# Evaluation of Altimetric Accuracy in the Integration of GNSS Data with Global and Regional Digital Terrain Models in the Context of Rural Property Georeferencing

**Melito Júlio AVALINHO, Paulo Sérgio DE OLIVEIRA Jr., Caio dos Anjos PAIVA, Fábio Pagliosa ULKOWSKI, Brazil**

**Keywords:** Digital Terrain Model, Orbital Sensors, GNSS, Data integration, Accuracy.

## SUMMARY

Digital Terrain Models (DTMs) are important in representing Earth's surface relief. Recent updates of Brazil's Technical Standard for Georeferencing of Rural Properties have made altimetric information a mandatory requirement for cadastral boundary delineation. Leveraging this regulatory advancement, the present study examines how the integration of GNSS survey data with both global elevation models and orbital radar sensors can enhance vertical accuracy and spatial coherence of DTMs in two Paraná municipalities (Reserva do Iguaçu and Guarapuava). This study aimed to evaluate the altimetric accuracy of integrating GNSS data with the Shuttle Radar Topography Mission (SRTM) and models derived from Sentinel-1 and ALOS PALSAR InSAR imagery. GNSS+SRTM integrated models were produced in QGIS, while Sentinel-1 and ALOS PALSAR were conducted in ESA's SNAP environment. Model accuracy was quantified through Mean Absolute Error (MAE), Standard Deviation (SD), and Root Mean Square Error (RMSE), with independent GNSS points reserved as checkpoints. Spatial diagnostics comprised error density curves, boxplots, and Moran's Index to assess residual clustering. Results revealed that GNSS+SRTM_IDW exhibited the poorest altimetric accuracy (RMSE up to 13.84 m; SD up to 6.88 m), reflecting high dispersion and systematic bias. In contrast, GNSS+SRTM_TIN consistently achieved the lowest errors (RMSE 1.99–2.88 m; MAE 1.26–1.91 m) and the most compact, symmetric error distributions. Among radar-based models, ALOS PALSAR outperformed Sentinel-1, with RMSE between 2.14–3.14 m versus 3.36–4.93 m, and demonstrated stronger spatial coherence. These findings underscore that TIN-based integration of GNSS and SRTM data - as well as ALOS PALSAR InSAR - offer the highest combination of accuracy and spatial reliability for altimetric applications. The study highlights the necessity of coupling global error metrics with spatial autocorrelation analyses to fully characterize DTM quality.

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## 1. INTRODUCTION

Digital Terrain Models (DTMs) are a fundamental tool in the representation of geospatial data, providing relevant information about the Earth's surface relief (Mohamed et al., 2024). In Brazil, especially in the context of the Georeferencing of Rural Properties (GIR – from pt-br: *Georreferenciamento de Imóveis Rurais*), in 2022, the update of the standards of the National Institute of Colonization and Agrarian Reform (INCRA – from pt-br: *Instituto Nacional de Colonização e Reforma Agrária*), known as the Technical Standard for Georeferencing of Rural Properties (NTGIR – from pt-br: *Norma Técnica de Georreferenciamento de Imóveis Rurais*), introduced significant methodological advances. Among these, the integration of altimetric information as a mandatory requirement has enabled the use of Digital Terrain Models (DTMs) as auxiliary tools for defining the altimetric position of vertices under certain conditions. This advancement enhances the positional accuracy in cadastral boundary delineation and the use of DTMs allows the reuse of previously georeferenced data produced under older standards for altitude determination (INCRA, 2022). Existing GNSS (Global Navigation Satellite System) survey data can be reprocessed to obtain altimetric coordinates for points where only planimetric information was previously available. For locations within the same region that contain reliable planimetric data but lack elevation values, an alternative is to generate an enhanced DTM by combining GNSS-derived height information with data from orbital sensors and/or open-access global models. This strategy expands the spatial coverage of points with known elevation values.

Over the past two decades, several satellite missions have generated Digital Elevation Models (DEMs) with global coverage. According to Aguilar et al. (2005), DEMs in which vegetation effects are removed are classified as Digital Terrain Models (DTMs), whereas those incorporating canopy influence are defined as Digital Surface Models (DSMs), even though vegetation-induced distortions do not accurately represent the actual Earth's surface. Despite their wide availability, global models remain subject to accuracy constraints, often determined by spatial resolution, sensor characteristics, terrain morphology, and land cover (Chen, 2013; Shen et al., 2023). In addition, Chaplot et al. (2006) highlight that in the case of DTMs generated from ground sample points, errors may also arise during data acquisition, depending on the surveying technology employed, the density and distribution of sampling points—which frequently justifies the integration of different datasets—and the interpolation technique applied.

Within this context, integrating GNSS survey data with global DTMs or orbital sensors emerges as a viable and cost-effective solution to improve altimetric quality, particularly in areas with dense vegetation or physical obstacles. Among the most widely used global models are the Shuttle Radar Topography Mission (SRTM), developed by the National Aeronautics and Space

Administration (NASA) and the National Geospatial-Intelligence Agency (NGA) of the United States of America (USA) in collaboration with the German and Italian space agencies, that consisted of the Spaceborne Imaging Radar-C (SIRC) hardware set modified with a Space Station-derived mast and additional antennae to form an interferometer with a 60-meter long baseline (Kobrick, 2006; NASA, 2025). In addition to global models, the use of freely available orbital sensors for altimetric data acquisition has become essential in geosciences. Among them, Interferometric Synthetic Aperture Radar (InSAR) sensors, such as Sentinel-1 (ESA) and ALOS PALSAR (JAXA), have been widely recommended for Digital Terrain Model (DTM) generation (Bhardwaj et al., 2019). InSAR techniques rely on high-quality interferograms derived from radar imagery, where phase differences between successive acquisitions are used to infer surface elevation and deformation (Ferretti et al., 2007).

Complementary to global models, modern Geographic Information Systems (GIS) integrate advanced tools for spatial analysis, enabling the combined processing of attribute and geometric data. A central application is surface modeling from sampled points, supported by interpolation techniques such as IDW, TIN, kriging, splines, and Natural Neighbor (Garnero; Godone, 2014). These methods are typically classified as global or local, depending on the spatial extent considered, and as deterministic, stochastics or geostatistical, depending on the underlying modeling approach (Hartkamp et al., 1999)

Among the available methods, Inverse Distance Weighting (IDW) is recognized for its simplicity and widespread application, estimating unknown elevations as a weighted mean of nearby sampled points, where weights decrease with distance, reflecting the principle of spatial continuity (Pavlova & Pavlova, 2017). Triangulated Irregular Networks (TIN), based on the Delaunay triangulation (Delaunay, 1934), construct continuous surfaces from non-overlapping triangles defined by sampled points, offering greater adaptability to complex terrain morphology and more accurate representation of abrupt variations in relief. The TIN and IDW interpolation methods are mathematically expressed by equations (1) and (2), respectively.

$$Z(x,y)=ax+by+c \tag{1}$$

$$Z_{(so)}=\sum_{i=1}^{n} w_i z_{(si)}=\frac{\sum_{i=1}^{n} z_{(si)} d_{io}^{-p}}{\sum_{i=1}^{n} \frac{1}{d_{io}^{-p}}} \tag{2}$$

Where, for Equation (1), the coefficients *a*, *b*, and *c* are obtained by solving the linear system formed by the coordinates of the three vertices; and for Equation (2), $Z(s_0)$ is the estimated elevation at the point of interest, $w_i$ is the weight of the reference point, $Z(s_i)$ is the known elevation of the reference point, $p$ is the exponent used to determine the weight (most commonly $p = 2$), $n$ is the number of reference points in the vicinity of $s_0$, and $d_{i0}$ is the distance between the known and unknown elevation points.

Several geospatial studies use statistical metrics such as Root Mean Square Error (RMSE), Standard Deviation (SD), Mean Absolute Error (MAE) and Mean Error (Bias) as standard measures for assessing the quality and reliability of cartographic products (Alganci et al., 2018; Jiménez-Jiménez et al., 2021; Giannetti et al., 2018). These metrics can be mathematically obtained, respectively, through Equations (3), (4), (5) and (6), as described below.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(z_i - \hat{z}_i)^2} \quad (3)$$

$$SD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(z_i - \bar{z}_i)^2} \quad (4)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|z_i - \hat{z}_i| \quad (5)$$

$$Bias = \frac{1}{n}\sum_{i=1}^{n}(z_i - \hat{z}_i) \quad (6)$$

Where $n$ is the number of observations, $z_i$ represents the observed value, $\hat{z}_i$ represents the estimated value, and $\bar{z}_i$ denotes the arithmetic mean of the observed values.
This study aimed to assess the altimetric accuracy of Digital Terrain Models (DTMs) using GNSS survey data as a reference for vertical datum definition and, in some cases, for model integration. Specifically, GNSS data were integrated with the Shuttle Radar Topography Mission (SRTM) to refine altimetric accuracy. Additionally, two DTMs generated from InSAR data — one derived from the Sentinel-1 mission and another from the ALOS PALSAR sensor onboard the ALOS satellite — were evaluated using GNSS points solely to reference the vertical datum.

## 2. MATERIALS AND METHODS

This chapter describes the location of the study area, the materials and methods employed, as well as the procedures adopted for data processing.

### 2.1. Localization of the study sites

This study was conducted in two regions located in the municipalities of Reserva do Iguaçu (25.8450° S; 52.0278° W) and Guarapuava (25.3933° S; 51.4553° W), all in the state of Paraná, Brazil. GNSS surveys were carried out in 2010, 2011, and 2010, respectively, using the static relative positioning technique to ensure centimeter-level accuracy in height determination, as described by Teunissen and Kleusberg (1998). Figures 1 and 2 illustrate the location of the study areas and the distribution of the sampling and checkpoint points.

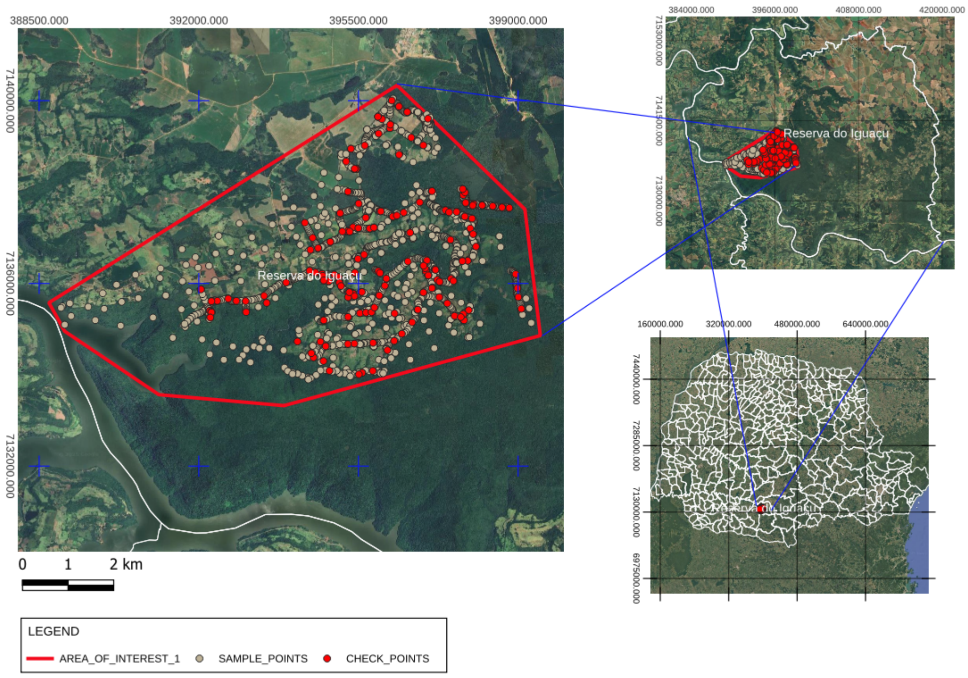


**Figure 1.** Location of the study site and the distribution of the sampling and checkpoint points at the municipality of Reserva do Iguaçu

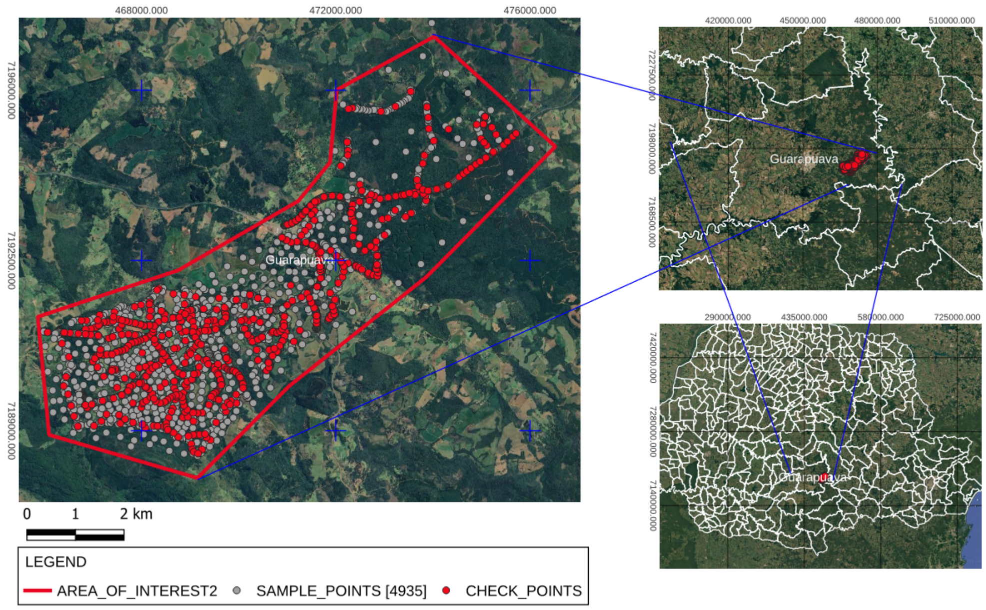


**Figure 2.** Location of the study site and the distribution of the sampling and checkpoint points at the municipality of Guarapuava

## 2.2. GNSS Data Survey

As stated, before a huge dataset of points with GNSS based heights were used to generate and assess the DTMs. A substantial portion of the sampling points from GNSS surveying used for integration with orbital imagery, and subsequent interpolation. Some of the GNSS points quality assessment of the generated DTMs, serving as checkpoints, were obtained from surveys carried out during field campaigns conducted between 2010 and 2011. An additional set of points was collected in more recent campaigns and employed to validate the data acquired in the earlier surveys.

Although models generated solely based on GNSS data have the potential to present low error values individually at checkpoints in regions with sufficient sampling points, this value tends to increase drastically in areas of the model lacking interpolation points. In addition, interpolation becomes necessary in regions outside the perimeter covered by the reprocessed GNSS points, where vertices require known altitude values. Thus, the use of GNSS-surveyed points without data integration or the use of orbital sensors would not be a sufficiently viable alternative for acquiring altimetric information.

## 2.3. Data processing and statistics analysis

To address the objectives of this study, a set of orbital sensors and altimetric models was selected, including SRTM (Shuttle Radar Topography Mission), ALOS PALSAR (Advanced Land Observing Satellite), and Sentinel-1. These datasets were clipped to match the spatial extent of the GNSS survey data and transformed into a unified geodetic reference system to ensure spatial compatibility. The initial processing involved integrating GNSS data with global elevation models within a single platform, followed by the application of altitude interpolation techniques. Two deterministic interpolation methods were applied: Triangulated Irregular Network (TIN) with linear interpolation and Inverse Distance Weighting (IDW). DTMs integrating GNSS and SRTM data were generated using QGIS, which provided the necessary interpolation and geoprocessing tools to align with ground control information. Meanwhile, DTMs derived from orbital sensors (Sentinel-1 and ALOS PALSAR) were processed in ESA's SNAP platform, which offers sensor-specific routines for calibration, correction, and terrain modeling. The evaluation of the resulting models followed a quantitative framework based on classical statistical metrics—mean error (bias), mean absolute error (MAE), standard deviation (SD), and root mean square error (RMSE)—in accordance with the methodologies proposed by Heng et al. (2010) and Mukherjee et al. (2013). These metrics were calculated by comparing the interpolated and integrated models against independent GNSS checkpoints, which were excluded from the interpolation process to ensure unbiased validation. Additionally, spatial error analysis was conducted through error density curves, boxplots, and Moran's Index to assess the spatial autocorrelation of residuals. Figure 3 illustrates the flowchart of the methodology used for data processing and analysis, where the raw data, the processing steps, the derived products, and the analytical procedures are presented.

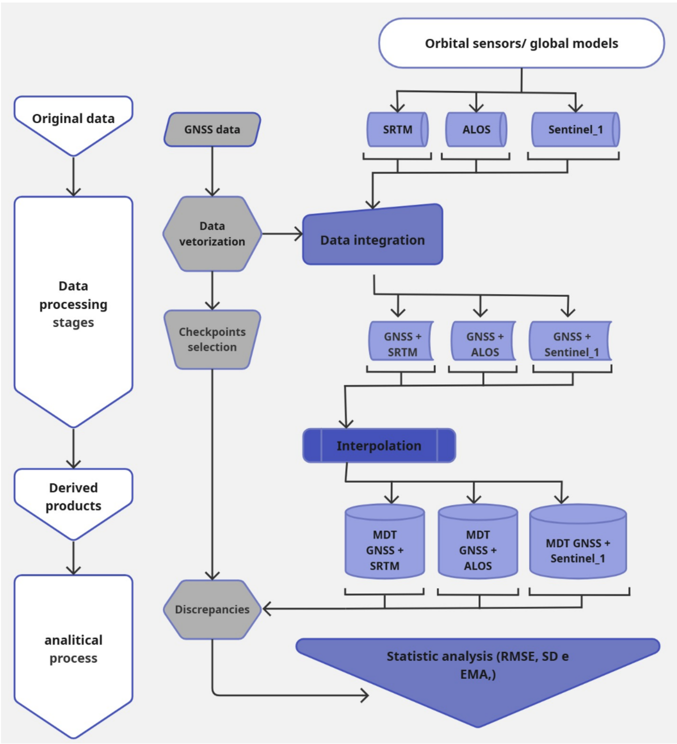


**Figure 3.** workflow of the methodology

## 3. RESULTS AND DISCUSSIONS

The evaluation of elevation models across both study areas highlights notable differences in accuracy. In Reserva do Iguaçu (figure 4), GNSS+SRTM_IDW showed the poorest performance, with RMSE, SD, and MAE all above 7 m, reflecting high variability and

systematic bias. By contrast, GNSS+SRTM_TIN presented much lower errors (RMSE and SD near 2 m, MAE 1.26 m and bias of 0.0.30 m), indicating more consistent performance. Radar-derived models yielded intermediate results: Sentinel-1 had RMSE close to 5 m with higher dispersion (SD = 2.22 m, MAE = 4.47 m) with a bias of 4.41 m, while ALOS PALSAR was more stable (RMSE = 2.14 m, SD = 2.14 m, MAE = 1.40 m, bias = -0.09 m). In Guarapuava (figure 5), errors were systematically larger, especially for GNSS+SRTM_IDW, where RMSE exceeded 13 m, SD reached 6.88 m, and MAE and bias also showed high values, confirming the method's sensitivity to complex terrain. GNSS+SRTM_TIN again outperformed IDW, with RMSE and SD around 2.8 m and lower MAE, though still higher than in Reserva do Iguaçu. Radar-based models showed moderate performance: Sentinel-1 had RMSE above 3 m and MAE around 1.55 m, while ALOS PALSAR presented similar values (RMSE = 3.14 m, SD = 3.14 m, MAE = 1.54 m).
Together, these results indicate that TIN-based integration consistently yields lower dispersion and absolute errors, while IDW produces the least reliable results, particularly in Guarapuava's rugged landscapes. Radar-derived models occupy an intermediate position, with ALOS PALSAR showing more balanced behavior than Sentinel-1

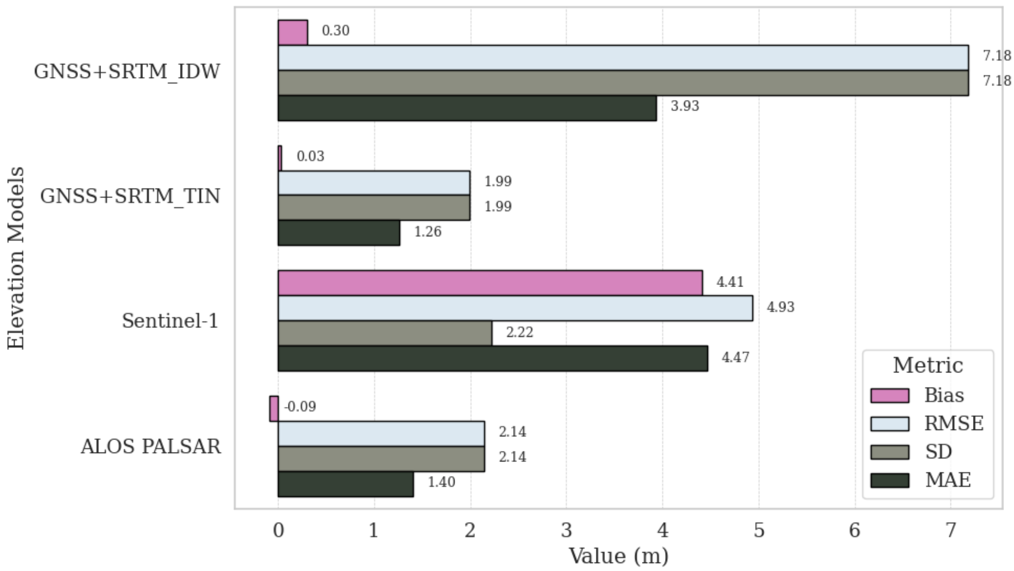


**Figure 4.** RMSE, SD, MAE AND bias for the region located in the municipality of Reserva do Iguaçu

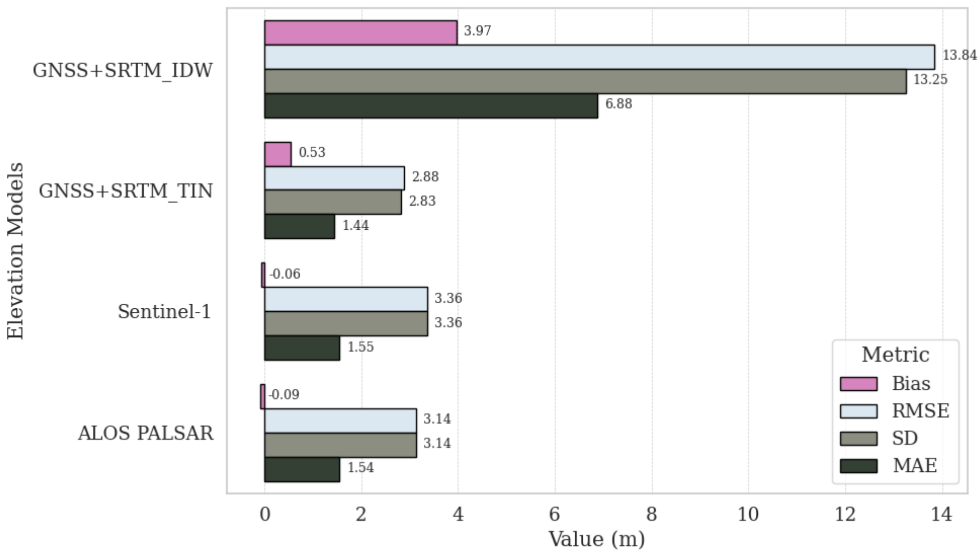


**Figure 5:** RMSE, SD, MAE AND bias for the region located in the municipality of Guarapuava.

The percentile analysis further highlights differences in model performance between Reserva do Iguaçu (figure 6) and Guarapuava (figure 7). In Reserva do Iguaçu, the GNSS+SRTM_IDW model again presented the largest variability, with errors reaching more than 9 m at the 95th percentile, while median errors remained close to zero. By contrast, the GNSS+SRTM_TIN model showed markedly reduced dispersion, with values below 2.5 m even at the 95th percentile. Both Sentinel-1 and ALOS PALSAR produced intermediate results, with consistent errors across percentiles, though slightly higher for Sentinel-1. In Guarapuava, discrepancies were more pronounced, particularly for GNSS+SRTM_IDW, where extreme errors exceeded 34 m at the 95th percentile. Although the median error was low, this indicates instability and a lack of robustness of this method in more complex terrain. The GNSS+SRTM_TIN model again demonstrated better reliability, with values below 4 m across all percentiles. Radar-based models (Sentinel-1 and ALOS PALSAR) showed relatively stable behavior, with percentiles remaining close to 4 m, though still less accurate than in Reserva do Iguaçu.
These results confirm that TIN interpolation offers greater stability than IDW when integrating GNSS and SRTM data, and that radar-based models are sensitive to regional characteristics. The higher errors in Guarapuava suggest a stronger influence of topography and land cover, reinforcing the importance of local conditions in determining the effectiveness of global elevation models.

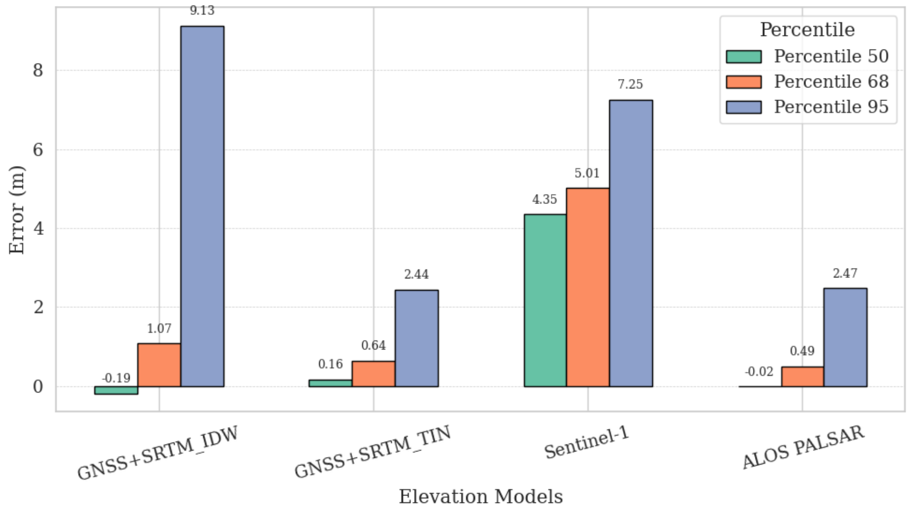


**Figure 6.** Percentiles 50, 68 and 95 for the region located in the municipality of Reserva do Iguaçu

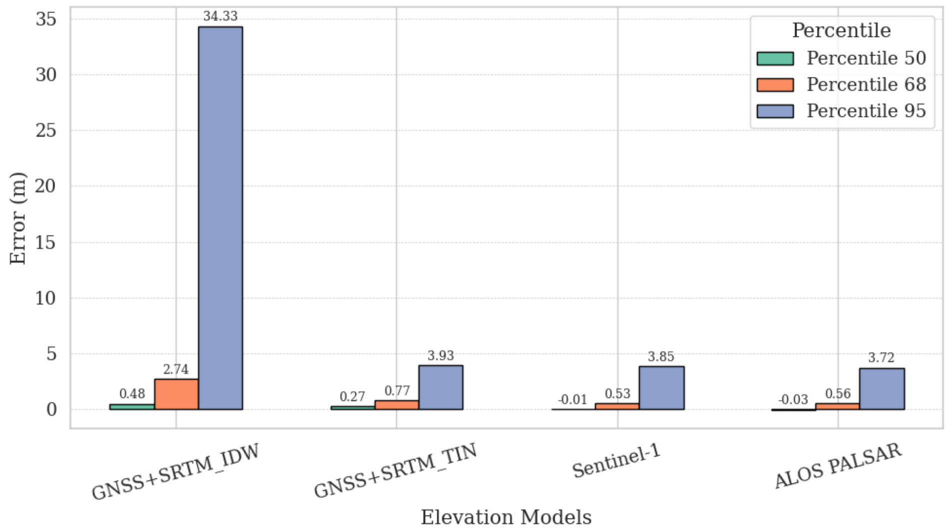


**Figure 7.** Percentiles 50, 68 and 95 for the region located in the municipality of Guarapuava

The combined analysis of error density distributions (Figures 8 and 9) and boxplots (Figures 10 and 11) reveal distinct contrasts between models and study regions. In Reserva do Iguaçu, the GNSS+SRTM_IDW model exhibited the broadest error dispersion, with outliers approaching ±30 m and a flattened density curve—consistent with its high RMSE (7.18 m) and standard deviation (3.93 m). In contrast, GNSS+SRTM_TIN showed a tighter concentration of errors around zero, fewer outliers (mostly within ±10 m), and lower global error metrics (RMSE = 1.99 m; MAE = 1.26 m). Sentinel-1 demonstrated intermediate performance, with a longer positive tail (errors >15 m) and a density peak shifted away from zero, aligning with its RMSE of 4.93 m. ALOS PALSAR presented compact error distributions, with most values between –10 m and +10 m and reduced dispersion (RMSE = 2.14 m; MAE = 1.40 m). In Guarapuava, these patterns were even more pronounced. GNSS+SRTM_IDW displayed extreme variability, with outliers exceeding ±60 m and a highly dispersed distribution, resulting in the highest error metrics across all models (RMSE = 13.84 m; SD = 6.88 m). Conversely, GNSS+SRTM_TIN and ALOS PALSAR maintained more symmetrical and compact distributions, with most errors within ±10 m and RMSEs of 2.88 m and 3.14 m, respectively. Sentinel-1 also showed relatively stable behavior (RMSE = 3.36 m), though with slightly longer positive tails compared to PALSAR. Table 1 summarizes the key performance indicators assessed across the models

**Table 1:** Overview of the performance results across the statistical metrics evaluated

| **STUDY SITE** | **METRIC** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Model | Bias (m) | RMSE (m) | SD (m) | MAE (m) | Percentile 50 (m) | Percentile 68 (m) | Percentile 95 (m) |
| **RESERVA DO IGUAÇU** | GNSS+SRTM_IDW | 0.30 | 7.18 | 7.18 | 3.93 | -0.19 | 1.07 | 9.13 |
| | GNSS+SRTM_TIN | 0.03 | 1.99 | 1.99 | 1.26 | 0.16 | 0.64 | 2.44 |
| | Sentine-1 | 4.42 | 4.93 | 2.22 | 4.47 | 4,35 | 5.01 | 7.25 |
| | ALOS PALSAR | -0.09 | 2.14 | 2.14 | 1.40 | -0.02 | 0.49 | 2.47 |
| **GUARAPUAVA** | GNSS+SRTM_IDW | 3.97 | 13.84 | 13.25 | 6.88 | 0.48 | 2.74 | 34.33 |
| | GNSS+SRTM_TIN | 0.53 | 2.88 | 2.88 | 1.44 | 0.27 | 0.77 | 3.93 |
| | Sentine-1 | -0.06 | 3.36 | 3.36 | 1.55 | -0.01 | 0.53 | 3.85 |
| | ALOS PALSAR | -0.09 | 3.14 | 3.14 | 1.54 | -0.03 | 0.56 | 3.72 |

Both the boxplots and density curves demonstrate that GNSS+SRTM_IDW is highly sensitive to extreme values, which inflate global error metrics—particularly in Guarapuava. In contrast, GNSS+SRTM_TIN and ALOS PALSAR consistently yield more concentrated and symmetric error distributions, underscoring their robustness across diverse landscapes.

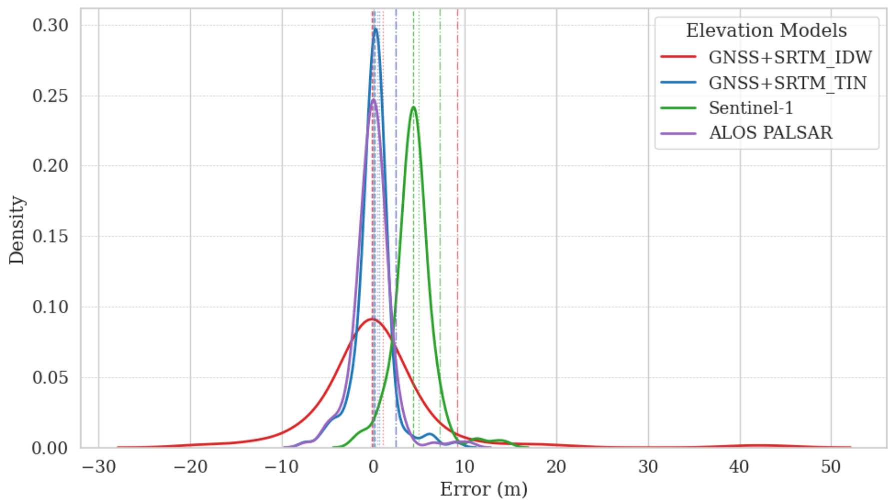


**Figure 8.** Error density distribution for the region located in the municipality of Reserva do Iguaçu

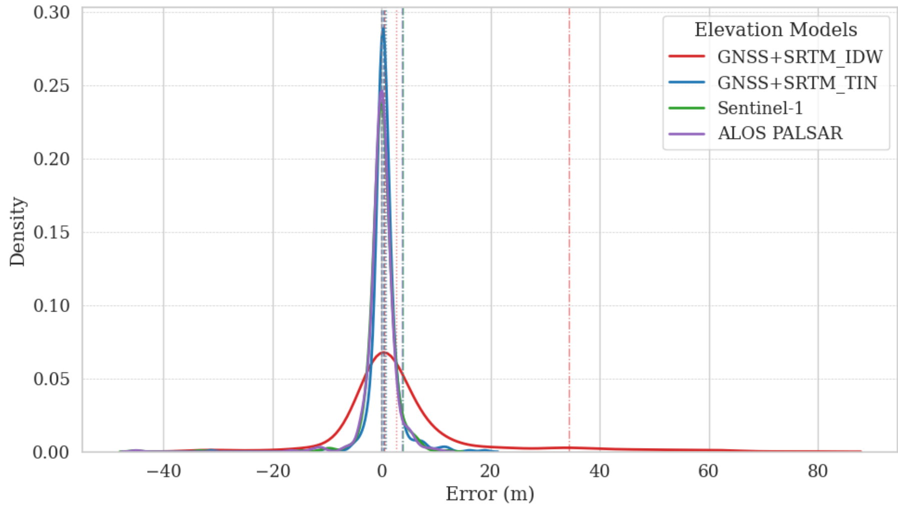


**Figure 9.** Error density distribution for the region located in the municipality of Guarapuava

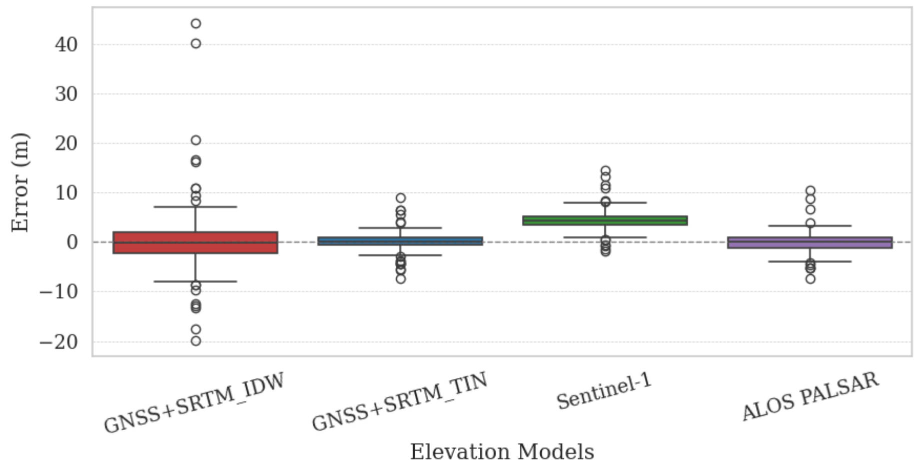


**Figure 10.** Boxplot of the errors for the region located in the municipality of Reserva do Iguaçu

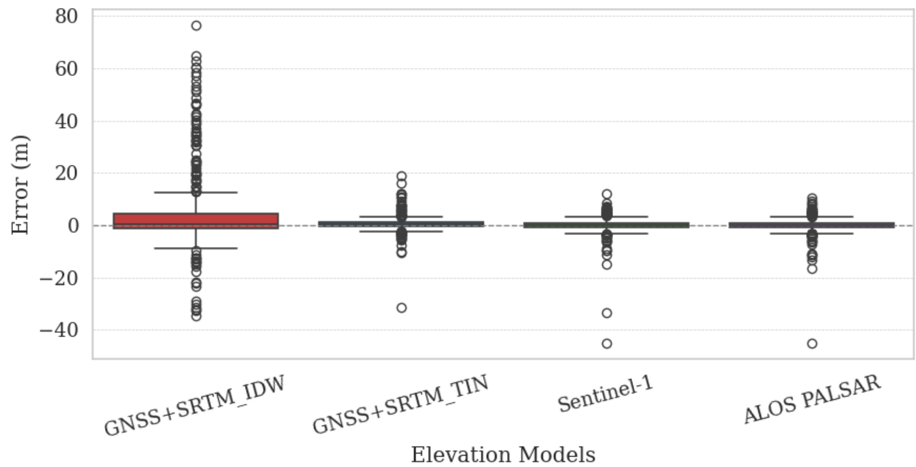


**Figure 11.** Boxplot of the errors for the region located in the municipality of Guarapuava

Moran's Index is a statistical measure that evaluates spatial autocorrelation, indicating whether errors are randomly distributed, clustered, or dispersed across space. Positive values reflect clustering of similar errors, negative values indicate dispersion of dissimilar values, and values near zero suggest randomness. In this study, the Moran's Index plots reinforce the patterns observed in the error density distributions and boxplots: GNSS+SRTM_IDW exhibits the weakest performance, with scattered points and poor spatial consistency, consistent with its inflated RMSE values (7.18 m in Reserva do Iguaçu – figure 12; 13.84 m in Guarapuava – figure 13); GNSS+SRTM_TIN and ALOS PALSAR maintain compact and symmetric distributions, confirming robustness and alignment with the lower global errors reported (RMSE between 1.99–3.14 m – figures 4 and 5, respectively); and Sentinel-1 occupies an intermediate position, showing clustering near zero but localized variability, in agreement with its moderate RMSE values (4.93 m and 3.36 m – figures 4 and 5, respectively).

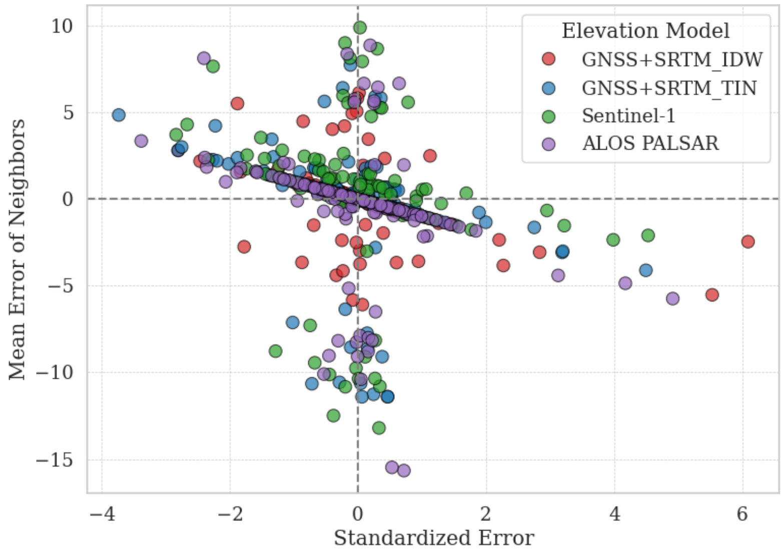


**Figure 12.** Moran's Index plots for the region located in the municipality of Reserva do Iguaçu

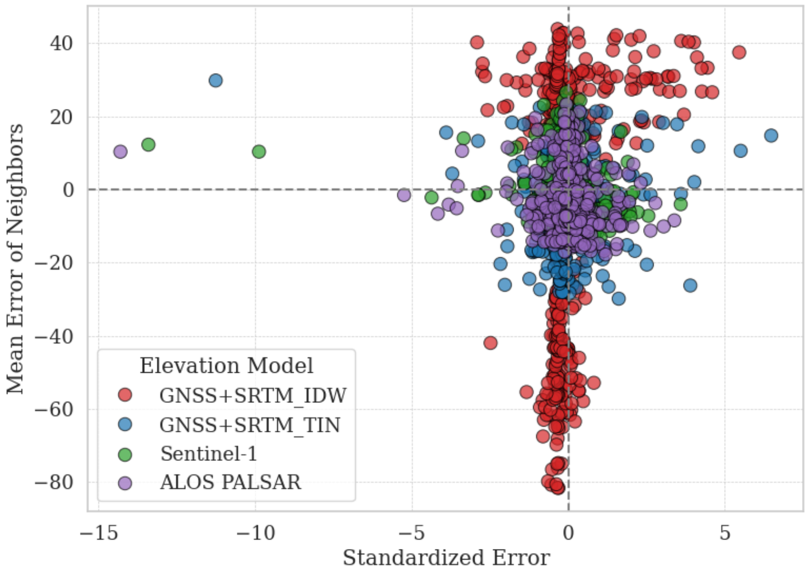


**Figure 13.** Moran's Index plots for the region located in the municipality of Guarapuava

## 4. CONCLUSIONS

This study evaluated the altimetric accuracy of Digital Terrain Models (DTMs) derived from GNSS integration with SRTM and from radar-based models (Sentinel-1 and ALOS PALSAR) in two municipalities of Paraná, Brazil. Results showed that interpolation methods and local conditions play a decisive role in accuracy. The GNSS+SRTM_TIN approach consistently outperformed others (RMSE = 1.99–2.88 m), while IDW showed the poorest performance (RMSE = 7.18–13.84 m), particularly in Guarapuava's rugged terrain. Radar-derived DTMs yielded intermediate results, with ALOS PALSAR providing more balanced performance (RMSE = 2.14–3.14 m) compared to Sentinel-1 (RMSE = 3.36–4.93 m).
The study confirms that integrating GNSS with global or orbital models is an effective and cost-efficient strategy for improving vertical positioning in cadastral applications, particularly under the updated NTGIR requirements. However, the results also underscore that model reliability is strongly conditioned by local morphology and land cover. Future research should consider hybrid approaches that combine GNSS, radar-derived DTMs, and advanced geostatistical interpolators to increase robustness and applicability across diverse landscapes in Brazil. Another consideration to be addressed in future stages is the resampling of both checkpoints and interpolation points to mitigate possible biases caused by data clustering or dispersion in certain regions, which may contribute to improving the overall quality of the generated DTMs.

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## CONTACTS

**Melito Júlio Avalinho**
Federal University of Paraná (UFPR) – Earth Sciences Sector – Department of Geomatics
Avenue Coronel Francisco Heráclito dos Santos, 210 – Jardim das Américas
Curitiba, PR
BRAZIL
E-mail: melito.avalinho@ufpr.br
Website: https://cienciasgeodesicas.ufpr.br

**Paulo Sérgio de Oliveira Júnior**
Federal University of Paraná (UFPR) – Earth Sciences Sector – Department of Geomatics
Avenue Coronel Francisco Heráclito dos Santos, 210 – Jardim das Américas
Curitiba, PR
BRAZIL
E-mail: paulo.junior@ufpr.br
Website: https://cienciasgeodesicas.ufpr.br

**Caio dos Anjos Paiva**
Federal University of Paraná (UFPR) – Earth Sciences Sector – Department of Geomatics
Avenue Coronel Francisco Heráclito dos Santos, 210 – Jardim das Américas
Curitiba, PR
BRAZIL
E-mail: anjospaiva@ufpr.br
Website: https://cienciasgeodesicas.ufpr.br:

**Fábio Pagliosa Ulkowski**
National Institute for Colonization and Agrarian Reform (INCRA)
Rua da Glória, 175
Curitiba, PR
BRAZIL
Tel: +55(41) 3360-6502
E-mail: fabio.pagliosa@incra.br
Website: https://www.gov.br/pt-br