AJLP & GS
African Journal on Land Policy and Geospatial Sciences

*e-ISSN : 2657-2664, Vol.7, Issue.4, September 2024*

*https://revues.imist.ma/index.php/AJLP-GS/index*

*https://doi.org/10.48346/IMIST.PRSM/ajlp-gs.v7i4.49875* *Category of the manuscript : Articles*

***Received in**: 01 July 2024* **Revised in:** 05 August 2024 ***Accepted in**: 30 September 2024*

# Evaluation of Different Digital Elevation Models (DEMs) for Geospatial Applications: A Case Study of Ibadan, Nigeria.

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***ABSTRACT***

**Context and background**

Digital elevation models (DEMs) are essential tools for a wide range of scientific and geospatial applications, providing critical data for elevation and terrain analysis. While remote sensing DEMs have gained popularity due to their extensive spatial coverage and detailed spectral characteristics, assessing their accuracy is crucial for ensuring the reliability of the information they provide.

**Goal and Objectives:**

This study aims to evaluate the accuracy and performance of various Digital Elevation Models (DEMs) for geospatial applications in Ibadan, Nigeria. The specific objectives are to assess the DEMs' accuracy using GPS point survey data and to identify the most suitable DEM for reliable topographic representation in the study area.

**Methodology:**

Seven DEMs were evaluated: Shuttle Radar Topography Mission with 30 m and 90 m resolution (SRTM30 and SRTM90), NASADEM with 30 m resolution, Copernicus DEM with 30 m and 90 m resolution (COP30 and COP90), Advanced Land Observing Satellite World 3D with 30 m resolution (AW3D30), and ALOS PALSAR with 12.5 m resolution. The DEMs' accuracy was assessed using mean error (ME), mean absolute error (MAE), standard deviation (STDE), and linear error metrics, validated against GPS point survey data.

**Results:**

The analysis revealed that AW3D30 consistently provided the highest accuracy, closely representing the actual terrain of Ibadan. NASADEM exhibited the lowest ME and MAE values, indicating high precision, while ALOS PALSAR demonstrated the greatest deviations, despite its STDE and linear error metrics being comparable to other models. This study underscores the importance of accuracy assessment for DEMs in geospatial applications and serves as a valuable reference for selecting appropriate DEMs for various geospatial tasks in Ibadan, Nigeria.

***Keywords:***

*Digital Elevation Models (DEMs), Accuracy Assessment, NASADEM, Copernicus DEM, Terrain Analysis*

## 1. INTRODUCTION

Digital Elevation Models (DEMs) play a pivotal role in geospatial analysis, providing essential information about the Earth's surface elevation that is integral to a wide range of applications, including hydrological modelling (Panda et al., 2024), flood hazards analysis (Al-Areeq et al., 2023), environmental modelling (Ebinne et al., 2022), glacier surface monitoring (Wang et al., 2022), terrain analysis (Ibrahim et al., 2020), vegetation mapping (Volarik, 2010) and so on. Apeh et al. (2019) and Yap et al. (2018) further classify the numerous areas where DEMs could be utilized into specific categories.

The use of space and airborne remote sensing imagery remains a widespread and cost-effective method for gathering elevation data (Dobre et al., 2021). DEMs can be generated through either passive or active sensor systems, depending on whether the detected radiation is naturally emitted or artificially induced. In passive remote sensing, stereo-photogrammetric image processing provides the basis for data acquisition, whereas radar interferometry serves as the primary technique in active remote sensing (Dobre et al., 2021). Advancements in remote sensing have significantly enhanced the visualization of the Earth's physical surface, enabling greater detail and accuracy (Adiri et al., 2022; Yap et al., 2018). With its ability to gather data at a regional scale and its observational capabilities, remote sensing facilitates the generation of high-quality DEMs across different levels of detail (Adiri et al., 2022; Lakshmi and Yarrakula, 2018; Tadono et al., 2016). Thus, numerous DEMs which are readily and freely available, have been generated utilizing remote sensing methodologies (Abdel Aziz and Rashwan, 2022). Examples of freely available DEMs include the Shuttle Radar Topography Mission (SRTM), initially published in 2003 with the latest version released in 2015, offering 30 and 90-meter resolution (SRTM1 and SRTM3, respectively); the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM), released in 2009 with 30-meter spatial resolution; the Advanced Land Observing Satellite World 3D Digital Surface Model (AW3D30), published in 2016, featuring 30-meter spatial resolution (Takaku et al., 2020); the Advanced Land Observing Satellite Phased Array Type L-band Synthetic Aperture Radar (ALOS PALSAR), released in 2006 (Khal et al., 2020); Copernicus DEM, introduced in 2019, providing 30 and 90-meter resolution (COP 30 and COP 90, respectively) global data; and the NASADEM, released in 2020, offering 30-meter resolution data (Bettiol et al., 2021).

These DEMs offer several advantages as an effective alternative to traditional surveys and interpretation of topographic maps (Adiri et al., 2022). They provide comprehensive coverage of large areas, allowing for efficient analysis of terrain characteristics. Additionally, DEMs enable rapid data acquisition, reducing the time and resources required for field surveys. Their digital format facilitates integration with Geographic Information Systems (GIS) for advanced spatial analysis (Adiri et al., 2022; Chang et al., 2019). However, many researchers (Adiri et al., 2022; Vaka et al., 2019; Yahaya & El Azzab, 2019; Uuemaa et al., 2020; Elkhrachy, 2017; Rabah et al., 2017; Mouratidis & Ampatzidis, 2019; Li et al., 2017; Jain et al., 2017; Florinsky et al., 2018) have evaluated the accuracy of these DEMs using diverse high-quality reference data such as Light Detection and Ranging (LiDAR) data, Global Positioning System (GPS) data, and reference DEMs across various geographical areas worldwide, reporting varied levels of accuracy. This variability arises from differences in source data, processing techniques, and geographic regions of interest, highlighting the necessity for comprehensive evaluation and comparison of different DEMs to ensure their suitability for specific geospatial applications within particular geographical contexts.

In the dynamic urban landscape of Ibadan, Nigeria, characterized by rapid growth and diverse terrain, the need for accurate and high-resolution DEMs is particularly definite. The effective planning and management of urban infrastructure, natural resources, and environmental hazards demand precise elevation data that capture the complexities of the local landscape. However, readily accessible topographic maps suitable for various geospatial applications are scarce. It is widely acknowledged that acquiring geospatial data through ground survey methods is significantly more labor-intensive, time-consuming, and costly compared to remote methods (Apeh et al., 2019).

Therefore, addressing these challenges, this study aims to evaluate the accuracy of several commonly used and recently released DEMs in Ibadan region. Specifically, we will assess the performance of SRTM30, NASADEM, SRTM90, COP30, COP90, AW3D30, and ALOS PALSAR data through comparison with ground survey GPS data. To our knowledge, no previous studies have conducted a comprehensive assessment and comparison of these DEMs together in the study area. Thus, this research represents the first assessment in the region. By conducting a comprehensive evaluation of these DEMs, our study seeks to provide valuable insights into the accuracy and utilization of these DEMs not only for local decision-makers, researchers, and practitioners in Ibadan but also for geospatial professionals worldwide.

## 2. MATERIALS AND METHODS

### 2.1 Study area

The study area encompasses Ibadan city, located in Oyo state in the South-Western part of Nigeria. It spans between latitude 7°02’49’’N to 7º43’21’’N and longitude 3°31’58”E to 4°08’20”E, with elevations ranging from 180 m to 275 m above sea level. Covering a total area of 6,800 sq.km, the city is home to an estimated population of 3.8 million people as of 2023, according to the Population Stat (Raufu, 2024). The climate in this region is characterized by a tropical wet and dry climate, featuring a prolonged wet season and relatively stable temperatures throughout the year. The average annual temperature in Ibadan is recorded at 26.46 °C. The wet season typically extends from March to October, with a brief dry period occurring in August. The city of Ibadan is naturally drained by four rivers, along with numerous tributaries. These rivers include the Ona River in the North and West, the Ogbere River in the East, and the Ogunpa and Kudeti Rivers, which flow through the central part of the city. Figure 1 depicts the location of the study area.

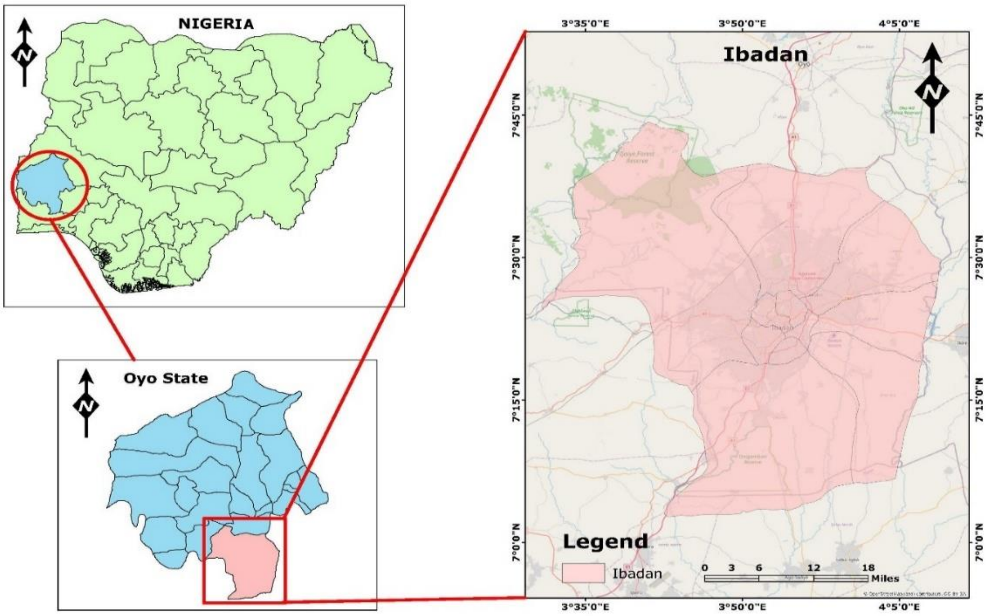



Figure 1: Map showing location of the study area (Raufu, 2024)

## 2.1 GPS survey data

In this study, one hundred (100) GPS ground survey points were utilized to independently assess the accuracy of the DEMs. The GPS data were obtained from the Office of the Surveyor General of Oyo State, Ibadan, Nigeria. The spatial reference system of the GPS points is the World Geodetic System (WGS) 1984 and Universal Transverse Mercator (UTM) zone 31N and the ellipsoidal heights of the points range from 88.60 m to 278.32 m with the root mean square error (RMSE) of 0.001 m to 0.015 m.

## 2.2 Digital elevation models

In this research, seven widely-used DEMs as shown in Table 2 are evaluated by comparing their elevation with GPS survey data. DEM serves as a generic term encompassing various forms of digital elevation models. It can denote the elevation of the bare ground, representing natural topography, thereby termed as a digital terrain model (DTM). Alternatively, DEM may encompass elevation values along with features such as vegetation heights, buildings, and other surface characteristics, referred to as a digital surface model (DSM) (Adiri et al., 2022; Mesa-Mingorance and Ariza-López, 2020).

Table 2: Properties of the DEMs under study

| DEM | Sensor | Resolution | Quantization | Horizontal datum | Vertical datum |
|---|---|---|---|---|---|
| SRTM | C-SAR | 30 m, 90 m | 16 bits | WGS 84 | EGM96 |
| NASADEM | C-SAR | 30 m | 16 bits | WGS 84 | EGM96 |
| Copernicus DEM | X-band radar | 30 m, 90 m | 16 bits | WGS 84 | EGM2008 |
| AW3D30 | Optical | 30 m | 16 bits | WGS 84 | EGM96 |
| ALOS PALSAR | L-SAR | 12.5 m | 16 bits | WGS 84 | EGM96 |

### 2.2.1 SRTM (30 m and 90 m)

SRTM is a digital elevation model acquired during NASA's Shuttle Radar Topography Mission in 2000. Employing radar interferometry, it measures elevation and offers global coverage of land surfaces.

The data is available in two resolutions: 30 meters (SRTM30) and 90 meters (SRTM90), utilizing the WGS 84 horizontal datum and EGM96 vertical datum. SRTM30, released in September 2014 by NASA, marks a significant enhancement over the lower-resolution SRTM90, particularly for regions outside the United States. This enhancement is achieved through data filling based on various datasets, including the ASTER Global Digital Elevation Model 2 (ASTER GDEM2), the USGS Global Multi-resolution Terrain Elevation Data (GMTED2010), and the USGS National Elevation Dataset (NED) (Adiri et al., 2022).

### 2.2.2 NASADEM

NASADEM represents an enhanced version of the SRTM DEM, developed by NASA to address limitations and improve accuracy. By integrating SRTM data with additional datasets and corrections, NASADEM achieves improved resolution and precision. The initial SRTM raw radar data was reprocessed utilizing advanced algorithms, and additional improvements were achieved by integrating data from ASTER and ICESat – Geoscience Laser Altimeter System (GLAS) instruments (Okoli et al., 2024; Buckley et al., 2020). These refinements aimed to expand data coverage and remove voids and other shortcomings present in the SRTM dataset (Bettiol et al., 2021; Uuemaa et al., 2020). NASADEM offers global coverage with a spatial resolution of 30 meters, utilizing the WGS 84 horizontal datum and EGM96 vertical datum.

### 2.2.3 Copernicus DEM (30 m and 90 m)

The Copernicus DEM is a product of the European Space Agency (ESA) under the Copernicus program. It originates from an edited DEM known as WorldDEM, which is derived from radar satellite data collected during the TanDEM-X Mission. This mission is supported by a public-private partnership between the German government, represented by the German Aerospace Center (DLR), and Airbus Defence and Space (Airbus 2020a). The Copernicus DEM is available at three resolutions: 10 meters (EEA-10, for EEA39 nations and regions), 30 meters (GLO 30), and 90 meters (GLO 90). It offers global coverage based on the WGS 84 horizontal datum and EGM2008 vertical datum.

### 2.2.4 AW3D30

AW3D30 is a global digital elevation model created by the Japan Aerospace Exploration Agency (JAXA) using data from the Advanced Land Observing Satellite (ALOS). Derived from the earlier ALOS DEM, which featured a spatial resolution of 5 meters and an accuracy of 5 meters, AW3D30 has undergone advancements. In April 2024, the latest version, 4.1, was released, incorporating improvements in data formatting, auxiliary data utilization, and processing techniques, including enhanced anomaly detection methods. AW3D30 ensures global coverage with a spatial resolution of 30 meters. For this study, version 3.2 which is for the study area was utilized.

### 2.2.5 ALOS PALSAR

ALOS PALSAR is a satellite sensor operated by JAXA. It uses radar technology to collect data, which can be used to generate DEMs with various spatial resolutions, depending on the specific product and processing techniques used (Khal et al., 2020). The spatial coverage of PALSAR data is between 60° N to 59° S, with a very fine spatial resolution of 12.5 m (Adiri et al., 2022; Shawky et al., 2019)

## 2.3 Data processing

A mosaic operation was first conducted for the ALOS PALSAR data using the "mosaic to new raster" tool in ArcGIS software because the use of four DEMs was needed in order to cover the entire study area. Thereafter, data harmonization was performed, in which all the DEMs were transformed from the geographic reference system to the World Geodetic System (WGS) 1984 and Universal Transverse Mercator (UTM) zone 31N reference system. The transformations were carried out using the "project raster" tool within ArcGIS software. This step is vital for preventing map distortion, which could result in height discrepancies between different DEMs and potentially lead to misinterpretation of the results. Additionally, the elevation data obtained from GPS surveys were converted from ellipsoidal heights to orthometric heights, with reference to the EGM2008 geoid, using Equation 1.

$$H = h - N \tag{1}$$

where H is the orthometric height, h is the ellipsoidal height, and N is the geoidal undulation.

The EGM2008 vertical datum was selected as the common reference for the DEMs in this study due to its superior accuracy in estimating topographical heights compared to EGM96 (Okoli et al., 2024; Tata and Olatunji, 2021; Pavlis et al., 2012). Consequently, it was necessary to convert the SRTM, NASADEM, AW3D30, and ALOS PALSAR DEMs to the EGM2008 datum. The EGM96 and EGM2008 geoid models were obtained from the website of the International Centre for Global Earth Models (Ince et al., 2019) in plain text format with a grid spacing of 0.0005°. These grids were then converted into raster surfaces using Inverse Distance Weighted (IDW) interpolation in ArcGIS software, and the differences in geoid heights were calculated. Subsequently, the vertical datum conversion from EGM96 to EGM2008 was performed using the 'raster calculator' tool in ArcGIS software, following the approach outlined by Okoli et al. (2024) and Üstün et al. (2016).

$$H_{EGM08} = H_{EGM96} + N_{EGM96} - N_{EGM08} = H_{EGM96} + \Delta N \tag{2}$$

where $H_{EGM08}$ is the orthometric height of DEM based on EGM2008 model, $H_{EGM96}$ is the orthometric height of DEM based on EGM96 model, $N_{EGM08}$ is the geoidal undulation based on EGM2008 model, $N_{EGM96}$ is the geoidal undulation based on EGM96 model, and ΔN is the geoidal undulation difference between EGM2008 and EGM96.

## 2.4 Accuracy assessment

The accuracy and performance of the DEMs in this study were evaluated by comparing the elevations extracted from them with GPS survey point data. The comparison utilized various statistical metrics, including mean error (ME), mean absolute error (MAE), standard deviation error (STDE), correlation coefficient ($R^2$), and linear error at 90% (LE90), 95% (LE95) and 99.73% (LE99.73) confidence levels, as defined in Equations (3-9).

$$\text{ME} = \frac{\sum_{i=1}^{n} H_{GPS} - H_{DEM}}{n} \tag{3}$$

$$\text{MAE} = \frac{\sum_{i=1}^{n} |H_{GPS} - H_{DEM}|}{n} \tag{4}$$

where; $H_{GPS}$ = orthometric heights from the GPS survey point data, $H_{DEM}$ = orthometric heights obtained from each individual DEM, n = number of GPS survey points.

The ME indicates the presence of bias (underestimation or overestimation) in the data, while the MAE represents the average magnitude of the elevation errors, irrespective of their direction.

$$STDE = \sqrt{\frac{\sum_{i=1}^{n}((H_{GPS,i} - H_{DEM,i}) - ME)^2}{n-1}} \quad (5)$$

Conversely, the STDE represent the square root of the average elevation errors between the DEM and the corresponding GPS elevations. When the STDE value approaches zero, the heights derived from DEMs are more accurate, while a greater distance from zero indicates less accuracy in the derived heights from DEMs.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(H_{GPS,i} - H_{DEM,i})^2}{\sum_{i=1}^{n}(H_{GPS,i} - \overline{H_{GPS,i}})^2} \quad (6)$$

Correlation analysis was utilized to examine the relationships between the GPS survey points elevation and DEM elevations. $R^2$ takes values between 0 and 1, with values closer to 1 indicating a better fit.

Additionally, the linear errors (LE) for each of the seven DEMs were computed at 90%, 95% and 99.73% confidence levels, assuming normal distribution of elevation errors and direct proportionality of linear errors to standard deviation errors (Grohmann, 2018).

$$\text{LE90} = 1.6449 \times STDE \quad (7)$$

$$\text{LE95} = 1.9000 \times STDE \quad (8)$$

$$\text{LE99.73} = 3.0000 \times STDE \quad (9)$$

## 3. RESULTS AND DISCUSSION

### 3.1 Elevation statistics of DEMs

The DEMs under study exhibit a range of elevation statistics, each providing unique understandings into the topographical features of the study area. The key descriptive statistics: minimum, maximum, mean, and STDE are analyzed for all the DEMs as shown in Table 3. According to Table 3, the minimum elevations ranges from 53 meters in the COP30 model to 82 meters in the ALOS PALSAR model, and the maximum elevations varies from 395 meters in the SRTM90 model to 428 meters in the ALOS PALSAR model; the mean elevations show a general consistency across most models; for instance, SRTM30 averages 185.03 meters and COP30 averages 183.35 meters, but ALOS PALSAR significantly deviates with a higher mean elevation of 210.08 meters, indicating potentially different processing methodologies or higher sensitivity to terrain variations, while the STDE values remain fairly uniform across the DEMs, ranging from 50.16 meters in AW3D30 to 50.77 meters in COP30, suggesting that despite differences in minimum, maximum, and mean elevations, the overall variability in the elevation data remains consistent across these models.

Table 3: Summary of elevation statistics for DEMs under study

| DEM | Min. (m) | Max. (m) | Mean (m) | STDE (m) |
|---|---|---|---|---|
| SRTM30 | 58 | 402 | 185.03 | 50.33 |
| SRTM90 | 59 | 395 | 185.04 | 50.29 |
| NASADEM | 55 | 398 | 182.67 | 50.26 |

| | | | | |
|---|---|---|---|---|
| COP30 | 53 | 407 | 183.35 | 50.77 |
| COP90 | 57 | 398 | 183.40 | 50.73 |
| AW3D30 | 58 | 400 | 184.76 | 50.16 |
| ALOS PALSAR | 82 | 428 | 210.08 | 50.56 |

## 3.2 Statistical comparison among the DEMs

The seven DEMs are compared with each other to evaluate their consistency and identify significant systematic errors in their elevation data (Yap et al., 2018; Li et al., 2016). Differences between models were computed at identical points across all model combinations. Table 4 summarizes the comparison of elevation statistics among different DEM pairs, including minimum, maximum, mean error, and STDE. STDE reflects surface quality and illustrates the distribution of deviations from the mean value.

Table 4: Summary of model to model statistics

| Comparison | Min. (m) | Max. (m) | Mean (m) | STDE (m) |
|---|---|---|---|---|
| ALOSPALSAR - AW3D30 | -54 | 90 | 25.31 | 1.97 |
| ALOSPALSAR - COP30 | 1 | 63 | 26.73 | 3.23 |
| ALOSPALSAR - COP90 | -22 | 74 | 26.68 | 3.86 |
| ALOSPALSAR-NASADEM | 6 | 46 | 27.41 | 1.30 |
| ALOSPALSAR-SRTM30 | 4 | 44 | 25.06 | 1.14 |
| ALOSPALSAR-SRTM90 | -20 | 59 | 25.03 | 2.27 |
| AW3D30 - COP30 | -66 | 79 | 1.38 | 3.30 |
| AW3D30 - COP90 | -66 | 88 | 1.40 | 3.76 |
| AW3D30 - NASADEM | -66 | 82 | 2.07 | 2.19 |
| AW3D30 - SRTM30 | -68 | 78 | -0.28 | 2.13 |
| AW3D30 - SRTM90 | -67 | 88 | -0.26 | 2.61 |
| COP30 - COP90 | -38 | 47 | -0.05 | 2.59 |
| COP30 - NASADEM | -35 | 31 | 0.68 | 3.36 |
| COP30 - SRTM30 | -39 | 30 | -1.67 | 3.39 |
| COP30 - SRTM90 | -47 | 33 | -1.71 | 3.37 |
| COP90 - NASADEM | -49 | 47 | 0.74 | 4.09 |
| COP90 - SRTM30 | -48 | 49 | 1.61 | 4.12 |
| COP90 - SRTM90 | -32 | 17 | -1.68 | 2.75 |
| NASADEM - SRTM30 | -14 | 11 | -2.35 | 0.75 |
| NASADEM - SRTM90 | -40 | 28 | -2.37 | 2.17 |
| SRTM30 - SRTM90 | -36 | 29 | -0.02 | 2.15 |

The model-to-model comparison of DEMs reveals that ALOS-PALSAR consistently shows higher elevation values compared to AW3D30, COP30, COP90, NASADEM, SRTM30, and SRTM90, with mean differences ranging from 25.03 to 27.41 meters. The comparisons with AW3D30, COP30, COP90, and SRTM90 also exhibit higher variability, indicated by larger STDE, while the differences are more consistent with NASADEM and SRTM30. This can be attributed to its advanced Synthetic Aperture Radar (SAR) technology, which can penetrate dense vegetation typical of tropical wet and dry climates, its precise geolocation accuracy, superior data processing techniques, and its higher spatial resolution of 12.5 meters. In contrast, the differences between AW3D30 and other DEMs, such as COP30, COP90, NASADEM, SRTM30, and SRTM90, generally show minimal mean differences, indicating closer agreement but with significant variability. The comparison between COP30 and COP90, NASADEM, SRTM30, and SRTM90 also demonstrates minimal mean differences with varying degrees of variability.

Additionally, the combination of NASADEM-SRTM30, as indicated by their low STDE of 0.75 meters from Table 4, demonstrates a strong agreement between the two datasets across the study area. This low STDE suggests minimal variation or dispersion of elevation values around their respective mean, indicating a high level of consistency and accuracy in the elevation data provided by NASADEM and SRTM30 models. Such agreement implies that these models reliably capture and represent elevation features with little variability across different locations within the study area. In contrast, COP90-SRTM30 shows a much higher STDE of 4.12 meters. This indicates a wider variability in elevation data points compared to the mean value, suggesting greater inconsistency in elevation estimation between COP90 and SRTM30 models. The higher STDE suggests that the differences in elevation values between these two models can vary significantly across different locations, indicating potential challenges in accurately assessing elevation features and terrain characteristics using these models in conjunction.

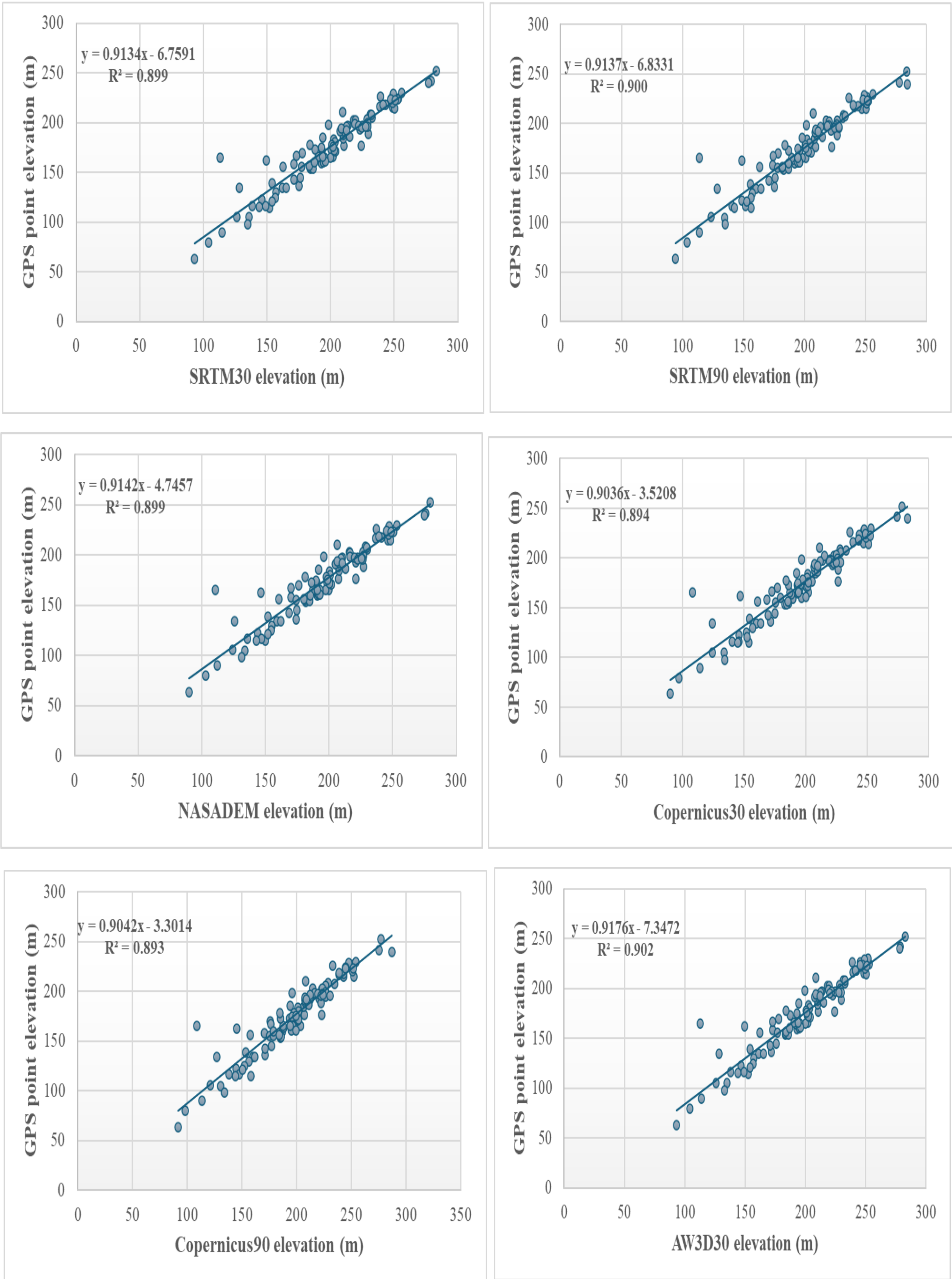
### 3.3 Correlation between GPS point elevation and the DEMs

To analyze the correlation between GPS point elevations and DEMs, the elevations from each DEM grid raster layer were extracted using the "spatial analyst" tool in ArcGIS, specifically the "extract multi values to points" function. This extraction was based on the coordinates of one hundred (100) GPS points and utilized bilinear interpolation from the surrounding grid points at the original spatial resolution of each DEM. Subsequently, the correlation coefficient ($R^2$) was calculated for all points, as shown in Table 5.

Table 5: Correlation coefficient ($R^2$) values between GPS elevations and various DEMs across different elevation ranges

| Elevation (m) | SRTM30 | SRTM90 | NASADEM | COP30 | COP90 | AW3D30 | ALOS PALSAR |
|---|---|---|---|---|---|---|---|
| All values | 0.899 | 0.900 | 0.899 | 0.894 | 0.893 | 0.902 | 0.900 |
| 0 - 80 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 81 - 160 | 0.807 | 0.808 | 0.805 | 0.785 | 0.781 | 0.816 | 0.812 |
| 161 - 240 | 0.741 | 0.735 | 0.743 | 0.734 | 0.730 | 0.750 | 0.744 |
| 241 - 320 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

Figure 2 illustrates that all DEMs exhibited high correlation with the GPS elevations. AW3D30 had the highest correlation coefficient at 0.902, followed closely by ALOS PALSAR and SRTM90, both with values of 0.900. SRTM30 and NASADEM both had a correlation coefficient of 0.899, while COP30 and COP90 had values of 0.894 and 0.893, respectively. These high correlation values indicate a strong agreement between the GPS point elevations and the DEM data, likely due to the well-distributed nature of the control points.


y = 0.9134x - 6.7591
R² = 0.899
GPS point elevation (m)
SRTM30 elevation (m)
y = 0.9137x - 6.8331
R² = 0.900
GPS point elevation (m)
SRTM90 elevation (m)
y = 0.9142x - 4.7457
R² = 0.899
GPS point elevation (m)
NASADEM elevation (m)
y = 0.9036x - 3.5208
R² = 0.894
GPS point elevation (m)
Copernicus30 elevation (m)
y = 0.9042x - 3.3014
R² = 0.893
GPS point elevation (m)
Copernicus90 elevation (m)
y = 0.9176x - 7.3472
R² = 0.902
GPS point elevation (m)
AW3D30 elevation (m)

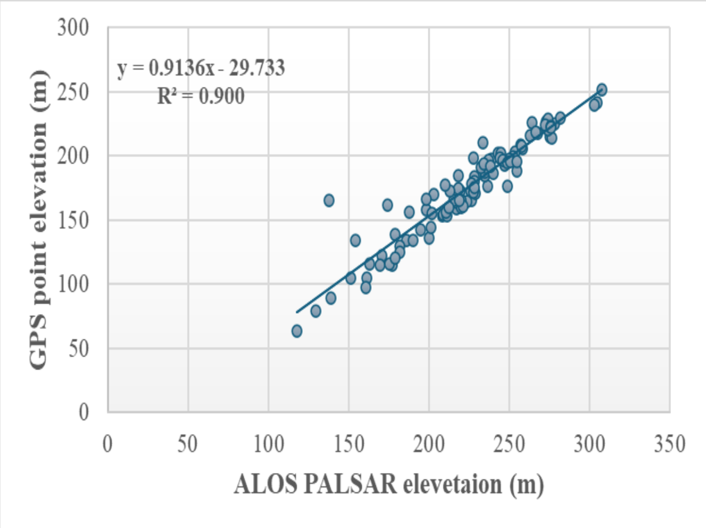



Figure 2: Correlations between GPS points elevation and each DEM for all points

To better analyze this correlation, four elevation ranges were selected: 0-80 m, 81-160 m, 161-240 m, and 241-320 m, representing approximately 2%, 29%, 67%, and 2% of all the points, respectively. For the first range (0-80 m), all DEMs exhibit a high correlation value of 1. In the range of 81-160 m, AW3D30 has the highest correlation with GPS elevation data ($R^2$ = 0.816), followed by ALOS PALSAR (0.812), SRTM90 (0.808), SRTM30 (0.807), and NASADEM (0.805), with COP30 (0.785) and COP90 (0.781) showing the lowest correlation values. For the 161-240 m range, AW3D30 shows the highest correlation (0.750), followed by ALOS PALSAR (0.744), NASADEM (0.743), and SRTM30 (0.741), with SRTM90 (0.735) and COP30 (0.734) slightly lower, and COP90 (0.730) having the lowest correlation. In the highest elevation range of 241-320 m, all DEMs again show a high correlation value of 1.

These results demonstrate that for elevations under 160 m, the DEMs generally have high correlations with GPS data, particularly AW3D30, ALOS PALSAR, and SRTM90, indicating good agreement in these elevation ranges. For elevations over 160 m, the correlation values slightly decrease, with SRTM90, ALOS PALSAR, and NASADEM performing better than other models, suggesting that these DEMs maintain relatively higher accuracy at greater elevations.

### 3.4 Statistics of the elevation differences between GPS points and DEMs

The accuracy of the elevation data is evaluated by comparing the DEM elevation values with the corresponding GPS point elevation values, thereby identifying the measured errors in the DEM under the assumption of a normal distribution. Positive errors indicate locations where the DEM elevation is higher than the GPS point elevation, while negative errors indicate locations where the DEM elevation is lower than the GPS point elevation. The elevation differences between each DEM and the one hundred (100) GPS points are depicted in Figure 3. Table 6 presents the statistical analysis of these discrepancies.

The analysis of the elevation differences between GPS points and various DEMs in Table 6 provides insight into the accuracy and consistency of each model. The minimum errors range from -57.11 m for COP30 to -27.32 m for ALOS PALSAR, indicating the largest underestimations occur in the COP30 model. The maximum errors range from 44.69 m for NASADEM to 72.41 m for ALOS PALSAR, suggesting that the largest overestimations occur in the ALOS PALSAR model. The calculated mean errors (ME) for all DEMs are positive, indicating a general tendency for the DEMs to overestimate elevation compared to the GPS points in the study area.

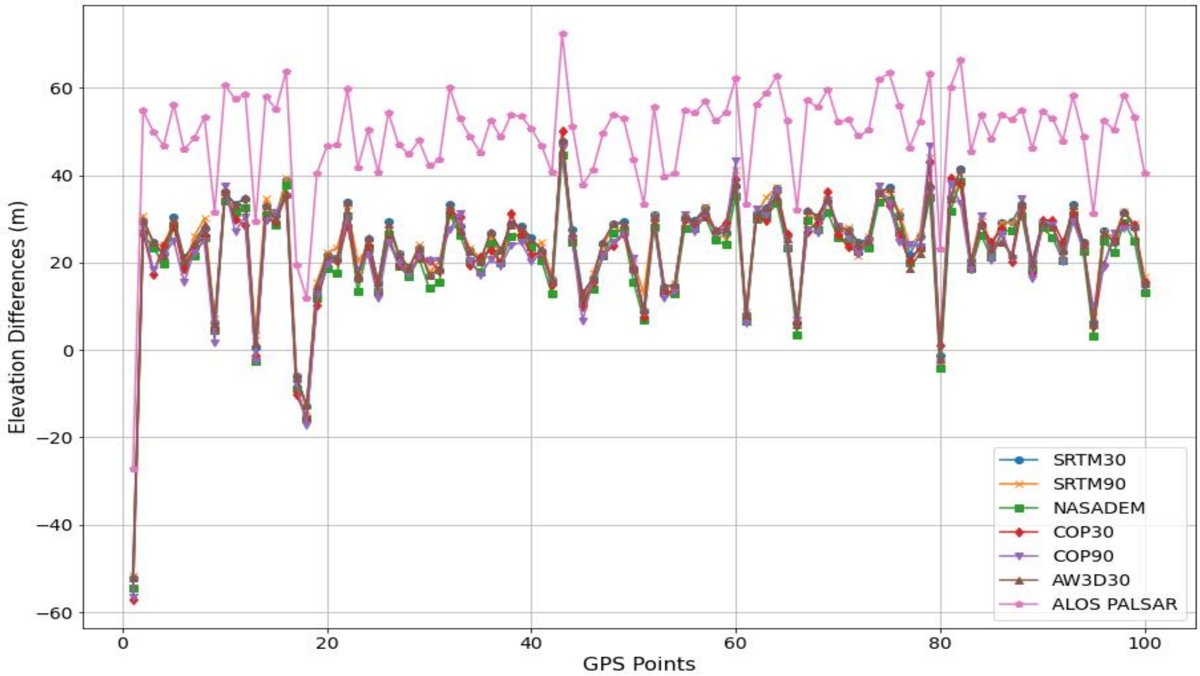



Figure 3: Differences in elevations obtained from each of the DEMs

Both SRTM30 and SRTM90 exhibit similar performance, with SRTM90 slightly outperforming SRTM30 in terms of MAE (25.16 m compared to 25.41 m) and STDE (12.49 m compared to 12.55 m). They show relatively moderate errors and variability, making them reliable for elevation data. NASADEM shows the best overall performance with the lowest mean error (ME = 21.59 m) and mean absolute error (MAE = 23.31 m), indicating it is the most accurate and consistent DEM. The LE90, LE95, and LE99.73 values for NASADEM are also competitive, suggesting high reliability in representing elevation. COP30 and COP90 demonstrate similar performance, with COP90 showing slightly better accuracy in terms of ME (-22.17 m compared to -22.55 m) and MAE (23.91 m compared to 24.23 m). However, they have the highest LE95 and LE99.73 values, indicating greater variability in some areas. AW3D30 performs comparably to the SRTM models, with slightly higher mean error (ME = 23.99 m) and mean absolute error (MAE = 25.49 m). It has the lowest STDE (12.43 m) among the DEMs, suggesting consistent performance. ALOS PALSAR exhibits the poorest performance with the highest mean error (ME = 49.07 m) and mean absolute error (MAE = 49.62 m). Despite having a similar STDE (12.50 m) to other DEMs, its significantly higher errors indicate a substantial underestimation of elevation, which may be attributed to its advanced SAR technology, which may not align well with the GPS data in the study area. This study's results for SRTM30 and AW3D30 align with the findings of Yap et al. (2018) in Cameroon, which reported STDE values of 13.25 m for SRTM30 and 13.07 m for AW3D30.

Table 6: Statistics of the differences between GPS elevation points and DEMs

| DEM | Min. (m) | Max. (m) | ME (m) | MAE (m) | STDE (m) | LE90 (m) | LE95 (m) | LE99.73 (m) |
|---|---|---|---|---|---|---|---|---|
| SRTM30 | -52.12 | 47.69 | 23.96 | 25.41 | 12.55 | 20.65 | 23.85 | 37.66 |
| SRTM90 | -52.17 | 47.99 | 23.69 | 25.16 | 12.49 | 20.54 | 23.73 | 37.47 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| NASADEM | -54.35 | 44.69 | 21.59 | 23.31 | 12.58 | 20.7 | 23.91 | 37.75 |
| COP30 | -57.11 | 50.12 | 22.55 | 24.23 | 12.99 | 21.36 | 24.68 | 38.97 |
| COP90 | -56.44 | 46.69 | 22.17 | 23.91 | 13.04 | 21.46 | 24.78 | 39.13 |
| AW3D30 | -51.55 | 46.00 | 23.99 | 25.49 | 12.43 | 20.45 | 23.62 | 37.29 |
| ALOSPALSAR | -27.32 | 72.41 | 49.07 | 49.62 | 12.50 | 20.56 | 23.74 | 37.49 |

Based on the results in Table 6, the AW3D30 model emerges as the best-performing model in the study area, demonstrating the most consistent elevation differences and a high proportion of its elevation differences within smaller error margins. Despite this, the NASADEM model shows the lowest mean error and mean absolute error, suggesting it may be the most accurate overall. ALOS PALSAR exhibits the poorest performance with the highest mean and mean absolute errors, suggesting significant deviations from the GPS elevations, although its standard deviation and linear errors are comparable to other models, indicating similar variability.

The seven DEMs show slightly higher overall accuracies than the error specifications reported by various nodal agencies, with values of 12.55 m (SRTM30), 12.49 m (SRTM90), 12.58 m (NASADEM), 12.99 m (COP30), 13.04 m (COP90), 12.43 m (AW3D30), and 12.50 m (ALOS PALSAR). These performance limitations can likely be attributed to the diverse characteristics of the study area, which include mountainous regions with steep relief, wet forests, varied land uses, and the presence of noise (Yap et al., 2018; Rodriguez et al., 2006).

Additionally, the elevations were categorized into 80-meter intervals to identify the elevation range that most accurately aligns with the GPS survey data. The standard deviations for each elevation range are shown in Figure 4, and the linear errors are detailed in Table 7.

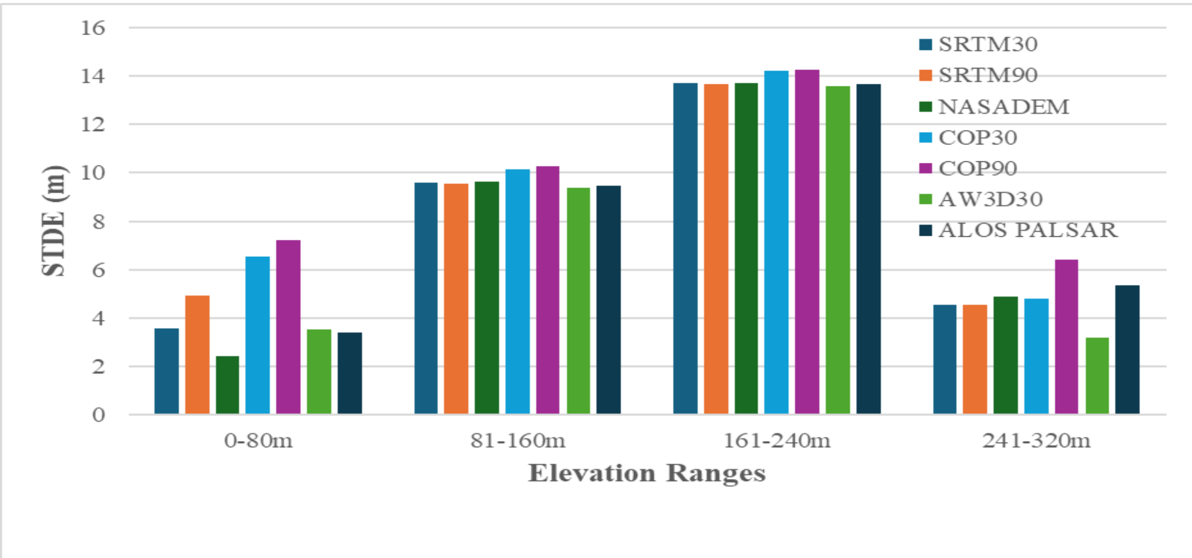



Figure 4: Standard deviation of the differences between GPS elevations and various DEMs across different elevation ranges

According to Figure 4, the standard deviation results across different elevation ranges indicate that for the 0-80m range, NASADEM shows the lowest variability with a standard deviation of 2.43 m, while COP90 has the highest at 7.21 m. In the 81-160m range, the values are relatively consistent across models, with AW3D30 showing the lowest variability at 9.37 m and COP90 again showing the highest at 10.26 m. For the 161-240m range, all models exhibit higher standard deviations, with COP90 showing the highest at 14.25 m and AW3D30 the lowest at 13.57 m. In the 241-320m range, AW3D30 has the lowest standard deviation at 3.19 m, whereas COP90 has the highest at 6.41 m. Therefore, it can be inferred that across most elevation ranges, the AW3D30 model demonstrated superior accuracy, while the COP90 model lagged significantly behind. This finding aligns with other studies, such as those by Apeh et al. (2019), Yap et al. (2018), Purinton and Bookhagen (2017), and Dawod and Al-Ghamdi (2017), which also found that AW3D30 outperforms other DEMs in terms of accuracy within the study area. Consequently, AW3D30 best represents the topography of the Earth's surface in this region.

Table 7: Linear errors of the DEMs across different elevation ranges

| Linear error at 90% confidence level | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Elevation range (m)** | SRTM30 | SRTM90 | NASADEM | COP30 | COP90 | AW3D30 | ALOS PALSAR |
| 0-80 | 5.91 | 8.11 | 3.99 | 10.79 | 11.86 | 5.79 | 5.59 |
| 81-160 | 15.78 | 15.71 | 15.87 | 16.71 | 16.88 | 15.42 | 15.57 |
| 161-240 | 22.55 | 22.5 | 22.59 | 23.36 | 23.44 | 22.32 | 22.46 |
| 241-320 | 7.47 | 7.44 | 8.07 | 7.92 | 10.54 | 5.25 | 8.78 |
| **Linear error at 95% confidence level** | | | | | | | |
| **Elevation range (m)** | **SRTM30** | **SRTM90** | **NASADEM** | **COP30** | **COP90** | **AW3D30** | **ALOS PALSAR** |
| 0-80 | 6.83 | 9.37 | 4.61 | 12.46 | 13.7 | 6.68 | 6.4 |
| 81-160 | 18.23 | 18.14 | 18.33 | 19.3 | 19.5 | 17.81 | 17.99 |
| 161-240 | 26.05 | 25.98 | 26.1 | 26.98 | 27.08 | 25.78 | 25.94 |
| 241-320 | 8.62 | 8.6 | 9.32 | 9.14 | 12.17 | 6.07 | 10.14 |
| **Linear error at 99.73% confidence level** | | | | | | | |
| **Elevation range (m)** | **SRTM30** | **SRTM90** | **NASADEM** | **COP30** | **COP90** | **AW3D30** | **ALOS PALSAR** |
| 0-80 | 10.78 | 14.79 | 7.28 | 19.68 | 21.63 | 10.55 | 10.2 |
| 81-160 | 28.78 | 28.65 | 28.95 | 30.48 | 30.79 | 28.12 | 28.4 |
| 161-240 | 41.13 | 41.03 | 41.2 | 42.6 | 42.76 | 40.7 | 40.96 |
| 241-320 | 13.62 | 13.58 | 14.71 | 14.44 | 19.22 | 9.58 | 16.02 |

The linear errors calculated for each elevation range at 90%, 95%, and 99.73% confidence levels, as shown in Table 7, also confirm that AW3D30 outperforms the other six DEMs evaluated in this study. This demonstrates that AW3D30 is highly reliable and can be utilized independently or in conjunction with ground survey data for various geospatial applications.

## 4. CONCLUSIONS

This study comprehensively evaluated the performance of various DEMs to determine their suitability for geospatial applications using GPS point survey data over Ibadan, Nigeria. The DEMs assessed include SRTM30, SRTM90, NASADEM, COP30, COP90, AW3D30, and ALOS PALSAR. In all the analyses based on standard deviation and linear error values, AW3D30 proved to be the most accurate DEM, effectively depicting the topography of the earth's surface in the study area. However, the NASADEM model shows the lowest mean error and mean absolute error values, while the ALOS PALSAR model exhibits the poorest performance with the highest ME and MAE values, indicating significant deviations from the GPS elevations. Despite this, ALOS PALSAR's standard deviation and linear errors are comparable to those of other models, suggesting similar variability.

Evaluating the accuracy of DEMs is crucial for geospatial applications, as it shows how precisely these models reflect the earth's surface, providing dependable data for applications such as topographic mapping, urban planning, environmental monitoring, and infrastructure development. This study supports findings from similar research, highlighting that the extent and severity of errors in DEMs are influenced by the study area, sensor resolution, environmental characteristics, data acquisition methods, and processing techniques. Therefore, this study should be used as a reference for selecting and utilizing these DEMs for geospatial applications in Ibadan, Nigeria.

**5. ACKNOWLEDGEMENT**

The author extends heartfelt gratitude to the Office of the Surveyor General of Oyo State in Ibadan, Nigeria, for providing the GPS survey data for this study.

**6. FUNDING**

No funding for this research

**7. AUTHORS' CONTRIBUTIONS**

All authors have contributed equally.

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