Evaluation of Global Digital Elevation Model (GDEM) over Peninsular

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Abstract

Open-source Digital Elevation Models (DEMs), such as Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Advanced World 3D (AW3D30), Forest and Buildings removed DEM (FABDEM), Global Land One-km Base Elevation (GLO-30), Multi-Error-Removed Improved-Terrain (MERIT), NASA Digital Elevation Model (NASADEM), Shuttle Radar Topography Mission (SRTM), and TanDEM-x, are widely used in environmental modelling and geospatial studies, where spatial resolution and vertical accuracy are critical. This study evaluates the accuracy of these DEMs by comparing their elevations with orthometric heights derived from Global Navigation Satellite System (GNSS) observations. Accuracy was assessed using Root Mean Square Error (RMSE) and the correlation coefficient (R^2). The results indicate that FABDEM achieves the highest performance, with an RMSE of 1.681 m and the strongest correlation with GNSS-derived heights 0.998, largely due to its effective removal of vegetation and building artefacts. These findings suggest that FABDEM is the most reliable DEM among those assessed, making it particularly suitable for coastal and flood-prone areas where precise elevation data are essential for risk assessment, hydrological modelling, and geoid determination.

Keywords: ASTER, AW3D30, FABDEM, GDEM, GLO, MERIT, Peninsular Malaysia, SRTM, TanDEM-x

1. Introduction

Global Digital Elevation Models (GDEMs) are essential geospatial datasets that provide gridded representations of the Earth's topographic surface, forming the foundation for a wide range of scientific research and practical applications. These datasets support geomorphological mapping, hydrological modelling, flood risk assessment [1], infrastructure planning, environmental monitoring, and geoid computation [2]. The increasing accessibility of open-source GDEMs has transformed the landscape of geospatial analysis, enabling researchers, policymakers, and engineers to conduct terrain-related studies at regional to global scales without the constraints of proprietary or expensive data sources. Early-generation GDEMs such as ETOPO1, GTOPO30, and GLOBE provided broad geographic coverage but were hindered by coarse spatial resolution and notable vertical inaccuracies, particularly in mountainous or poorly surveyed regions [3]. To address these limitations, more refined models like the Shuttle Radar Topography Mission (SRTM) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) were introduced. These datasets offered improved spatial resolution of approximately 30 meters and greater global accessibility.

However, issues such as data voids, elevation noise, and vegetation-induced elevation bias persisted, necessitating post-processing techniques like filtering, interpolation, and dataset fusion to enhance usability [4].

With recent advancements in remote sensing technology and data processing methodologies, newer and more accurate GDEMs have emerged. Notably, the Advanced Land Observing Satellite World 3D 30 m (AW3D30) and TanDEM-x 90 m DEMs leverage stereo and interferometric synthetic aperture radar (InSAR) techniques to achieve higher vertical accuracy. The TanDEM-x model, for instance, provides near-global coverage with reported vertical accuracy better than 2 meters in many regions, although challenges remain in representing water bodies and correcting steep terrain distortions [5]. Similarly, the Multi-Error-Removed Improved-Terrain DEM (MERIT DEM) offers hydrologically conditioned elevation data by integrating and correcting SRTM and other global sources to reduce striping, void artifacts, and other systematic errors [6].One of the latest developments in this domain is the Forest and Buildings removed DEM (FABDEM), which further enhances elevation accuracy by correcting SRTM-derived surfaces with canopy height data. FABDEM employs machine learning techniques to remove vegetation and building structures, resulting in a more realistic bare-earth model suitable for hydrological and urban studies. Meanwhile, the NASA DEM refines original SRTM datasets by improving void-filling and geolocation accuracy, and the GLO-30 DEM provides updated global elevation coverage as another accessible alternative [7].

The evolution of GDEM products is closely linked to advancements in satellite-based Earth observation missions, sensor technologies, and data fusion algorithms. High-resolution elevation datasets are now integral to disaster risk reduction efforts, climate change modelling, sea-level rise simulations, and precision agriculture. Their value lies not only in spatial and vertical detail but also in their ability to provide consistent, repeatable, and scalable terrain information for temporal analysis and change detection. In recent years, evaluating the reliability and fitness-for-use of GDEMs has become a critical research focus. Several studies have assessed the vertical accuracy of DEMs by comparing them against ground control points obtained from GNSS surveys, airborne LiDAR data, or national geodetic frameworks. Commonly used statistical metrics such as Root Mean Square Error (RMSE), Mean Absolute Error (MAE), standard deviation (SD), and bias are employed to quantify DEM accuracy. In addition, qualitative evaluations such as terrain profile analysis, slope and aspect comparison, and hydrological validation are applied to determine DEM suitability for specific applications [8]. These evaluations help users select the m[illegible]e DEM product based on project requirements and regional terrain characteristics.

GDEMs are fundamental datasets widely applied in hydrology, geomorphology, geodesy, and disaster risk management. Over the past two decades, advancements in remote sensing have produced multiple freely available DEMs such as SRTM, ASTER, AW3D30, TanDEM-x, MERIT, FABDEM, and NASA DEM each with unique strengths and limitations [9][10] and [11]. These models have transformed global terrain mapping, yet their accuracy remains uneven across different landscapes, especially in areas with dense vegetation or complex topography. While the performance of global DEMs has been evaluated in many regions worldwide, limited studies have focused on Southeast Asia, and even fewer on Peninsular Malaysia. The region encompasses rugged highlands, low-lying floodplains, and dense tropical forests, all of which present unique challenges that can reduce the precision of satellite-derived DEMs. For Peninsular Malaysia, accurate elevation data is particularly critical for applications such as precise geoid modelling, flood hazard mapping, hydrological analysis, and infrastructure planning. Inaccuracies in DEMs may therefore propagate errors into geoscientific research and decision-making, limiting their reliability for both scientific and practical uses. However, despite the availability of various global DEMs, no comprehensive validation has yet been carried out for Peninsular Malaysia, leaving uncertainties about their accuracy and applicability in this topographically diverse tropical environment. Addressing this gap, the present study conducts a systematic evaluation of multiple global DEMs over Peninsular Malaysia to determine their accuracy and suitability for regional geospatial applications.

The aim of this study is to assess the accuracy of selected global DEMs using GPS-derived orthometric heights as ground truth. Specifically, the study seeks to (i) quantify the accuracy of each DEM through statistical measures such as RMSE, MAE analysis; (ii) evaluate spatial variations in DEM performance across different terrain types; and (iii) provide recommendations on the most suitable DEMs for geoscientific and engineering applications in Peninsular Malaysia. This study contributes to improving the reliability of geospatial datasets in tropical, topographically complex regions and provides a benchmark for future DEM validation efforts in Southeast Asia.

Therefore, this paper aims to provide a comprehensive overview of the most widely used GDEM products to evaluate the GDEMs' elevation accuracy using statistical metrics (RMSE and R²). By comparing their performance and accuracy across different terrain types, this study contributes to the ongoing discourse on best practices for selecting and applying elevation data in diverse geoscientific and engineering contexts.

2. Study Area and Datasets

2.1 Study Area

In this study, Peninsular Malaysia was selected to achieve the aims of this study. The study area covers Peninsular Malaysia, extending approximately from 1.0°N to 7.0°N latitude and 99.0°E to 104.0°E longitude (Figure 1). Peninsular Malaysia provides a particularly important test region for the validation of global Digital Elevation Models (DEMs) due to its complex and heterogeneous landscape. The topography ranges from coastal lowlands and floodplains near sea level to mountainous regions exceeding 2,000 m, combined with dense tropical vegetation and varied geological structures. These conditions can introduce significant elevation errors in DEMs derived from remote sensing, particularly in areas of steep relief or heavy canopy cover. Furthermore, Peninsular Malaysia plays a critical role in applications such as precise geoid determination, flood risk management, hydrological modelling, and infrastructure planning, all of which require reliable elevation data. Accurate DEM validation in this region is therefore not only essential for improving geospatial datasets locally but also contributes to advancing global DEM evaluation in tropical, topographically diverse environments.

2.2 Global Digital Elevations Model (GDEM)

2.2.1 ASTER

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is a high-resolution optical sensor onboard NASA's Terra satellite, widely used for generating global digital elevation models (GDEMs) through near-infrared (NIR) stereo image pairs [12]. ASTER GDEM Version 2 and Version 3 offer near-global coverage between 83°N and 83°S at approximately 30-meter (~1 arc-second) resolution and are freely available for a wide range of applications including topographic mapping, hydrological modelling, geomorphological analysis, and environmental monitoring. Unlike radar-based DEMs such as SRTM, ASTER's optical-based elevation extraction is sensitive to cloud cover, snow, vegetation, and surface reflectance, leading to variations in accuracy and artifacts in the data [13]. The vertical accuracy of ASTER DEMs is terrain-dependent; studies have reported a root mean square error (RMSE) of approximately 10.241 meters higher than SRTM's 6.276 meters especially in rugged and forested areas.

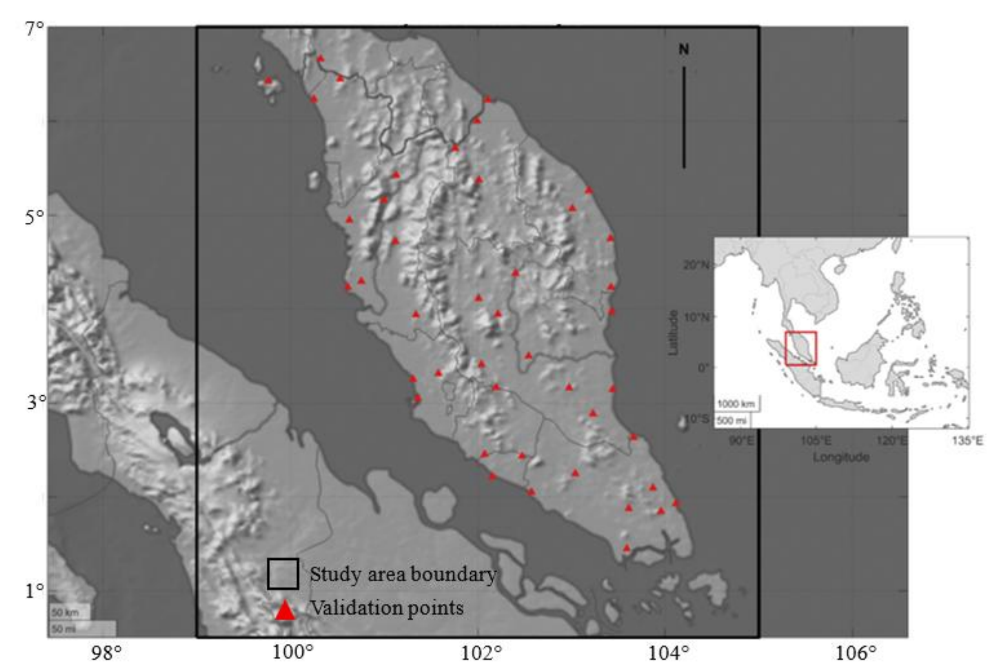

Figure 1: Peninsular Malaysia

Terrain features such as slope and land cover significantly influence ASTER's performance, with higher errors observed in steep, complex, or densely vegetated landscapes. Comparative studies have shown that SRTM generally yields better accuracy, as demonstrated in case studies in Turkey and the northwestern Himalayas. Despite these limitations, ASTER DEMs remains valuable due to their finer spatial resolution, particularly in regions where higher-resolution data are scarce or unavailable. Their usability can be significantly enhanced through post-processing techniques such as random forest regression, machine learning-based error correction, or data fusion with other DEMs like SRTM to reduce elevation noise and fill data gaps. For critical geospatial applications in complex terrain such as hydrological modelling, slope analysis, and geoid computation users are strongly encouraged to apply correction models or validate ASTER-derived elevations against ground-truth measurements, such as GNSS or LiDAR data, to improve reliability and accuracy. This approach ensures that the inherent limitations of ASTER DEMs are mitigated while maximizing their spatial detail and utility in various scientific and engineering contexts. The dataset can be accessed from NASA's LP DAAC portal (https://lpdaac.usgs.gov/products/astgtmv003/)."

2.2.2 SRTM 30m

The Shuttle Radar Topography Mission (SRTM), conducted in February 2000, marked a major milestone in Earth observation by producing the first publicly available near-global high-resolution Digital Elevation Model (DEM). The mission successfully mapped approximately 80% of the Earth's land surface using space-borne radar interferometry, providing coverage between 60°N and 56°S. SRTM data is released at 1-arc-second (~30 m) resolution for the United States and 3-arc-second (~90 m) resolution globally [14]. The vertical accuracy of SRTM data is influenced by several factors, including topography, slope, vegetation, and land cover, often showing elevation overestimation in forested areas and underestimation in valleys and steep slopes. Reported Root Mean Square Error (RMSE) values for SRTM vary according to terrain complexity, with figures ranging from below 50 meters in flat areas to over 70 meters in rugged landscapes. Additionally, data voids frequently occur in regions with complex terrain, persistent cloud cover, or low radar backscatter, such as deserts and water bodies. These gaps are commonly addressed through interpolation or integration with complementary datasets like ASTER or InSAR-derived DEMs. Despite its limitations, SRTM remains a vital and widely used elevation dataset due to its broad coverage, consistent processing methodology, and free accessibility. It plays a central role in applications across hydrology, geomorphology, forest monitoring, glaciology, and volcanology. Comparisons with DEMs from ASTER, ICESat, and other sources have shown that SRTM generally provides robust and reliable elevation data; however, calibration and correction are often required in vegetated and mountainous regions to account for systematic errors. Techniques such as ground control point adjustment, vegetation correction models, and integration with higher-resolution DEMs are commonly applied to enhance SRTM's accuracy for critical geospatial analyses. The SRTM dataset is available via USGS EarthExplorer (https://earthexplorer.usgs.gov/).

2.2.3 AW3D30

The Advanced Land Observing Satellite (AW3D30) series, developed by the Japan Aerospace Exploration Agency (JAXA), plays a key role in providing high-resolution digital surface models (DSMs) for global geospatial analysis. One of its primary products, the ALOS World 3D – 30 m (AW3D30) dataset, offers near-global DSM coverage at a 30-meter spatial resolution (1 arc-second), derived from the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) onboard the original AW3D30 satellite [15]. Validated against 5,121 global ground control points, AW3D30 demonstrates a vertical root mean square error (RMSE) of approximately 4.40 meters [13], making it a reliable elevation data source for applications such as terrain modelling, land cover classification, hydrological analysis, and infrastructure planning. Building upon this foundation, the AW3D30 mission, as the successor to AW3D30, introduces enhanced optical imaging capabilities. It is equipped with a panchromatic sensor offering 0.8-meter ground resolution and a multispectral sensor with six bands at 3.2-meter resolution. With a wide 70 km swath at nadir and large body-pointing capabilities up to ±60°, AW3D30 facilitates stereo imaging that supports the generation of high-quality DSMs. The mission is designed to serve diverse objectives, including disaster monitoring, frequent geospatial data updates, environmental management, and societal infrastructure development. Together, AW3D30 provide global, high-resolution DSMs that are freely accessible for both scientific and operational uses. Their combination of fine spatial detail, validated vertical accuracy, and broad coverage establishes them as vital tools in various applications such as environmental monitoring, disaster response, urban planning, and resource management.

Their continuous contribution to the geospatial community reflects the importance of satellite-based elevation models in supporting sustainable development and risk mitigation efforts worldwide. The 30 m resolution version (AW3D30) is freely available through JAXA (https://www.eorc.jaxa.jp/ALOS/en/ aw3d30/).

2.2.4 NASADEM

NASADEM is a refined digital elevation model introduced by NASA as an enhancement of the original Shuttle Radar Topography Mission (SRTM) dataset. It was developed with the aim of improving the quality of SRTM data through updated radar processing techniques and the inclusion of supplementary datasets. Key advancements in NASADEM include the application of more accurate phase unwrapping algorithms, improved void-filling processes, and enhanced geolocation adjustments [16]. Like its predecessor, NASADEM provides near-global coverage between 60°N and 56°S at approximately 30-meter (1 arc-second) spatial resolution. However, it offers notable improvements in vertical accuracy and a reduction in data voids compared to SRTM. NASADEM incorporates additional elevation information from sources such as ICESat and ASTER GDEM to more effectively address gaps and correct elevation artefacts caused by vegetation cover and radar imaging limitations such as layover effects [17]. Initial evaluations show that NASADEM delivers greater spatial consistency and improved vertical precision, making it particularly useful for applications like terrain analysis, hydrological studies, and broader geospatial modelling, especially in regions where SRTM's performance was limited [18]. As a freely accessible dataset under NASA's open data initiative, NASADEM significantly expands the utility of global elevation data for both scientific research and practical applications in areas such as disaster management, infrastructure development, and environmental monitoring. The NASA DEM is accessible from NASA Earthdata (https://earthdata.nasa.gov/esds/competitive-programs/measures/nasa-dem).

2.2.5 TanDEM-x 90m

The TanDEM-x 90 m Digital Elevation Model (DEM) represents a significant advancement in global topographic data, developed through the German TanDEM-x mission in collaboration with TerraSAR-X. Launched in 2010, TanDEM-x operates in a closely coordinated single-pass interferometric synthetic aperture radar (InSAR) formation, maintaining a separation of approximately 200 to 500 meters between satellites. This configuration allows for highly precise elevation measurements by avoiding common challenges such as temporal decorrelation and atmospheric disturbances that affect repeat-pass InSAR methods. By 2016, the final global TanDEM-x DEM product was made available, offering near-complete Earth coverage with remarkable accuracy achieving absolute vertical accuracy better than 1 meter and relative vertical accuracy of approximately 0.8 meters in flat regions [19]. These attributes make TanDEM-x DEM particularly valuable for high-precision applications such as geodesy, hydrology, landform analysis, and disaster risk assessment, where consistent and reliable elevation information is essential. To promote scientific research, a coarser-resolution 90-meter version was made freely available to users, significantly enhancing access to high-quality elevation data for global studies. The TanDEM-x 90 m dataset (TDM90) can be downloaded from DLR's Geoservice (https://geoservice.dlr.de/web/dataguide/tdm90/).

2.2.6 MERIT DEM

The Multi-Error-Removed Improved-Terrain Digital Elevation Model (MERIT DEM) is a globally available elevation dataset specifically developed to overcome the limitations of widely used DEMs such as SRTM and AW3D30. By addressing multiple sources of error including vegetation bias, striping noise, and absolute bias MERIT DEM offers a more accurate representation of bare-earth topography [20]. It is derived by integrating and correcting multiple existing datasets, ensuring globally consistent and high-quality elevation data. One of the key advantages of MERIT DEM lies in its superior accuracy in both flat and mountainous terrains, which has been demonstrated through lower root mean square error (RMSE) values in comparison to SRTM in several validation studies [21]. MERIT DEM is distributed by the University of Tokyo (http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/).

2.2.7 FABDEM

Forest And Buildings removed Copernicus DEM (FABDEM) is a new dataset created by using machine learning techniques. The building and tree height bias from Copernicus GLO-30 DEM is removed to become new model of digital of elevation. The new dataset covers the globe between 60°S and 80°N at a 1-arcsecond (~30 m) grid spacing and is the first global DEM to remove both vegetation and buildings [11].

The FABDEM is a bias technique to correct due to buildings and trees, which suitable to use in flood-risk management, where the high accuracy of DEMs is efficient in planning and live savings. Copernicus GLO-30 DEM is a digital surface model (DSM) which created from edited WorldDEM and product of SAR Inferometry (InSAR)-based TanDEM-x DEM [22]. By applying convolutional neural networks trained on LiDAR reference data, FABDEM improves terrain accuracy, making it highly suitable for applications such as flood risk assessment, hydrological modelling, urban planning, and geoid determination. Its open-access availability under a Creative Commons license further enhances its usability for both scientific research and operational purposes worldwide. FABDEM can be accessed from the University of Bristol repository (https://data.bris.ac.uk/data/dataset/s5hqmjcdj8yo2ibzi9b4ew3sn).

2.2.8 GLO-30 DEM

The Copernicus GLO-30 Digital Elevation Model (DEM) is a high-resolution global elevation dataset produced by the European Space Agency as part of the Copernicus program. GLO-30 is a global Digital Surface Model (DSM) that provides elevation data at approximately 30-meter (1 arc-second) spatial resolution, derived mainly from the TanDEM-x product and supplemented with additional sources such as ASTER, SRTM, and AW3D30 to address voids and enhance global coverage. As a DSM, GLO-30 captures both the bare-earth terrain and elevated surface features like buildings and vegetation. In terms of vertical accuracy, GLO-30 reports an absolute vertical accuracy better than 4 meters at a 90% confidence level, with relative accuracy typically below 2 meters in flat areas and below 4 meters in steeper landscapes. Independent validation efforts have documented RMSE values ranging from approximately 2 to 6.7 meters, depending on the local topography and the reference data employed. These accuracy characteristics make GLO-30 a practical elevation dataset for diverse geospatial applications, including terrain analysis, hydrological modelling, slope stability assessment, and urban or infrastructure development planning. Notably, in Brazil, GLO-30 has been validated against the Brazilian Cartographic Accuracy Standard for Digital Cartographic Products (PEC-PCD), meeting requirements for map scales up to 1:50,000 [23]. Comparative studies involving other DEM products such as AW3D30 and ASTER GDEM have indicated that GLO-30 generally offers superior performance in urban environments and open, non-vegetated regions, although it may present challenges in areas with rugged terrain or dense forest cover, where its vertical accuracy can vary. For example, in Italian Trentino Province, GLO-30 performed better in urbanized and gentle slope areas compared to AW3D30. However, since GLO-30 includes vegetation and man-made structures, it is not ideal for bare-earth modelling. For such applications, the FABDEM (Forest and Buildings removed Copernicus DEM) is a better alternative, as it offers a corrected version of GLO-30 that removes surface features to better approximate ground elevation. The Copernicus DEM GLO-30 dataset is available via Copernicus Space Data Portal (https://planetarycomputer.microsoft.com/dataset/cop-dem-glo-30).

2.2.9 Summary of Global DEMs

Global DEMs provide elevation data of the Earth's surface and are essential in various disciplines such as geomatics, hydrology, disaster management, and environmental monitoring. Each DEM offers unique characteristics in terms of resolution, accuracy, and application suitability. Table 1 Shows the concise summary of global Digital Elevation Models (DEMs). Table 1 provides a comparative overview of several widely used open-access global Digital Elevation Models (DEMs).

Table 1: Comparative insights

DEM	Resolution (m)	RMSE (m)	Best Use Cases	Citation
ASTER	30	±10.2 to 13.0	General topography, less relief	[24][25] and [26]
SRTM	30	±7.0 to 17.8	Low relief, hydrology, urban planning	[27] and [28]
AW3D30	30	± 4.8 to 5.7	Complex topography, detailed studies	[29] and [30]
TanDEM-x	90	±1.4 to 8.7	High accuracy applications	[9][31][32][33] and [34]
MERIT DEM	90	± 1.7 to 3.0	Reduced striping and voids, hydrologically corrected	[35] and [36]
FABDEM	30	± 2.8 to 6.0	Tree-height corrected SRTM-derived DEM for bare-earth modelling	[37]
NASADEM	30	±2.4 to 4.5	Updated SRTM with improved void filling and geolocation	[38] and [39]
GLO-30 DEM	30	± ≤ 0.55	Global coverage; based on TanDEM-x; suitable for many terrain types	[40] and [41]

Table 2: Reference datums of the GDEMs used in this study

DEM	Vertical Datum Reference	Geoid Model
ASTER	Mean Sea Level	EGM96
SRTM	Mean Sea Level	EGM96
AW3D30	Mean Sea Level	EGM96
TanDEM-x	Ellipsoid	WGS84
MERIT DEM	Mean Sea Level	EGM96
FABDEM	Mean Sea Level	EGM2008
NASADEM	Mean Sea Level	EGM96
GLO-30 DEM	Mean Sea Level	Presumed orthometric

Each DEM is listed with its spatial resolution, reported root mean square error (RMSE), typical application domains, and relevant citations. The table highlights the variation in vertical accuracy across DEMs, with RMSE values ranging from sub-meter (e.g., GLO-30 DEM, ≤0.55 m) to more than 10 m in some cases (e.g., ASTER DEM). DEMs such as SRTM, AW3D30, and TanDEM-x demonstrate a balance between spatial resolution and accuracy, making them suitable for hydrological modeling, urban planning, and terrain analysis. Newer datasets such as MERIT DEM, FABDEM, NASADEM, and GLO-30 have introduced improvements in void filling, geolocation accuracy, and vegetation correction, thereby enhancing their reliability for diverse applications. Overall, the table underscores that DEM selection should be guided not only by resolution but also by accuracy requirements and study objectives.

Table 2 summarizes the native vertical datums of all DEMs used in this study. All DEMs except TanDEM-x 90 m are referenced to a geoid (i.e. represent orthometric heights). TanDEM-x 90 m, however, uses the WGS84 ellipsoid as its vertical datum; thus, its heights are ellipsoidal. Because our validation reference (GPS + geoid model) yields orthometric heights, we converted TanDEM-x heights using Equation 1:

$$H \approx h - N$$

Equation 1

Where h is the ellipsoidal height from TanDEM-x, N is the geoid undulation at that point, and H is the orthometric height for direct comparison with other DEMs and GPS reference heights. EGM undulation (N) used for converting ellipsoidal heights to orthometric heights were obtained from the International Centre for Global Earth Models (ICGEM) service: https://icgem.gfz-potsdam.de/.

3. Methodology

3.1 Pre-processing

Before performing any accuracy assessment, it is essential to ensure that all Digital Elevation Models (DEMs) used are in a consistent format. This includes having the same coordinate system (typically WGS84), spatial resolution (e.g., 30m or 90m), and file format (such as ASCII, GeoTIFF, or. grd). Uniformity ensures that the comparison between different DEMs or between DEMs and reference data is valid and not influenced by mismatched grids or projections. A crucial step in DEM preparation involves harmonizing the vertical reference system. Many global DEMs are referenced to the WGS84 ellipsoid (i.e., they contain ellipsoidal heights. In this study, the Earth Gravitational Model 1996 (EGM96) was adopted as the vertical reference, as it is the default geoid model embedded in most widely used open-access DEMs, including SRTM, ASTER, AWD3D, TanDEM-x, and FABDEM. The use of EGM96 ensures consistency across the datasets and avoids introducing additional transformation uncertainties that could arise when converting to another vertical datum. Although the Earth Gravitational Model 2020 (EGM2020) provides improved spatial resolution and accuracy, it was not applied here because the primary objective of this study is to evaluate DEMs in their original form, as typically accessed and used by the global user community. The implications of adopting EGM96 rather than EGM2020 are acknowledge, and this limitation is considered in the interpretation of results. The calculations are conducted using Equations 2 and 3:

$$H_{MSL} = h_{gps} - N_{EGM96}$$

Equation 2

$$\Delta H = H_{GDEM} - H_{MSL}$$

Equation 3

Where h represents the height or elevation of a point above the reference ellipsoid. H_{MSL} represents the height or elevation of the same point above mean sea leve N_{EGM96} represents the geoid undulation. Equation 2 and 3 describe the conversion and comparison procedures used in this study. First, the GPS ellipsoidal height (h_{gps}) was converted to an orthometric height (H_{MSL}) using geoid undulations

(N_{EGM96}) from the EGM96 global geopotential model. The resulting orthometric height (H_{GDEM}) was compared with the GPS-derived orthometric height (H_{MSL}) to compute the elevation difference (ΔH). Positive values of ΔH indicate that the DEM height is higher than the GPS-derived orthometric height, while negative values indicate that the DEM underestimates the actual elevation. The preprocessing of DEMs prior to accuracy assessment follows a structured workflow in Figure 2.

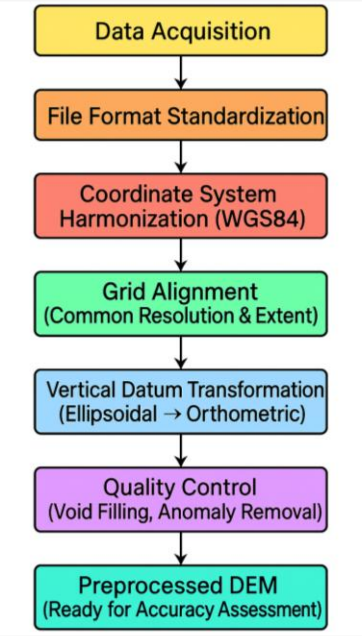

Figure 2: Workflow diagram of DEM preprocessing steps prior to accuracy assessment

3.2 Accuracy Assessment

To quantitatively evaluate the accuracy of global Digital Elevation Models (DEMs) against a reference dataset (typically ground truth benchmarks or GPS-derived orthometric heights), several statistical metrics are employed. These metrics help characterize the error behaviour of each DEM and provide insights into their overall quality and suitability for geodetic or topographic applications. The Mean Absolute Error (*MAE*) and Root-Mean-Square Error (*RMSE*) can be computed using the Equation 4 and 5, respectively:

$$MAE = \frac{\sum_{i=1}^{n} \left| H_{GDEM} - H_{MSL} \right|}{n}$$

Equation 4

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(H_{GDEM} - H_{MSL} \right)^2}{n}}$$

Equation 5

The evaluation of GNSS leveling and orthometric heights obtained from GDEM can be affected by various sources of error. To assess the accuracy of the DEMs, statistical error indicators were calculated. The Mean Absolute Error (*MAE*) Equation 4 measures the average magnitude of the differences between DEM-derived elevations (H_{GDEM}) and GPS-derived orthometric heights (H_{MSL}). The Root Mean Square Error (*RMSE*) Equation 5 quantifies the overall magnitude of errors by squaring the individual differences, averaging them, and then taking the square root. While MAE provides a straightforward interpretation of the average error, RMSE is more sensitive to large deviations, thus offering a more conservative measure of DEM performance. Both metrics are expressed in metres, and smaller values indicate higher DEM accuracy. The processing and validation workflow was implemented using EGM Lab (Earth Gravity Model Laboratory), a MATLAB-based computational environment for analysing Global Geopotential Models (GGMs) and related datasets. In this study, EGM Lab was used to extract gravity-related quantities, process DEM and GNSS data, and compute the statistical accuracy indicators described above. The complete sequence of steps is illustrated in Figure 3, a diagram showing the accuracy assessment process for Global Digital Elevation Models (GDEMs).

3.3 Global Reference Surface

MyGEOID is the official gravimetric geoid model of Malaysia developed and maintained by the Department of Survey and Mapping Malaysia (DSMM). Two main versions have been released, myGEOID2004 and the improved MyGEOID2017, with the latter providing a more precise fit to GNSS/levelling benchmarks by incorporating airborne gravity, terrestrial gravity, marine gravity, and the latest global geopotential models (GGMs). The models have a spatial resolution of approximately ±4–5 cm and provides geoid undulation values with a typical accuracy of 0.01° (~1 km) relative to the national levelling network. MyGEOID is used as the national vertical datum to transform GNSS-derived ellipsoidal heights into orthometric heights, thereby ensuring consistency in height-related applications across Malaysia. In this study, MyGEOID was adopted as the reference surface against which DEM elevations were validated. This ensured that the GNSS/DEM comparisons were tied to the national vertical datum, providing a reliable framework for assessing the vertical accuracy of open-source GDEMs in Peninsular Malaysia.

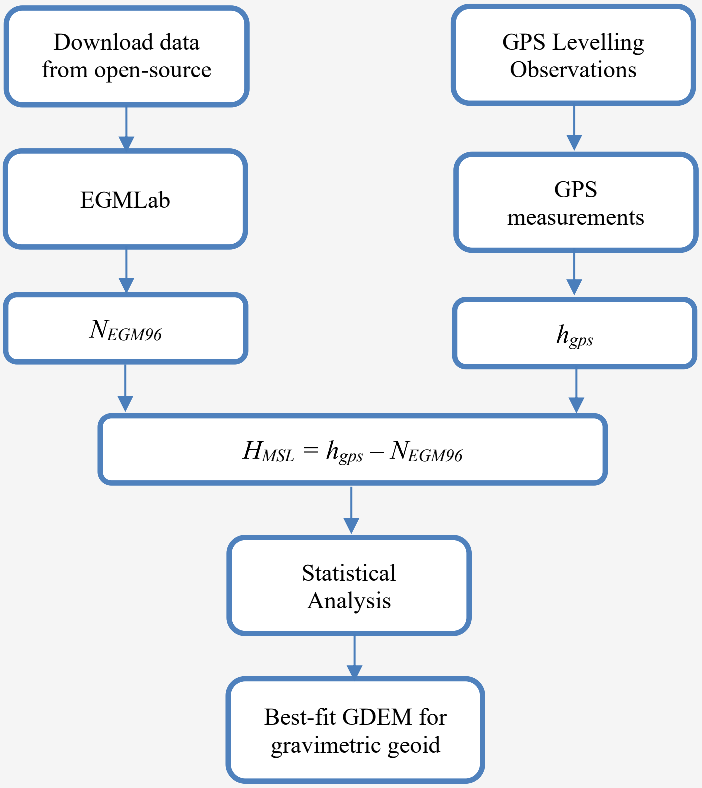

Figure 1 : Diagram illustrating the accuracy assessment process for GDEM

3.4 GNSS Levelling Data

A total of 45 reference points were used to validate the DEMs in this study. These points correspond to Benchmarks (BM) and Secondary Benchmarks (SBM) provided by the Department of Survey and Mapping Malaysia (DSMM), where both precise GNSS ellipsoidal heights and levelling-derived orthometric heights are available. The selection of points was based on data quality, ensuring that only benchmarks with consistent GNSS and levelling records were included, while redundant or erroneous points were removed following a cross-validation procedure. To guarantee reliable representation of terrain variability across Peninsular Malaysia, the points were distributed across different regions, covering coastal, inland, and highland areas, with allocations in the northern, central, southern, and eastern zones. This distribution ensures comprehensive coverage of the study area and captures the influence of varying topography on DEM accuracy. The spatial distribution of the reference points is illustrated in Figure 1, which confirms that the network provides adequate density and spread for robust accuracy assessment.

3.5 GNSS Measurements

GNSS-based orthometric heights were obtained using dual-frequency geodetic receivers (Trimble R10 and Leica GS18). Data collection employed static post-processing and RTK techniques. Static observations were conducted with a minimum one-hour occupation per benchmark at a 30-second sampling rate and a 15° cutoff angle to reduce multipath effects. Processing was performed in Trimble Business Centre using precise ephemerides and ionospheric-free combinations to derive ellipsoidal heights, which were later converted to orthometric height using the computed gravimetric geoid. For accessible sites, RTK observations were performed through the Malaysia Real-Time Kinematic GNSS Network (MyRTKnet), with each station observed for at least five minutes. The derived coordinates were validated against known benchmarks to ensure consistency and centimetre-level accuracy. The collected GNSS data were processed in Trimble Business Center (TBC) software using baseline processing and least-squares network adjustment. Reference coordinates were obtained from nearby Continuously Operating

Reference Stations (CORS) operated by the Department of Survey and Mapping Malaysia (DSMM). The resulting ellipsoidal heights (h) were then used to derive GNSS/levelled orthometric heights (H) for comparison with DEM-derived and gravimetric geoid heights.

4. Result and Discussion

The results of the accuracy assessment of the Global Digital Elevation Models (GDEMs) over Peninsular Malaysia are presented and discussed in this section. Statistical metrics, including Mean Absolute Error (MAE), Root Mean Square Error (RMSE), bias, and the coefficient of determination R^2, were computed to evaluate the vertical accuracy of each GDEM against GNSS-derived orthometric heights. The findings are structured to highlight the comparative performance of the DEMs, their spatial variability across different terrain types, and the implications for geodetic and geospatial applications in the study area.

4.1 GDEM RMSE

The vertical accuracy of the GDEMs was first evaluated using the Root Mean Square Error (RMSE), which quantifies the average magnitude of elevation differences between the DEM values and GNSS-derived orthometric heights. Figure 4 illustrates the comparison between the derived elevations from SRTM, ASTER, MERIT, FABDEM, GLO-30, NASADEM, AW3D30, and TanDEM-x with the GNSS levelling dataset.

As shown in Figure 4, most DEMs follow the general elevation profile captured by the GPS reference points, with TanDEM-x, SRTM, and NASADEM showing the closest agreement. In contrast, ASTER and AW3D30 deviate more noticeably, particularly in areas of higher elevation, reflecting their lower relative accuracy. The analysis highlights clear differences in the performance of the global DEMs. FABDEM shows the best agreement with GNSS-derived elevations, producing the lowest RMSE, followed closely by GLO-30 DEM and NASADEM, which also perform well. These models benefit from recent updates and improved error correction, particularly in areas with vegetation and rugged terrain. In contrast, TanDEM-x and ASTER exhibit relatively high RMSE values, reflecting larger discrepancies that may be linked to radar signal penetration in dense forest regions (TanDEM-x) and noise or cloud contamination in optical imagery (ASTER). Systematic underestimations are observed in DEMs with negative mean differences (e.g., NASADEM and TanDEM-x), while positive means (e.g., SRTM and AW3D30) suggest a tendency to overestimate elevations. Overall, the results indicate that newer DEMs with refined error-mitigation strategies (e.g., FABDEM and GLO-30 DEM) provide more reliable elevation information for Peninsular Malaysia compared to earlier generations such as ASTER or SRTM. The RMSE analysis revealed clear differences in the vertical accuracy of the GDEMs over Peninsular Malaysia in Table 3.

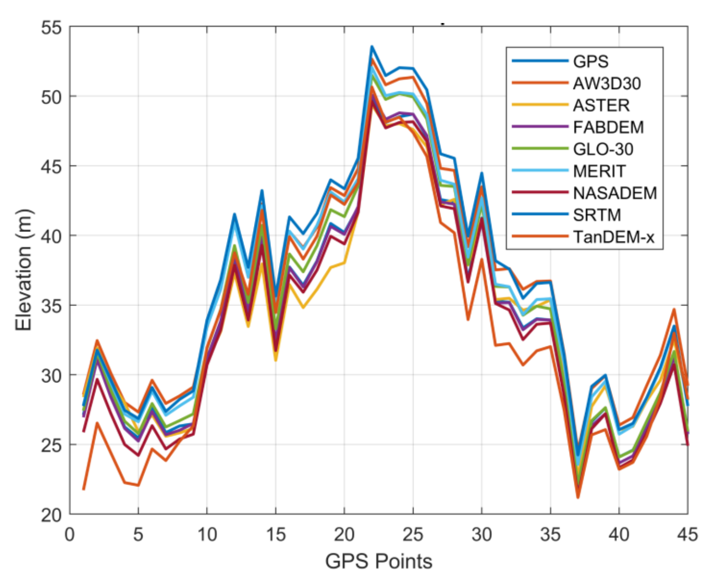

Figure 2 : A comparative analysis was conducted between GNSS levelling data and eight open-source Digital Elevation Models (DEMs)

Table 3: Comparative assessment of Global Digital Elevation Models (GDEMs)

DEM	**Statistical Analysis (m)**				
	Mean	**StdDev**	**Min**	**Max**	**RMSE**
ASTER	0.124	6.688	-13.543	15.958	6.614
SRTM	2.603	3.369	-6.667	11.311	4.227
AW3D30	2.415	2.519	-4.323	6.496	3.469
TanDEM-x	-0.672	6.640	-16.998	11.680	6.600
MERIT DEM	1.717	2.828	-4.489	10.071	3.282
FABDEM	**-0.123**	**1.695**	**-4.323**	**4.265**	**1.681**
NASADEM	-0.610	2.961	-9.038	6.311	2.991
GLO-30 DEM	0.706	1.959	-4.323	7.006	2.061

4.2 GDEM Correlational Coefficient

To evaluate the accuracy of the DEMs, the Root Mean Square Error (RMSE) and correlation coefficient (R^2) were calculated for each open-source DEM model. By comparing the derived orthometric heights from GNSS levelling with the corresponding orthometric heights from each DEM, the correlation coefficient (R^2) was determined, as illustrated in Figure 5. The strength of the relationship whether strong or weak between the orthometric heights can be assessed based on the R^2 and RMSE values. Based on these metrics, the most suitable DEM model will be identified as the best option for geoid applications.

Figure 5 presents the coefficient of determination (R^2) between GNSS-derived elevations and DEM-derived elevations. While (R^2) does not measure accuracy in terms of error magnitude, it provides valuable information on the strength of correlation between the two datasets. A high (R^2) indicates that the DEM closely follows the spatial variability of the GNSS heights, suggesting that the DEM reliably represents elevation trends across the study area. However, accuracy is assessed more directly through MAE and RMSE values, which quantify the magnitude of deviations. Thus, Figure 5 is intended to complement, rather than replace, the error statistics. The analysis revealed that SRTM have correlation coefficients of 0.992. Meanwhile, ASTER, MERIT, FABDEM, GLO-30, NASADEM, AW3D30, and TanDEM-x exhibit correlation coefficients of 0.963, 0.994, 0.998, 0.997, 0.994, 0.995 and 0.964 respectively. Based on the statistical evaluation of all five DEM datasets, FABDEM demonstrates the highest accuracy, with a Root Mean Square Error (RMSE) of 1.681 m and a correlation coefficient of 0.998, making it the most reliable among the open-source DEMs. In contrast, ASTER shows the poorest performance, with the highest RMSE of 6.614 m and the lowest correlation coefficient of 0.963. Table 3 presents the comprehensive statistical analysis of all DEMs compared to the GNSS levelling data, while Figure 6 illustrates the RMSE and correlation coefficient (R^2) for each DEM.

The comparison of RMSE and correlation coefficient (R^2) provides additional insights into the performance of the open-source DEMs against GPS reference data. Among the datasets, FABDEM demonstrates the best overall performance, achieving the lowest (1.681m) and the highest R^2 (0.998)), indicating both minimal vertical error and very strong agreement with GPS elevations. GLO-30 DEM also performs well, with RMSE of 2.061 m and R^2 of 0.997, closely matching FABDEM in reliability. NASADEM (RMSE=2.991 m, R^2=0.994) and MERIT DEM (RMSE=3.282M, R^2 =0.994) show consistent accuracy with strong correlation, suggesting they are robust alternatives. AW3D30 performs comparably with RMSE = 3.469 m and R^2=0.995, slightly less accurate than FABDEM but still reliable. In contrast, ASTER (RMSE = 6.614 m, R^2 = 0.963) and TanDEM-X (RMSE = 6.600 m, R^2 = 0.964) exhibit significantly higher errors despite moderate correlations, indicating limitations likely linked to terrain-induced distortions and radar-shadowing effects. SRTM, although widely used, records an RMSE of 4.227 m and a relatively lower R^2 value (0.992), making it less precise than FABDEM, Copernicus GLO-30, and AW3D30 for high-accuracy applications. Overall, the results show that FABDEM provides the most accurate and consistent performance, followed closely by GLO-30 and AW3D30, while ASTER and TanDEM-X should be applied cautiously due to their higher vertical errors.

Figure 7 presents the Mean Absolute Error (MAE) values and associated standard deviations for all evaluated DEMs. The results indicate clear performance differences, with FABDEM exhibiting the lowest MAE, reflecting its superior terrain representation across Peninsular Malaysia. GLO-30 also performs well, with MAE values slightly higher than FABDEM but still within the 1–1.5 m range. DEMs such as ASTER and TanDEM-X show noticeably higher MAE values, aligning with their weaker RMSE and correlation statistics.

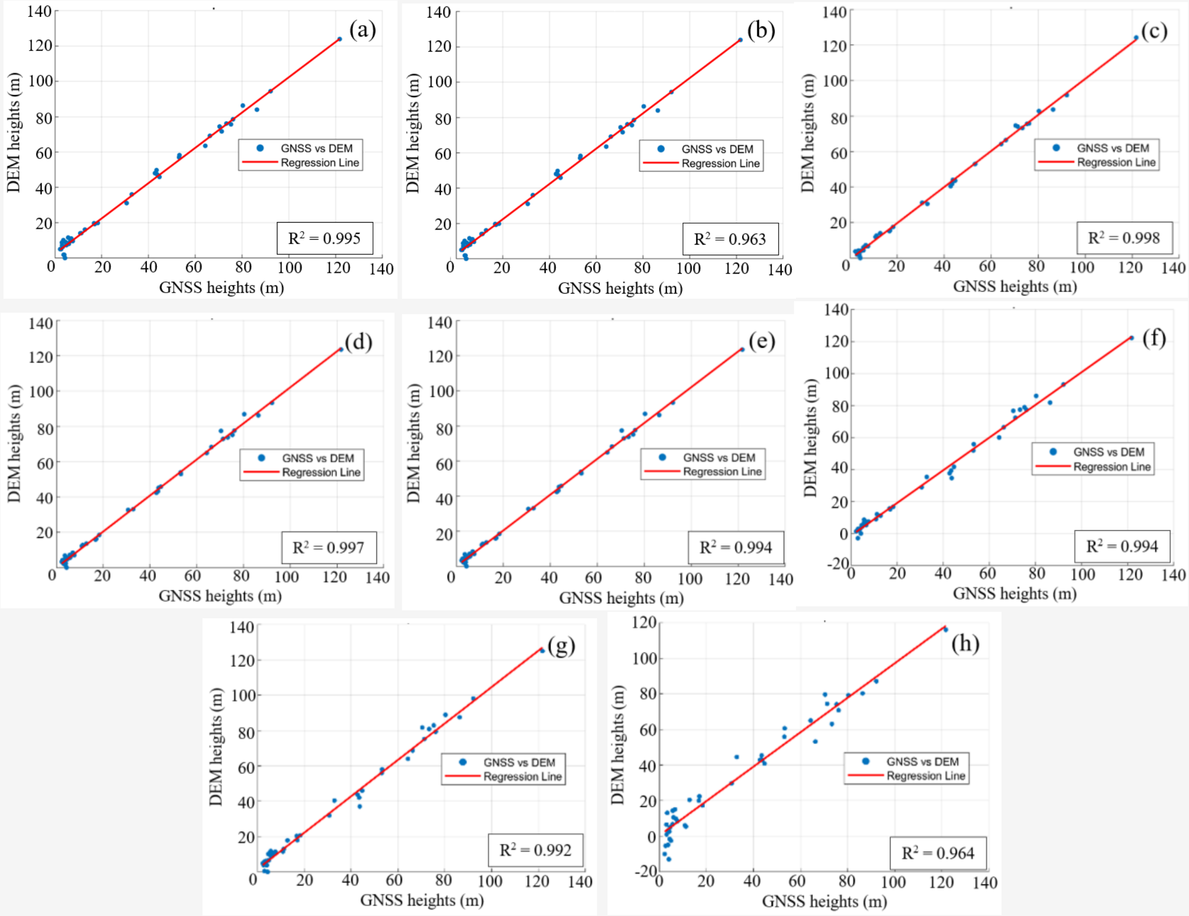

Figure 5: Correlation coefficient (R²) analysis between open source DEMs and GNSS data (a) AW3D30, (b) ASTER, (c) FABDEM, (d) GLO-30, (e) MERIT, (f) NASADEM (g) SRTM, and (h) TanDEM-x

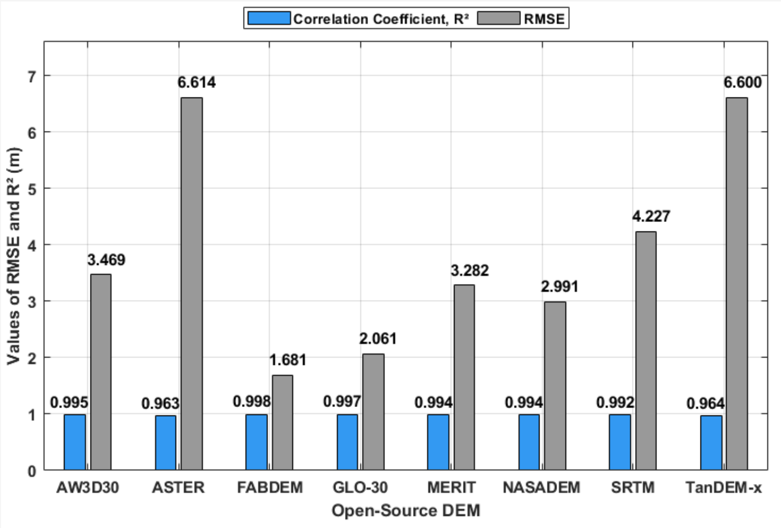

Figure 6: Overall assessment of RMSE and correlation coefficient for all DEMs

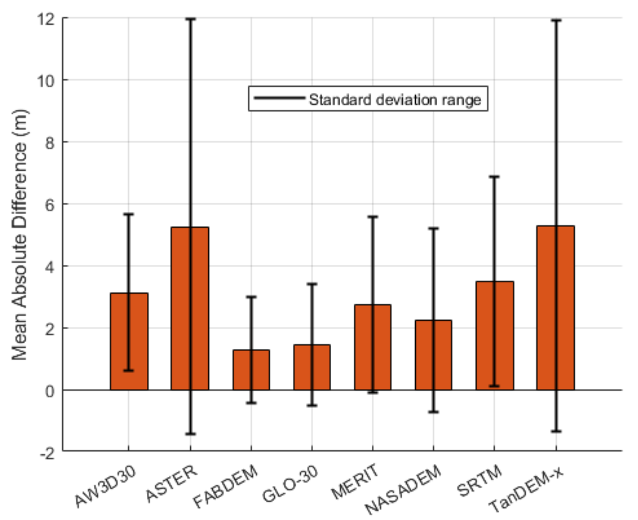

Figure 7: Accuracy assessment for all Global Digital Elevation Models

Their higher accuracy is primarily attributed to the terrain filtering and bias-correction algorithms applied during data processing FABDEM integrates machine-learning-based filtering to remove vegetation and built-up features, while GLO-30 benefits from Copernicus DEM's precise vertical calibration and mosaicking procedures. In contrast, ASTER GDEM and TanDEM-x show the highest MAE values (≈5 m) and the greatest standard-deviation ranges, indicating larger spatial variability in elevation error. The reduced accuracy of ASTER GDEM is linked to cloud contamination, shadow effects, and sensor noise inherent in optical stereo-correlation, whereas TanDEM-X being a Digital Surface Model (DSM) captures the tops of vegetation and man-made structures, producing elevated heights relative to GNSS benchmarks. MERIT, NASADEM, SRTM, and AW3D30 yield intermediate MAE values (≈2–3.5 m), performing consistently well in low-relief and moderately vegetated areas but with some degradation in rugged terrain. These findings confirm that newly refined DEMs such as FABDEM and GLO-30 outperform earlier models due to enhanced post-processing and filtering techniques. The removal of the previous t-test results ensures that the discussion is now based solely on descriptive error analysis, providing a clear and accurate interpretation of DEM performance across Peninsular Malaysia.

Based solely on the Root Mean Square Error (RMSE) and correlation coefficient (R^2) values 1.681 m and 0.998, respectively FABDEM is identified as the most appropriate open-source Digital Elevation Model (DEM) for geoid applications. Its high accuracy and strong correlation with GNSS levelling data make it the most reliable option among the evaluated DEMs for representing terrain elevations in the study area. These findings are in line with those reported by [11], who introduced FABDEM through the application of advanced machine learning methods aimed at improving the Copernicus GLO-30 DEM by eliminating elevation artefacts from vegetation and buildings. FABDEM was developed using a convolutional neural network (CNN) specifically trained to refine terrain representation, with its accuracy validated against independent ground-control datasets. Consistent with both global evaluations and the regional assessment presented in this study, FABDEM demonstrates superior reliability and vertical accuracy compared to other open-source DEMs. This confirms its suitability as the most dependable elevation dataset currently available for applications such as topographic analysis, flood risk management, and coastal monitoring in Peninsular Malaysia.

5. Conclusion

This study evaluated the vertical accuracy of eight open-source DEMs against GNSS levelling data across Peninsular Malaysia. The results show that FABDEM achieved the lowest RMSE (1.681 m) and the highest correlation coefficient ($R^2 = 0.998$), demonstrating superior accuracy and consistency compared to other datasets. In contrast, DEMs such as ASTER and TanDEM-x exhibited much larger RMSE values (above 6 m), confirming FABDEM's clear advantage. For Malaysian agencies such as DSMM and other stakeholders, FABDEM offers practical benefits in applications that require precise elevation data, including flood risk assessment, hydrological modelling, infrastructure development, and geoid determination. Its reliability in areas with dense vegetation and urban features conditions common in Malaysia further supports its suitability for regional use. Beyond accuracy, FABDEM's open accessibility and ease of integration into geospatial workflows make it a cost-effective choice for government agencies and planners. By identifying FABDEM as the most suitable DEM for Peninsular Malaysia, this study provides not only academic insights but also practical guidance for end-users in Malaysia and other regions with comparable terrain conditions.

6. Limitations and Future Research

Despite the robust findings, several limitations should be acknowledged. First, this analysis relied on 45 GNSS observation points, which, although well distributed across Peninsular Malaysia, may not fully capture the region's terrain variability. Increasing the number of GNSS control points in future studies would enhance spatial representativeness and strengthen statistical reliability. Second, most global DEMs derived from satellite sources represent Digital Surface Models (DSMs) rather than Digital Terrain Models (DTMs). As such, the inclusion of surface features such as vegetation, buildings, and other man-made structures may contribute to vertical discrepancies when compared against GNSS-measured terrain elevations. These effects were mitigated through careful site selection and preprocessing but were not completely removed and thus remain a potential source of error.

Third, the evaluation was conducted within a single regional context (Peninsular Malaysia). Results may differ when applied to regions with contrasting topography, vegetation density, or urban complexity. Future research should extend the assessment to East Malaysia (Sabah and Sarawak) and other parts of Southeast Asia to examine the consistency and transferability of DEM performance under differing environmental and geological conditions. To minimize elevation discrepancies between DEM pixels and point-based GNSS observations, the GNSS checkpoints were selected on flat, homogeneous, and obstacle-free terrain such as paved areas, cleared fields, and levelled ground—to ensure minimal pixel-level elevation variation. Sites with visible obstructions (trees, buildings, or elevated infrastructure) were excluded from the analysis. DEM elevation values at each GNSS location were extracted using bilinear interpolation, which smooths elevation transitions by considering the four nearest pixels. Although this method reduces abrupt elevation differences, it does not fully eliminate terrain variability within a pixel, particularly in rugged or high-relief areas.

A fundamental limitation in this comparison arises from the DSM–DTM discrepancy. Satellite-derived DEMs (e.g., TanDEM-x, SRTM, ASTER GDEM) capture the reflective surface of the Earth including vegetation canopies and rooftops whereas GNSS-derived orthometric heights correspond to the bare-earth terrain. This mismatch can introduce elevation differences within a 30 × 30 m pixel footprint and should be interpreted as a combination of model-specific surface bias and terrain heterogeneity rather than absolute elevation error. Future studies should consider the use of higher-resolution DTMs (e.g., LiDAR or photogrammetric datasets) or apply surface-object filtering and machine-learning-based correction techniques to better reconcile DSM–DTM elevation differences. Additionally, integrating multiple DEM sources and adopting updated reference datums such as EGM2020 could further improve the regional applicability and accuracy of DEM validation frameworks.

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