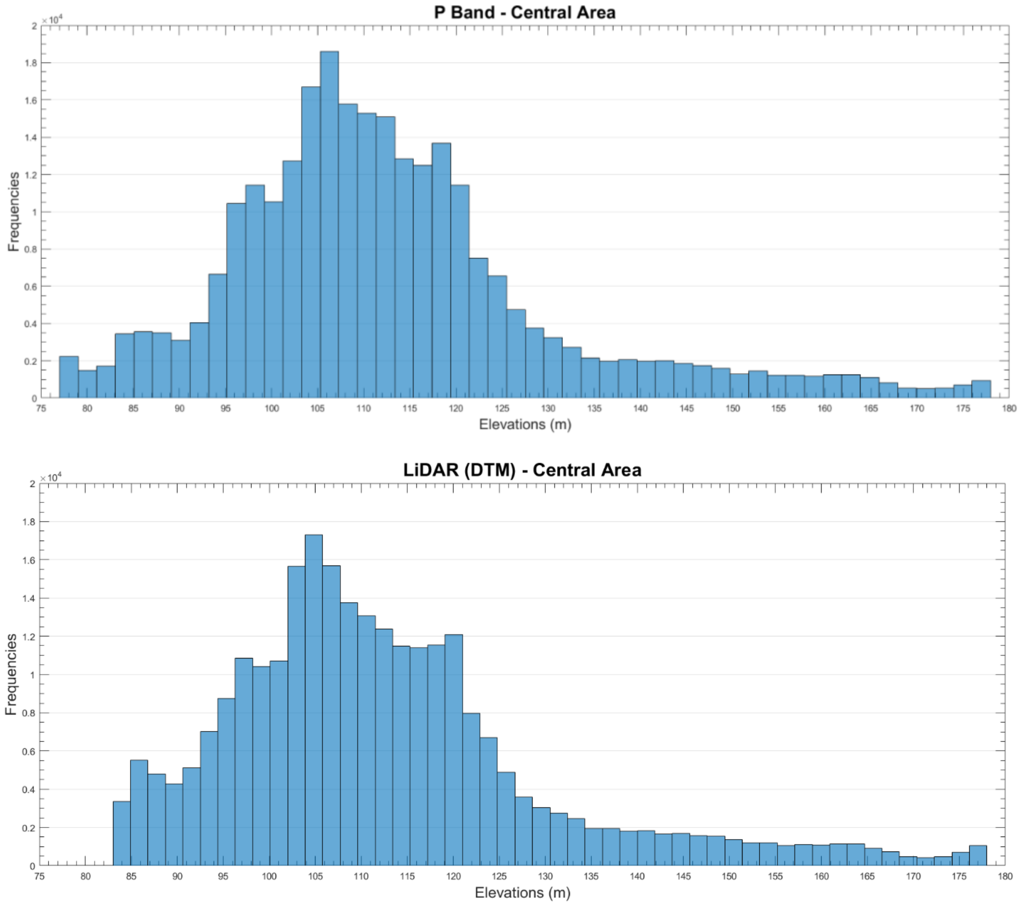
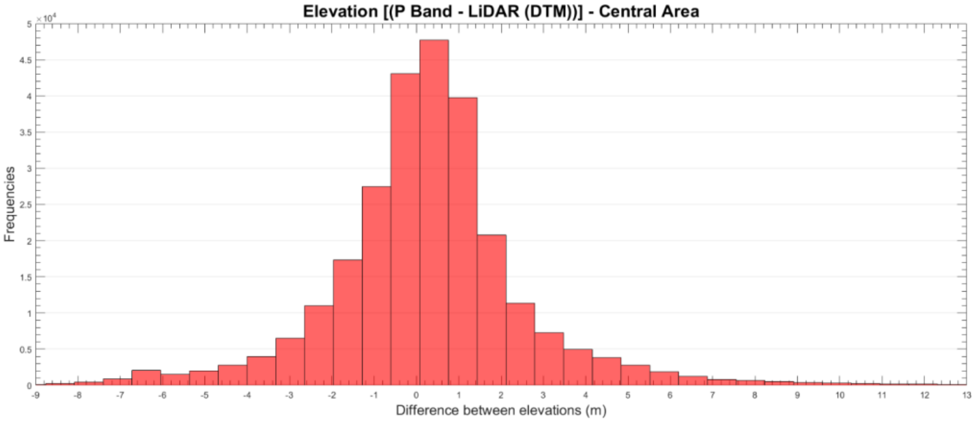


Figure 4 – Histograms of the MDT generated by P Band and LiDAR, respectively, from the central study area. Source: Authors (2022)

The histogram of the differences (Figure 5), for all study regions, exhibits a Gaussian behavior for both elevations and slopes, and the statistical data are represented by Figures 6 and 7.



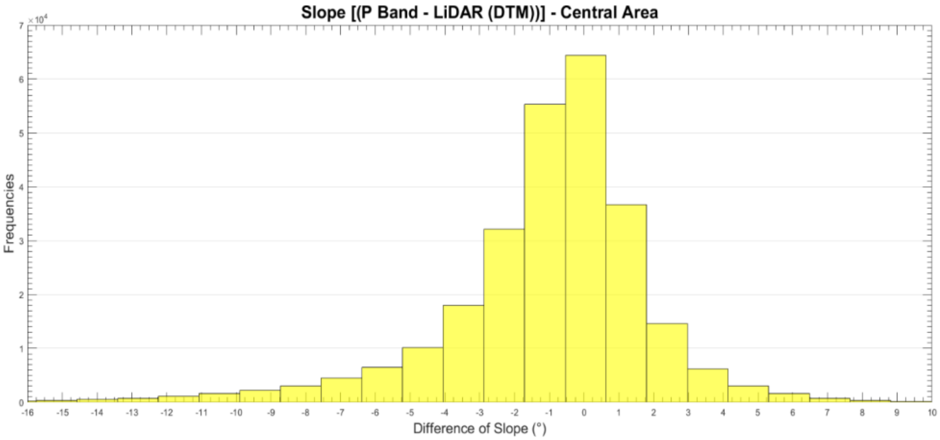


Figure 5 – Histograms of the difference in elevations and slopes between the P Band and LiDAR MDTs of the central region, respectively.
Source: Authors (2022)

It is noticeable that the average value of the elevation difference varies between 0.20 m and -1.18 m across the 4 regions. However, even considering the highest value of elevation difference, it can be observed that this error is relatively low, staying below 2 m of error, while the standard deviation is below 4 meters, largely due to the precision of the P Band interferometric data (Figure 6). The difference in standard deviations between the North, South, and West areas compared to the Central area is justified by the fact that they have very dense vegetation, causing the LiDAR points that touch the ground to be a smaller percentage compared to the Central area. However, despite the non-uniform standard deviation among the areas, the great potential of P Band radar data in terms of absolute elevation accuracy can be observed.

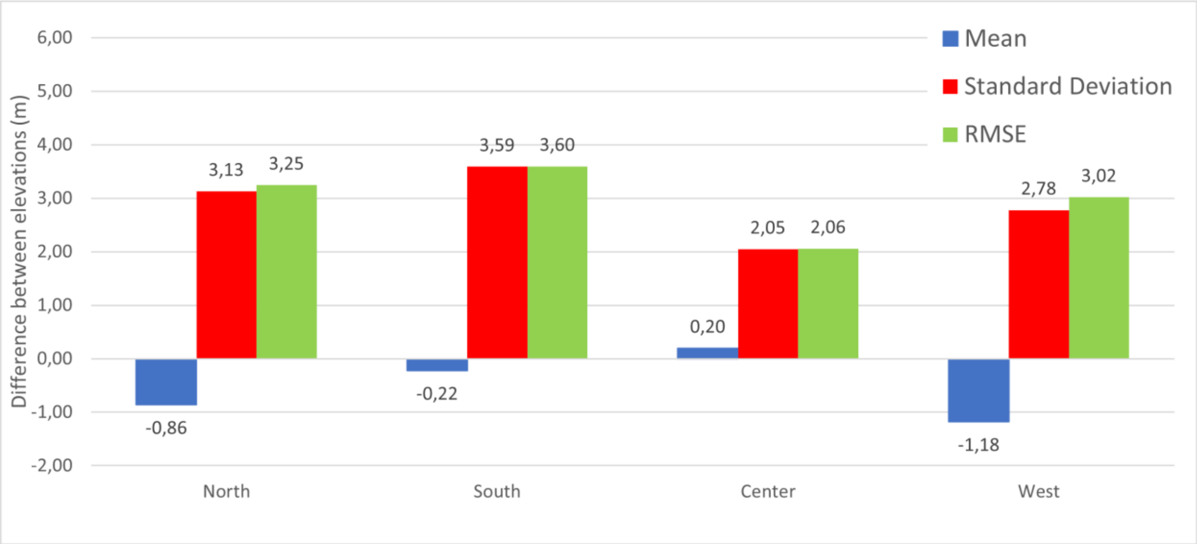


Figure 6 – Statistics of the elevation difference among the four study areas.
Source: Authors (2022)

The results obtained from the difference in slope between the four study areas show that the mean values (bias) vary between -1° and -5°, accompanied by the standard deviation and RMSE (Figure 7), indicating a strong correlation in both elevation and slope data.

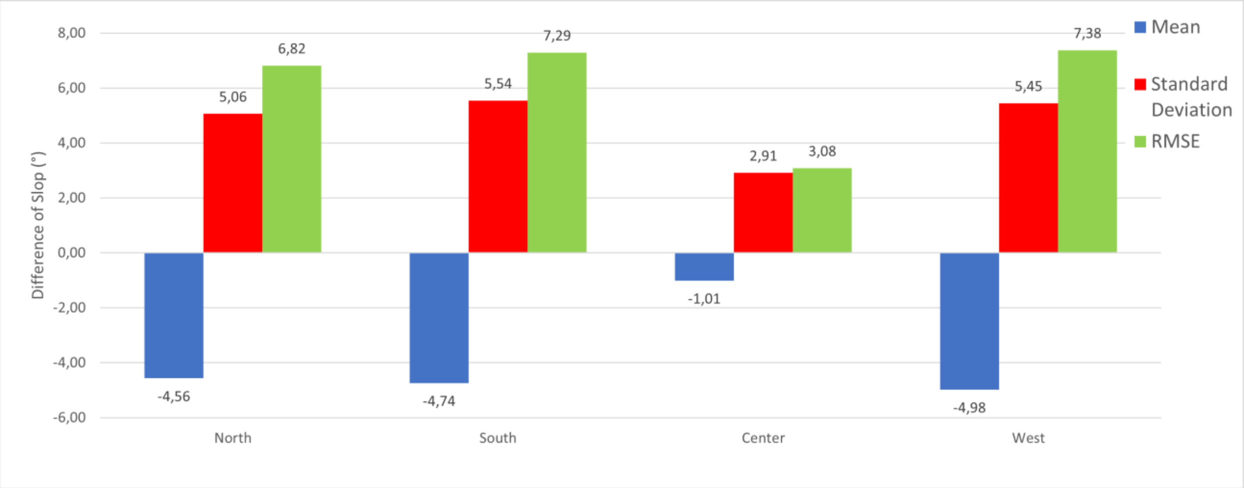


Figure 7 – Statistics of the slope difference among the four study areas.
Source: Authors (2022)

In order to compare the terrain shape in the two MDTs, an altimetric profile was generated for a portion of the models. In Figure 8, it can be observed that the models exhibit a close resemblance in their shape. However, some micro-reliefs are also noticeable in the LiDAR-generated MDT, which may result in slight errors in its slope. Such errors do not render the use of the LiDAR MDT as a reference impractical, as the statistics presented in the previous graphs demonstrate the great potential of its data.

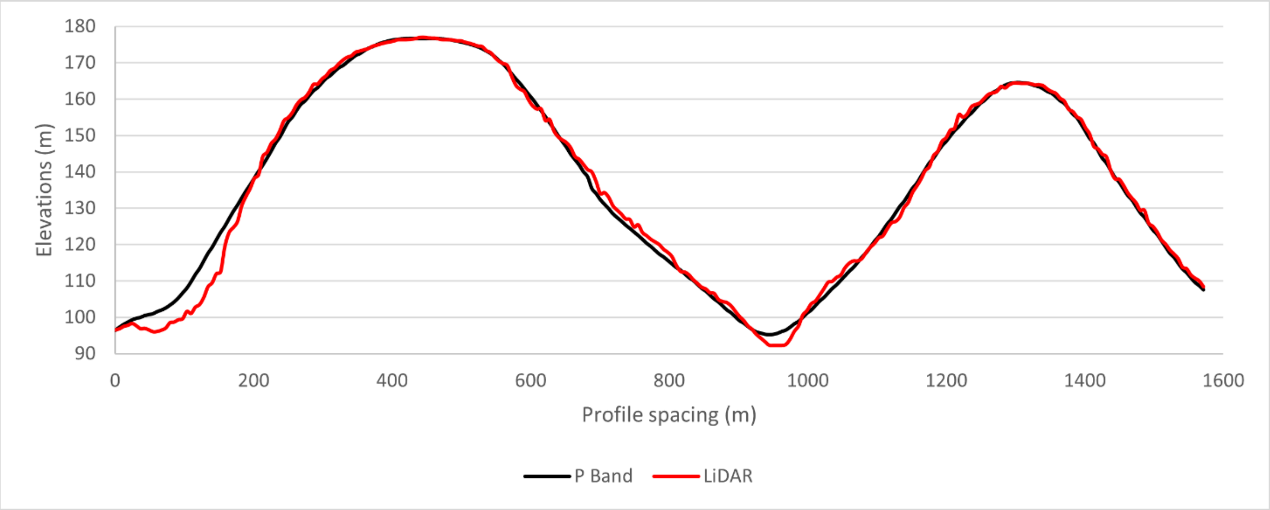


Figure 8 – Profile of a portion of the terrain in the Central area, representing the MDT from P Band and LiDAR.
Source: Authors (2022)

For a comprehensive analysis of the study region, the statistical data from Figure 9 (Mean, Standard Deviation, and RMSE) can be examined. Once again, a low average value is observed for the difference in elevations, with a value below 1 meter, and the standard deviation and RMSE are below 3 meters. These findings demonstrate the high correlation between the two analyzed MDTs, indicating that P Band exhibits significant potential in terms of absolute elevation accuracy.

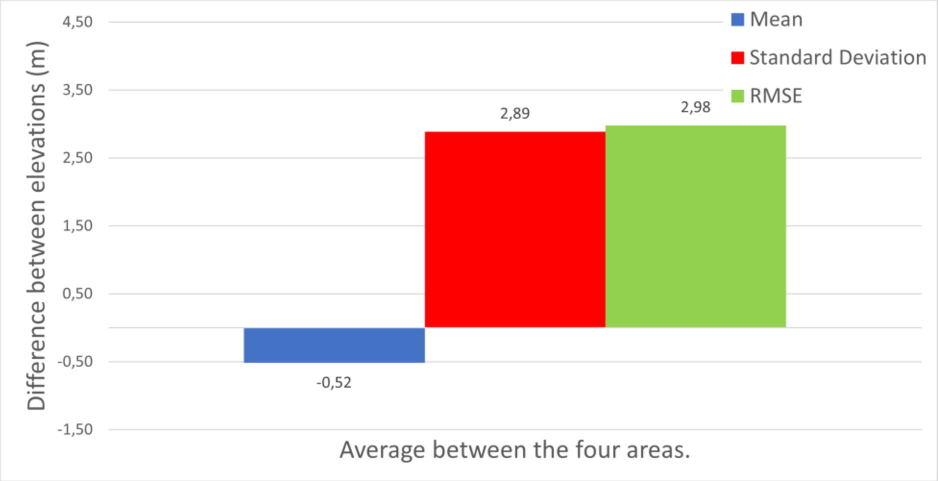


Figure 9 – Mean difference in elevation among the four study areas.
Source: Authors (2022)

When the average slope is analyzed, it can be observed in Figure 10 that the mean difference in slope for the four regions is approximately -4°, suggesting that the P Band radar interferometry underestimates the slopes, resulting in a smoother and more smoothed relief, as also illustrated in Figure 8, with an average standard deviation of 4.74° and an average RMSE of 6.14°. The slope results have a higher value due to the high sensitivity of LiDAR data in generating its measurements, where small micro-reliefs are observed. It is uncertain whether these micro-reliefs actually belong to the terrain or if they are small fragments of vegetation that remained in the model during filtering, which can interfere with the slope of the terrain, causing the negative bias. These values indicate the accuracy of the slope, an essential quality criterion for applications such as geomorphological analysis or automatic extraction of the drainage network.

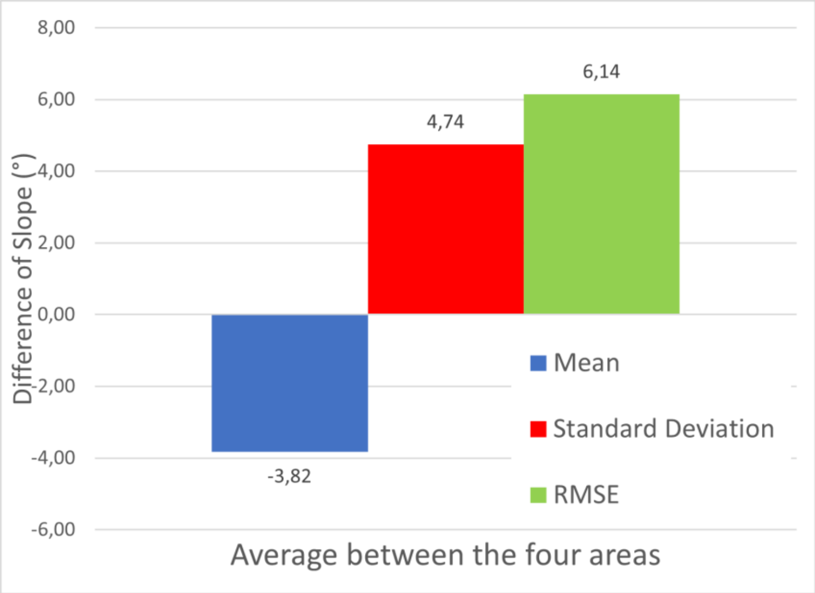


Figure 10 – Mean difference in slope among the four study areas.
Source: Authors (2022)

Despite these limitations, this study serves as a basis for future research in larger areas, including the detection of morphological inconsistencies in MDTs obtained by P Band radar interferometry, focusing on more diverse configurations, especially in terms of terrain topography, vegetation cover, or acquisition parameters. This study confirms the great potential of using the Radar-generated Digital Terrain Model (DTM) as a substitute for the freely available global Digital Terrain Models, which represent Digital Surface Models rather than Digital Terrain Models and are therefore poorly suited for areas with dense forests, such as the Amazon, as well as in geomorphology, hydrology, and other geoscience areas.

4. Conclusion

The quality of a Digital Terrain Model (DTM) is crucial for various applications, such as hydrological modeling, urban planning, landslide analysis, and climate change studies. It is necessary to carefully analyze all stages of the DTM generation process, from data collection to interpolation and resampling, taking into account the local influence of terrain slope and coverage.

One way to assess the quality of a DTM is to compare it with a reference product. In this case, LiDAR was used as it provides better results in areas with dense vegetation. However, LiDAR becomes impractical for large-scale applications. In this context, P Band radar data emerges as a promising alternative for representing the topography of extensive forested areas, such as the Amazon.

An accuracy assessment of the P Band-generated DTM was conducted by comparing it with a reference LiDAR survey. The results showed a very small bias (mean error) in the elevation of the P Band DTM, with a standard deviation and mean RMSE below 3 meters, making the results compatible with Class A specifications at a 1:25,000 scale. Regarding slope, an average difference of -4° was observed, with a standard deviation and mean RMSE of 4.74° and 6.14°, respectively.

These results indicate that P Band radar data has high potential for accurately representing the terrain topography under forest cover. This is particularly relevant for studies and applications in tropical forest areas, where vegetation density can hinder the acquisition of precise data using techniques such as LiDAR. However, it is important to note that the quality of P Band radar data may vary depending on various factors. Additionally, appropriate methodologies for data interpolation and resampling need to be used to avoid artifacts and errors in the final DTM.

In summary, the accuracy assessment results demonstrate that P Band radar data is a promising option for representing the topography of forested areas, complementing or replacing traditional techniques such as LiDAR in some situations. However, further improvements and validation of these data in different scenarios and conditions are necessary.

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