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ASSESSING THE VERTICAL ACCURACY OF FREE GLOBAL DIGITAL ELEVATION MODELS OVER EGYPTIAN TERRITORY

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ABSTRACT

The Advanced Land Observing Satellite (ALOS World-30m), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER-30 m), and Shuttle Radar Topography Mission (SRTM-30m) are freely available global digital elevation models (GDEMs) with a 30-meter horizontal resolution. These DEMs have applications in areas like topography, geomorphology, and hydrology. The study evaluated the vertical accuracy of these three DEM products over 4 selected regions in Egypt using ground control points (GCPs) from differential global positioning system (DGPS) as a reference. The results showed that the ALOS DEM had the lowest root mean square error (RMSE) compared to the SRTM-30m and ASTER GDEM2 products across the 4 study areas. Specifically, the ALOS DEM RMSE ranged from 0.95m to 2.59m, while the SRTM-30m RMSE was 2.21m to 4.47m, and the ASTER GDEM2 RMSE was 6.74m to 17.42m. The ALOS DEM tended to overestimate the true ground elevations, also its vertical accuracy was superior to the other two DEM products tested. Based on the results, ALOS can be used for producing 1:50,000 topographic maps, its elevation RMSE is less than half of the contour interval used in these maps. analysis concluded that the ALOS DEM is more accurate than SRTM-30m and ASTER GDEM2 for the regions studied and that users of these global DEM datasets in Egypt should be aware of their relative vertical accuracy when applying them to various applications.

KEYWORDS: DEMS, ASTER, SRTM, ALOS, Vertical Accuracy, Evaluation, GPS.

تقييم الدقة الرأسية لبعض من نماذج الارتفاعات الرقمية المجانية الحديثة فوق الأراضي المصرية

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الملخص

تعتبر نماذج الارتفاعات الرقمية DEMs مصدر هام من مصادر الحصول علي الارتفاعات المستخدمة في العديد من التطبيقات الهندسية ومن أهمها انتاج الخرائط الطبوغرافية. تتاح هذه النماذج لجميع المستخدمين مجانًا وتغطي معظم مساحة العالم بدقة أفقية تبلغ ٣٠ مترًا . في هذه الدراسة ، تم اختيار ثلاث من هذه النماذج وهي SRTMو ALOSو ASTER وتم تقييم الدقة الرأسية لها وذلك في ٤ مناطق دراسة مختارة في أماكن مختلفة من مصرلضمان التغطية الممكنة لمساحة القطر المصري. تم الاعتماد علي عدد كافي من نقاط تحكم أرضية مرصودة بتقنية الرصد الثابت باستخدام نظام التموضع العالمي التفاضلي DGPS داخل كل منطقة دراسة وذلك لتقييم الدقة الرأسية لهذه النماذج علي كل منطقة دراسة. أظهرت النتائج أن نموذج ALOS أفضل نموذج من حيث الدقة الرأسية حيث يمتلك اقل جزر تربيعي لمتوسط الاخطاء (RMSE) وذلك في مناطق الدراسة الأربع ويأتي في المرتبة الثانية نموذج SRTM-30 بينما نموذج ASTER كان في المرتبة الأخيرة من حيث الدقة الرأسية . أظهرت النتائج أيضا ان تفوق نموذج ALOS في الدقة كان متسقا مع جميع مناطق الدراسة وأنواع الأراضي المختارة (مسطحة أو شديدة الانحدار). استنادا إلى النتائج التي تم الحصول عليها تحتاج نماذج ASTER وSRTM إلى تحسين قيم الارتفاعات الخاصة بها على أساس نقاط تحكم أرضية كافية وذلك عند استخدامها في تطبيقات انتاج الخرائط الطبوغرافية. بينما نموذج ALOS من الممكن الاعتماد عليه في انتاج خرائط طبوغرافية بمقياس رسم ١:٥٠٠٠٠ باعتباران قيمة الجزر التربيعي لمتوسط الأخطاء

لهذا النموذج RMSE اقل من نصف الفترة الكنتورية المستخدمة في هذه الخرائط. ومن ناحية أخرى يجب أن لا يمهل مستخدم نماذج الارتفاع الرقمية في مصر عملية التحسين ويجب أخذها في الاعتبار عند اتخاذ القرارات المتعلقة بالتطبيقات المختلفة لمنتجات هذه النماذج كلا حسب الدقة المطلوبة.

الكلمات المفتاحية : نماذج الارتفاعات الرقمية، الدقة الرأسية ، نظام التموضع العالمي، نقاط التحكم الأرضية .

1. INTRODUCTION

Digital elevation models (DEMs) provide an important topographic dataset that is fundamental for many scientific and commercial applications [1]. However, traditional methods of acquiring information for DEM generation can be expensive and time-consuming due to the need for land surveying [2]. On the other hand, in the last decade, various DEM products from multiple sources have been made freely available to geospatial users, so it is important to investigate their potential applications by assessing their accuracy [3]. Sources of satellite-based DEM are increasing. So, there is a potent need for accurate precision estimation of these available DEMs to be used in the appropriate application. Since several satellite sensors utilize various wavelength zones and/or viewing geometries, results obtained via these sensors may give a little different, but complementary information [4].

ASTER Global DEM Version 2 (GDEM2), ALOS World 3D - 30m (AW3D30), and SRTM-30m are Digital Elevation Models (DEMs) that have the same resolution in their final form. These DEMs cover most of the globe and they are available to the public free of charge. Also, an essential advantage of these DEMs is the highest accuracy of their elevations which are 30 m. ALOS is the recent release of these DEMs. Assessing the accuracy of DEMs requires further attention, as there are still no standardized guidelines for this assessment process, despite technological advances in the creation and availability of these products [1]. Much research has been achieved to estimate the vertical accuracy of ASTER and SRTM DEMs over several regions in the world. Assessment of the DEM's quality and accuracy is a very important task to verify their suitability for a wide range of engineering and non-engineering applications such as geomorphology, hydrology, topography, archaeology, ecology, and many others. On the contrary, vertical accuracy assessment of the current DEMs in several different locations around the world is significant for enhancing the following generation of universal DEMs [5].

The accuracy of DEM products has been regularly investigated to evaluate their applicative potential, thus improving mapping methods [6]. Most of these experiments involve comparing the extracted data from DEMs to a set of reference data, such as control points, using statistical accuracy indicators like mean difference, standard deviation, or root mean square error [7]. other studies have assessed the vertical accuracy of global DEM datasets like the Shuttle Radar Topography Mission (SRTM) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM). For example, comparing SRTM and ASTER GDEM data to airborne laser scanning over the European Alps, found SRTM to be more accurate overall [8]. Similarly, the evaluation of SRTM and ASTER GDEM against LiDAR data in the Czech Republic, concluded that SRTM had lower elevation errors [9]. Regarding regional studies [10] assessed the vertical accuracy of SRTM, ASTER GDEM, and TanDEM-X DEMs over Turkey using ground control points, finding that TanDEM-X was the most accurate. Likewise, comparing SRTM, ASTER GDEM, and a national DEM in Hungary, determining the national DEM to be superior in quality [11]. For specific applications, an evaluation of the suitability of SRTM and ASTER GDEM data for hydrological modeling in Java, Indonesia, concluded that SRTM was more suitable [12].

Assessed the use of SRTM and national DEMs for flood modeling in the United States, finding that the national DEM data provided better results[13]. While many studies have focused on global and regional DEM products, there is also research on the accuracy of national or local DEM datasets. For example, Jacobsen and Csynthetic Aperture Radar (SAR) interferometry (InSAR) [14]. Some authors in Egypt have been carried out to evaluate the vertical accuracy of ASTER and SRTM DEMs products [15]. The quality and vertical accuracy of the DEMs utilized and their appropriateness for many applications was not adequately estimated over Egypt's territory. Most of the studies in Egypt involved ASTER and SRTM products for the evaluation process, but ALOS did not assess widely over Egypt territory until now. In this paper, the vertical accuracy of (ALOS) was checked against ASTER GDEM2 and SRTM-30m DEMs over different regions in Egypt.

2. Study Area and Tested Data

Four study areas were selected in different regions in Egypt: (A) New Malawi City, located in the El-Menia governorate in central Egypt. and (B) New Al-Obour City, located in the east Cairo governorate. (C) The New Administrative Capital is located southeast of the Cairo governorate. (D) New Sadat city is located northwest of Cairo governorate. All selected areas are considered as flat and sim-flat terrain in topography. Figure 1 shows the location of each study area, as well as the distribution of the tested ground control points (GCPs) across all study areas. Table 1 provides additional information about these study areas. The study utilized three globally available digital elevation model (DEM) datasets - SRTM, ASTER, and ALOS - as the primary sources of terrain elevation information. To assess the vertical accuracy of these DEM products, the researchers collected ground control point (GCP) elevation data using high-precision dual-frequency GPS surveying techniques. These GCP elevations, obtained through static GPS measurements, served as the reference vertical data against which the DEM elevations were evaluated. The GCP locations were distributed across the four defined study areas, as indicated by the red dots in Figure 1. The GPS-derived elevations were established based on a national control network maintained by the Egyptian surveying authority ESA. This provided a consistent vertical datum and reference frame for the GCP data collection.

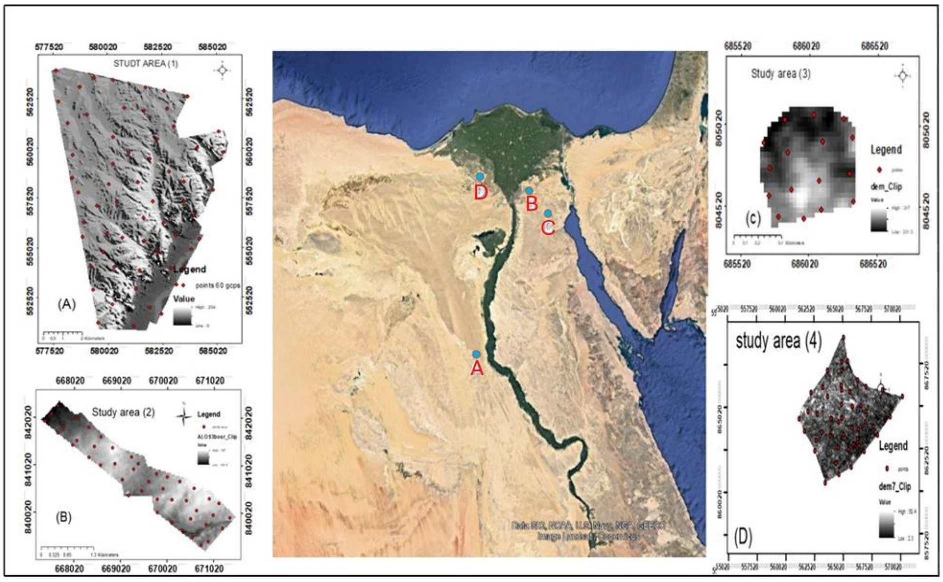


Fig.1. Four study areas' locations(A, B, C, and D), red dots represent the tested points (control points) over each region.

Table 1. Information about the selected study areas.

Study Area ID / location	**(A)**	**(B)**	**(C)**	**(D)**
	New Melawi city	New AL-Obour city	New administrative capital	New Sadat city
Area/ hectares	9,000	1,260	65	9,000
Elevation ranges - m above MSL	53 :156	152:182	334:342	28:37

No of tested points (GCPs)	57	44	16	33

It is important to note that the three DEM datasets differ in their production methodologies. The SRTM DEM was generated using radar interferometry technology, while the ASTER and ALOS DEMs were created through digital image correlation of stereo imagery. These varying approaches can lead to differences in the spatial resolution, coverage, and potential systematic biases inherent in each DEM product. To ensure the reliability of the GCP vertical data used for validation, various quality assurance and error mitigation strategies were employed. This could have included statistical analysis of the GCP elevation data, considerations of local geoid undulations, and sensitivity analyses to quantify the potential impact of GCP measurement uncertainties. Thoroughly addressing the quality and limitations of the reference data is crucial for accurately interpreting the comparative DEM accuracy assessments. The study's methodological details in this regard would provide important context for evaluating the reliability and implications of the reported findings.

1.1.SRTM-30

The Shuttle Radar Topographic Mission (SRTM) was a NASA project that collected topographic data covering most of the globe between 60°N and 56°S latitudes. The original SRTM data had a spatial resolution of approximately 90 meters. In September 2014, the higher-resolution SRTM-30m (1 arc-second) dataset was made publicly available for the entire coverage area. The availability of the SRTM-30m dataset has opened up new opportunities for scientific analysis and applications that require higher-resolution terrain information. Evaluating the quality and accuracy of the SRTM-30m DEM data is important, especially for regions outside the United States where it was originally measured at the 30-meter resolution. The vertical accuracy of the SRTM DEM dataset is reported to be approximately 16 meters, while the absolute horizontal accuracy is around 20 meters[16]. The improved spatial resolution and widespread availability of the SRTM-30m DEM make it an important global elevation dataset for a variety of geospatial applications. Understanding its inherent quality and limitations through rigorous accuracy assessments is crucial for ensuring the reliable use of this valuable terrain information. SRTM, ASTER and ALOS DEMs data are available in the Earth Explorer site through the link: https://earthexplorer.usgs.gov[16].

1.2. ASTER GDEM V2

The ASTER GDEM was the highest resolution free global DEM dataset when Version 2 was released in 2011. Compared to the initial Version 1 released in 2009, ASTER GDEM v2 included several enhancements: (1) Improved spatial coverage (2) Refined horizontal resolution (3) Increased horizontal and vertical accuracy (4) Water masking (5) Inclusion of additional ASTER stereo image results to fill voids and correct artifacts. However, the ASTER GDEM v2 dataset still exhibits some elevation errors in the form of outliers (humps/bumps) and pits, which can impact its use in certain applications. The ASTER GDEM is generated using optical stereo image matching techniques applied to images acquired by the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) sensor. The vertical accuracy of the original ASTER GDEM v1 (30-meter resolution) was reported to be 20 meters at the 95% confidence interval . With the release of ASTER GDEM v2, the vertical accuracy was improved to 8.86 meters[17]. The enhanced spatial resolution, coverage, and accuracy of the ASTER GDEM v2 dataset have made it a valuable global elevation dataset, although users should be aware of the remaining elevation errors that may need to be addressed for specific applications. Comparing the performance of ASTER GDEM against other global DEM products, such as SRTM, is an important aspect of evaluating the strengths and limitations of these freely available terrain datasets. ASTER DEM data are Available in Jet Propulsion Laboratory through the link https://asterweb.jpl.nasa.gov/gdem.asp [18].

1.3. ALOS – 30 M

AW3D30 is a global DEM dataset produced by the Japan Aerospace Exploration Agency (JAXA) using sensors onboard the Advanced Land Observing Satellite (ALOS). It has a horizontal resolution of approximately 30 meters (1 arc-second). AW3D30 is a resampled version of the higher-resolution 5-meter "World 3D Topographic Data" released by JAXA in 2015, which was considered the most precise global-scale elevation dataset at the time. The AW3D30 dataset is freely available for download from the JAXA website. The production technology for AW3D30 utilizes the traditional optical stereo matching technique applied to imagery acquired by the PRISM (Panchromatic Remote-sensing Instrument for Stereo Mapping) sensor on the ALOS satellite. The reported vertical accuracy of the AW3D30 DEM is 8 meters at the 90% confidence interval, with a planimetric accuracy of 15 meters at the 90% confidence interval [19]. Table 2 summarizes the key details of this and the two other open-source global DEM datasets, such as SRTM and ASTER GDEM, which is useful context. The availability of high-quality, high-resolution global DEM datasets like AW3D30 has greatly expanded the opportunities for terrain-based analysis and applications across various fields. Understanding the strengths, limitations, and accuracy of these freely available DEM products is crucial for ensuring reliable use of the data. SRTM, ASTER and ALOS DEMs data are available in the Earth Explorer site through the link: https://earthexplorer.usgs.gov//[16].

Table 2. Data descriptions of used world DEMs.

Product/ item	ALOS- 30 m	ASTER – 30 m	SRTM -30 m
Data capture	2015	1999-2009	2000
Technology	optical stereo images	optical stereo images	Sar interferometry
Resolution	30 m	30 m	30 m
Coverage	Global	83°N-83°S	60°N-56°S
Vertical datum	EGM 96	EGM96	EGM96
Horizontal Datum	WGS 1984	WGS 1984	WGS 1984

3. Methodology

The data sources mentioned - ALOS, SRTM, and ASTER - all provide elevation data that is collected in geographical coordinate formats based on the WGS1984 world horizontal datum. This is a common global reference system used for many geospatial datasets. In contrast, the GPS elevation points were collected using the local Egyptian datum (Egypt 1907) and the Egyptian Transverse Mercator (ETM) coordinate system, which is a metric-based coordinate system specific to Egypt. To unify the reference and DEM data formats, a crucial step was to transform the DEM data from the geographical WGS1984 coordinates to the local ETM coordinate system used for the GPS points. This involved applying specific parameter settings in the Global Mapper software, including:

- False easting of 615,000 m
- False northing of 810,000 m
- Central meridian of 31°E
- Scale factor of 1 at the central meridian
- 4° wide projection strips

Additionally, the default datum transformation parameters in Global Mapper were used to convert from the global WGS1984 datum to the local Egyptian datum. After this coordinate and datum transformation process, the vertical accuracy of each DEM dataset was evaluated over the four study areas. This involved comparing the DEM elevations to the elevations measured at 57, 44, 16, and 30 GPS reference points, respectively, for each study area. The elevation differences between the DEM pixels and the GPS points were calculated, and the root mean square error (RMSE) was used as the primary statistic to quantify the vertical accuracy of each DEM product. RMSE is a widely accepted metric for assessing the quality and reliability of elevation data [15]. This comprehensive process of unifying the data formats, coordinate systems, and datums, followed by a rigorous vertical accuracy assessment, helps ensure the DEMs can be properly integrated and used in further spatial analysis and modeling work within the Egyptian study areas.

RMSE can be given by,

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{k=1}^{n}(V_k)^2} \qquad (1)$$

$$V_k = H_k - H'_k \qquad (2)$$

Where,
n, is the number of checkpoints for each study area,
H_k is the known elevation of GPS points for each study area,
H'_k is interpolated elevation from the DEMs of point k in each study area.

Before assessment, the quality of the control points should be evaluated and filtered to eliminate the points with gross error. In that regard, all GPS points were subjected to a validation process that aimed to filter out any data element, which lacked a minimal level of reliability. So, the GPS points were used to determine the standard deviation value for the three DEMs in the selected study areas. Then, one rejects the control point if:

$$|\boldsymbol{V_k}| > 3.0\,\sigma \qquad (3)$$

Where (σ) is the standard deviation of the differences (residuals).

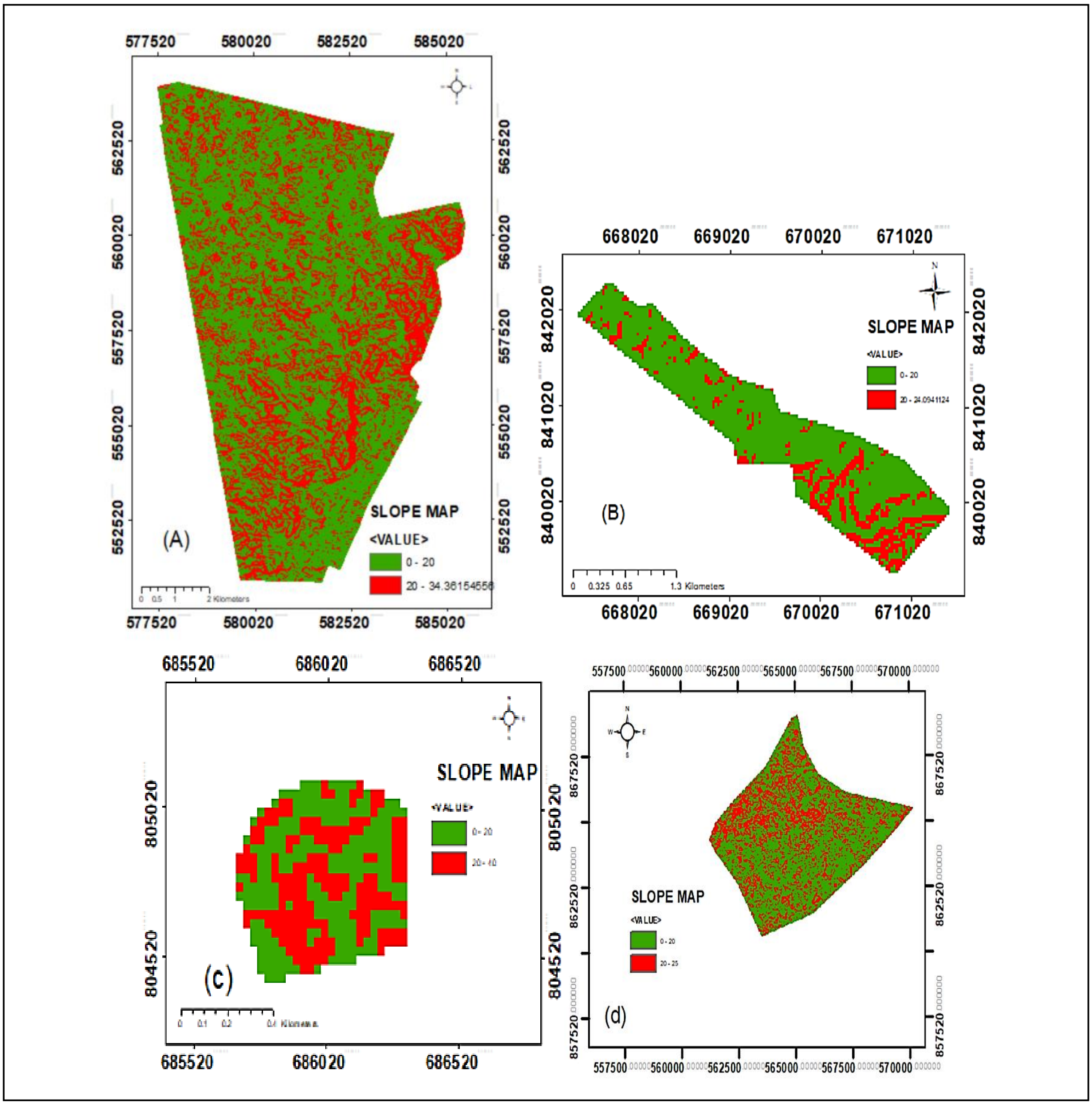
the researchers conducted a vertical accuracy assessment of the various DEM datasets across the four study areas. As part of this assessment, they compared the DEM elevations to GPS reference points collected in the field. For this validation, several GPS points were rejected from the test group - specifically, 4, 2, 2, and 1 points were removed from the 1st, 2nd, 3rd, and 4th study areas respectively. The remaining GPS points, 53, 42, 13, and 15 respectively, were then used to evaluate the vertical accuracy of the three DEM products (ALOS, SRTM, ASTER) over the four study regions. The rationale for rejecting these GPS points is due to they were identified as outliers or had quality issues that made them unsuitable for the validation assessment. Removing unreliable reference data is a common practice to ensure the accuracy evaluation is based on high-quality ground truth. TerrainAnalysis is conducted using the slope tool in ArcGIS. The slope is a fundamental terrain parameter that quantifies the steepness or gradient of the landscape. It is typically expressed either in degrees or as a percent rise. The percent rise metric can be more intuitively understood as the ratio of the rise over the run, multiplied by 100. When the slope angle is 45 degrees, the percent rise is 100%, as the rise and run are equal. As the slope approaches vertical (90 degrees), the percent rise tends towards infinity. Using the ArcGIS slope tool, slope maps for the ASTER DEM data across the four study.

areas were derived. These slope maps visually depict the terrain, with steeper slopes shown in shades of red. The text then classifies the terrain into two categories - flat/semi-flat (0-20% slope) and steep (>20% slope). This is a common way to characterize terrain for many applications, as it provides a simple but meaningful distinction between relatively level areas and more rugged, challenging terrain. Based on the derived slope maps, the maximum slope values were 34%, 24%, 40%, and 25% for the 1st, 2nd, 3rd, and 4th study areas, respectively. Since most of the GPS validation points were located in the flat/semi-flat terrain (0-20% slope), data indicates that all four study areas can be considered representative of the semi-flat terrain conditions. Overall, this combination of vertical accuracy assessment using GPS reference data and terrain characterization using slope analysis provides a comprehensive evaluation of the DEM dataset quality and suitability for the topography applications within the study regions. Slope maps derived by ARCGIS for ASTER DEMs over all study areas are illustrated in Figure (2).

Fig. 2. Slope maps derived from ASTER DEM for the four study areas.

4. Results and Discussions

A comparative analysis of three different digital elevation model (DEM) datasets - ASTER, SRTM, and ALOS - across several study areas was introduced. A combination of visual inspection, elevation profile analysis, and quantitative accuracy assessment to evaluate the performance of these DEM products. ArcGIS program is used to derive image maps, elevation maps, and slope maps from the three DEM datasets. Through a qualitative visual inspection of these maps, some observations were made, the ASTER DEM showed a poor representation of the topography and included many outliers in the topography data. The SRTM DEM provided a moderate representation of the topography. The ALOS DEM gave the best representation of the topography, with well-defined drainage networks, especially in the steeper terrain areas. The superior performance of the ALOS DEM was attributed to its higher native resolution of 5m x 5m, compared to the coarser resolutions of the other



DEMs. Figure 3 shows the derived image maps, elevation maps, and slope maps from the three DEM datasets over 1st study area. Regarding, DEMs elevation ranges, the elevation ranges for the three DEMs were: (1)SRTM: 47 - 140 m, (2) ASTER: 41 - 149 m, (3) ALOS: 52 - 140 m. The ASTER DEM showed a downward shift in both the minimum and maximum elevations compared to SRTM and ALOS, which had very similar elevation ranges. The downward values were 6 and 11m in minimum elevations and 9m in maximum for both ALOS and SRTM compared with SRTM and ALOS DEMs, respectively. A Profile of ASTER, SRTM, and ALOS over selected study areas for nearly 970 pixels was shown in Figure 4 left side. From this figure, one can note that SRTM and ALOS profiles are similar in elevation behavior over the selected profile area. elevation profiles across the study areas were Plotted, from these profiles it was observed that the SRTM and ALOS DEMs had very similar elevation behaviors, with their profiles being adjacent and nearly identical in most areas. In contrast, the ASTER DEM elevations showed a consistent downward shift compared to the other two DEMs, especially in areas of higher elevation. This analysis suggests that the ASTER DEM may require co-registration or other corrections to better align its elevations with the SRTM and ALOS products, figure 4 right side. Using the available GPS reference points, a rigorous statistical analysis to assess the vertical accuracy of the three DEMs was conducted. Four metrics evaluated statistics were included;(1)Root Mean Square Error (RMSE) (2) Minimum and maximum elevation differences (3) Mean elevation difference (4) Correlation coefficients between GPS and DEM elevations. The results of the statistical analysis for all study areas are presented in Tables 3 to 6.

For study area 1, the number of checkpoints (GPS elevation points) was 57. The maximum, minimum, and mean elevation differences between the GPS elevations and the corresponding elevations from the ASTER, SRTM, and ALOS digital elevation models (DEMs) were 6.12 m, 1.02 m, and -0.03 m, respectively. The calculated root-mean-square error (RMSE) values were 6.74 m for ASTER, 2.23 m for SRTM, and 0.95 m for ALOS. The correlation coefficients between the GPS points and the corresponding DEM elevations were 0.990 for ASTER, 0.995 for SRTM, and 0.999 for ALOS. These results indicate that the ALOS DEM had the lowest RMSE and the highest correlation coefficient in this study area, while SRTM performed slightly better than ALOS and ASTER performed the worst.

For study area 2, the number of checkpoints was 44. The maximum, minimum, and mean elevation differences were 12.39 m, -0.59 m, and 0.28 m, respectively, for ASTER, SRTM, and ALOS. The RMSE values were 13.50 m for ASTER, 2.21 m for SRTM, and 1.26 m for ALOS. The correlation coefficients were 0.57 for ASTER, 0.90 for SRTM, and 0.96 for ALOS. Similar to study area 1, the ALOS DEM had the lowest RMSE and the highest correlation coefficient, while SRTM performed slightly better than ALOS and ASTER performed the worst. The results for study areas 3 and 4, with 16 and 30 checkpoints, respectively, were similar to those of study areas 1 and 2. A slightly higher error was observed in the areas with higher elevations for the ASTER DEM, likely due to poor stereo-matching caused by partial cloud cover. Across the four study areas, the results consistently showed that the ALOS DEM had the lowest RMSE and the highest correlation coefficients, indicating the best vertical accuracy. The SRTM DEM also performed well, with only minor differences compared to ALOS. However, the ASTER DEM exhibited the highest RMSE and lowest correlation, suggesting it had the poorest vertical accuracy, especially in areas of higher elevation. The reason for the lower accuracy of the ASTER DEM in high-elevation areas to potential issues with the stereo-matching algorithms used to derive the elevations, likely due to partial cloud cover in those regions. Overall, this comprehensive analysis provides valuable insights into the relative strengths and limitations of the three DEM datasets, which can inform appropriate usage and applications depending on the specific requirements of the end-users.

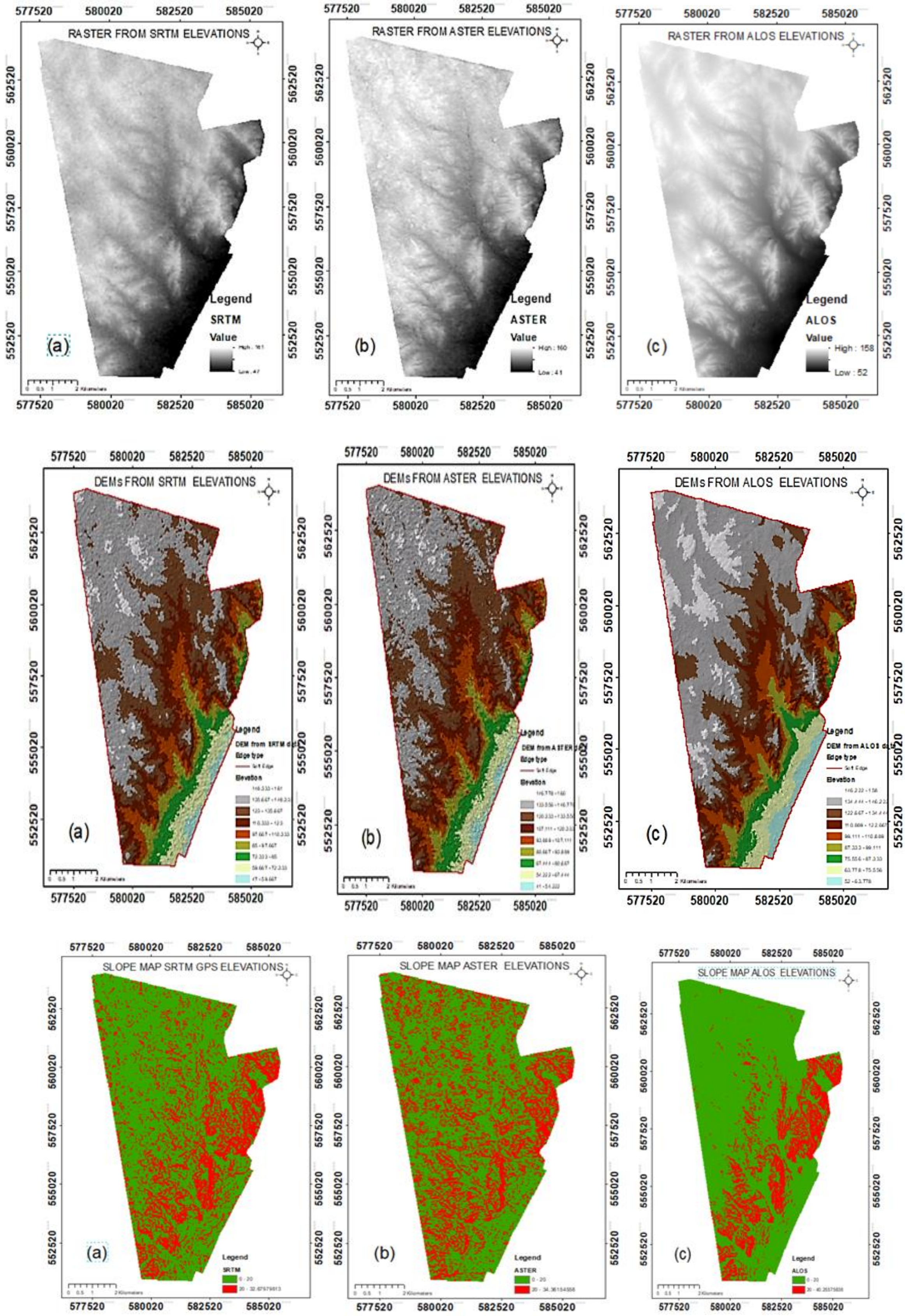


Fig. 3. Raster images, Digital elevation models and slope maps produced from a-ASTER, b-SRTM, c-ALOS for the 1st study area (Malawi city).

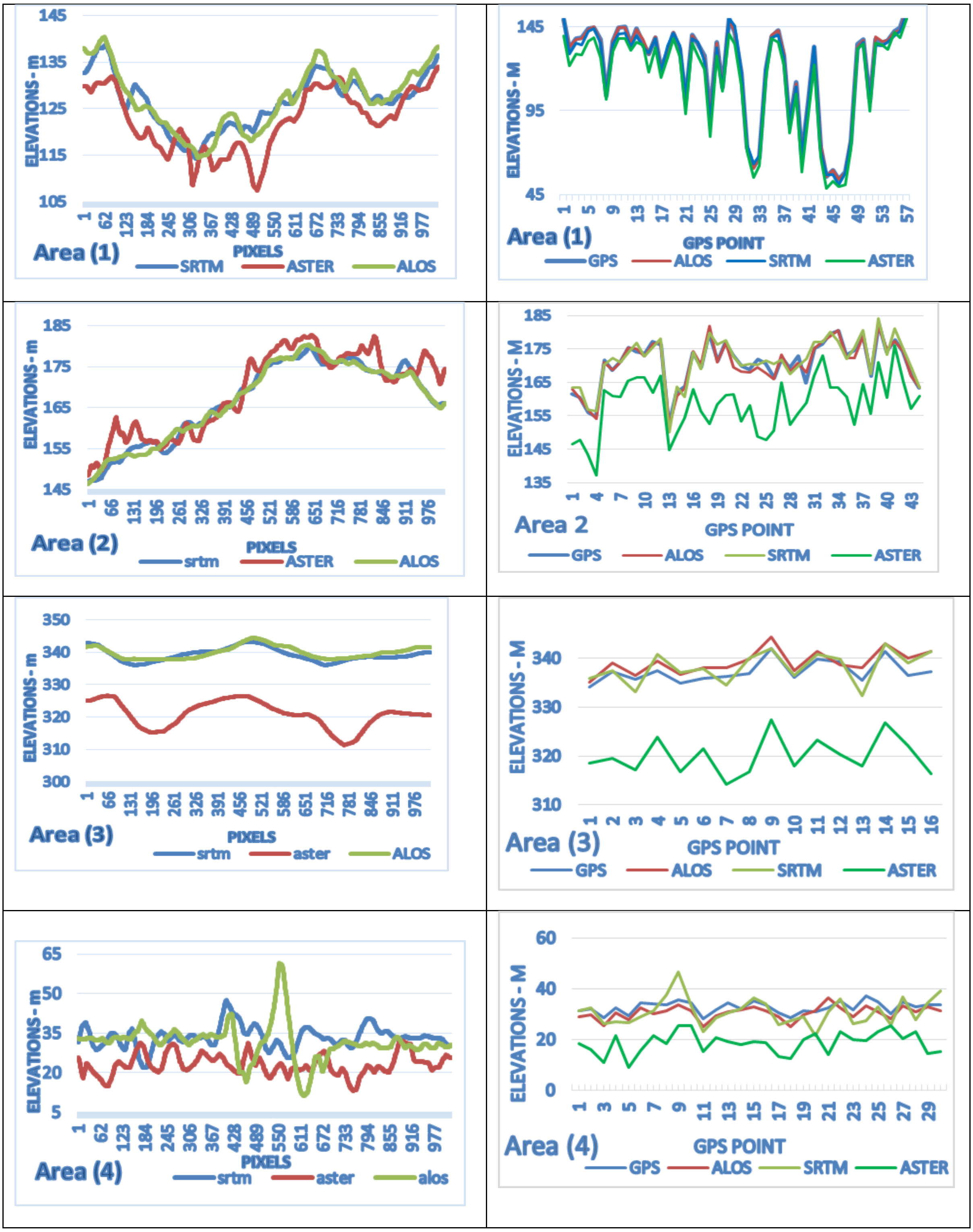


Fig. 4. A profile for SRTM, ASTER, and ALOS DEMs over the 4 study areas in the form of DEM pixels at left side and the A relation between GPS elevations and corresponding DEMs elevations over the 4 study areas at right side

Similarly, a higher magnitude of RMSE was observed for the SRTM in areas with higher slopes. This effect was likely due to the lower accuracy of the SRTM data in regions with steeper terrain. In contrast, the ALOS

DEM showed a low magnitude of RMSE across all areas, both higher and lower elevation regions. This is likely due to the high-quality stereo-matching in the ALOS raw data, which has a native resolution of 5 m by 5 m. Figures 5 and 6 illustrate the relationship between the estimated elevations from the DEMs and the actual GPS elevations for the 4 study areas. In Figure 5, the correlation between the GPS elevations and the ASTER DEM elevations is low for the first and second study areas. However, the correlation is good for the SRTM and ALOS DEMs in these same two study areas. Similarly, in Figure 6, the correlation between the GPS elevations and the ASTER elevations is very low for the third and fourth study areas. The correlation is moderate for the SRTM DEM and good for the ALOS in these two study areas. The good correlation between the GPS elevations and the ALOS DEM elevations across all study areas demonstrates the high accuracy of the ALOS elevation data.

Table 3. Vertical accuracy assessment of the World DEMs for 1st study area (MALAWI).

DATA SOURCE	H- DIFFERENCE, M			NO. OF CHECKPOINTS	RMSE (M)	CORRELATION V'S GCPS
	Min	Max	Mean			
ASTER-30m	0.36	13.6	6.12	57	6.74	0.990
SRTM -30m	-3.9	4.65	1.02		2.23	0.995
ALOS -30m	-2.26	2.22	-0.03		0.95	0.999

Table 4. Vertical accuracy assessment of the World DEMs for 2nd study area (ABOUR).

DATA SOURCE	H- DIFFERENCE, M			NO. OF CHECKPOINTS	RMSE (M)	CORRELATION V'S GCPS
	Min	Max	Mean			
ASTER-30m	1.56	12.17	12.39	44	13.5	0.57
SRTM -30m	-7.17	27.14	-0.59		2.21	0.90
ALOS -30m	-3.14	3.31	0.28		1.26	0.96

Table 5. Vertical accuracy assessment of the World DEMs for 3rd study area (ASEMA).

DATA SOURCE	H- DIFFERENCE, M			NO. OF CHECKPOINTS	RMSE (M)	CORRELATION V'S GCPS
	Min	Max	Mean			
ASTER-30m	13.55	22.16	17.25	16	17.42	0.58
SRTM -30m	-4.22	3.32	-0.96		2.25	0.56
ALOS -30m	-4.21	0.53	-1.91		2.19	0.79

Table 6. Vertical accuracy assessment of the World DEMs for 4th study area (SADAT).

DATA SOURCE	H- DIFFERENCE, M			NO. OF CHECK POINTS	RMSE (M)	CORRELATION V'S GCPS
	Min	Max	Mean			
ASTER-30m	4.87	20.62	13.96	30	14.43	0.25
SRTM -30m	-11.07	9.51	1.75		4.47	0.42
ALOS -30m	-3.78	3.97	2.14		2.59	0.66

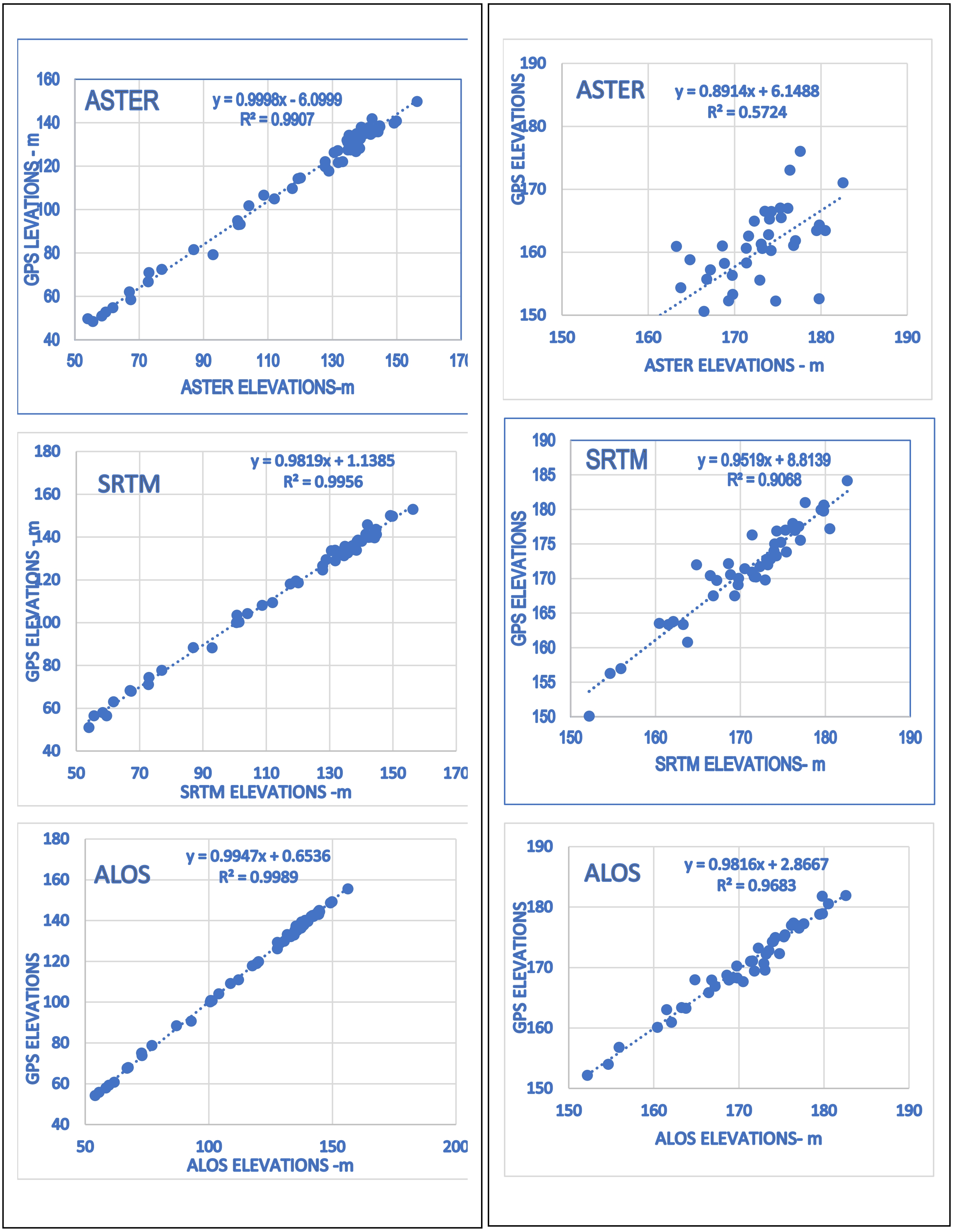


Fig. 5. Relationship between estimated elevation and actual elevation. In the left is the ASTER, SRTM, and ALOS DEM for the 1st study area (MALAWI), in the right is the ASTER, SRTM, and ALOS DEM for the 2nd study area (ABOUR). The dotted line in each case represents 1:1 prediction line.

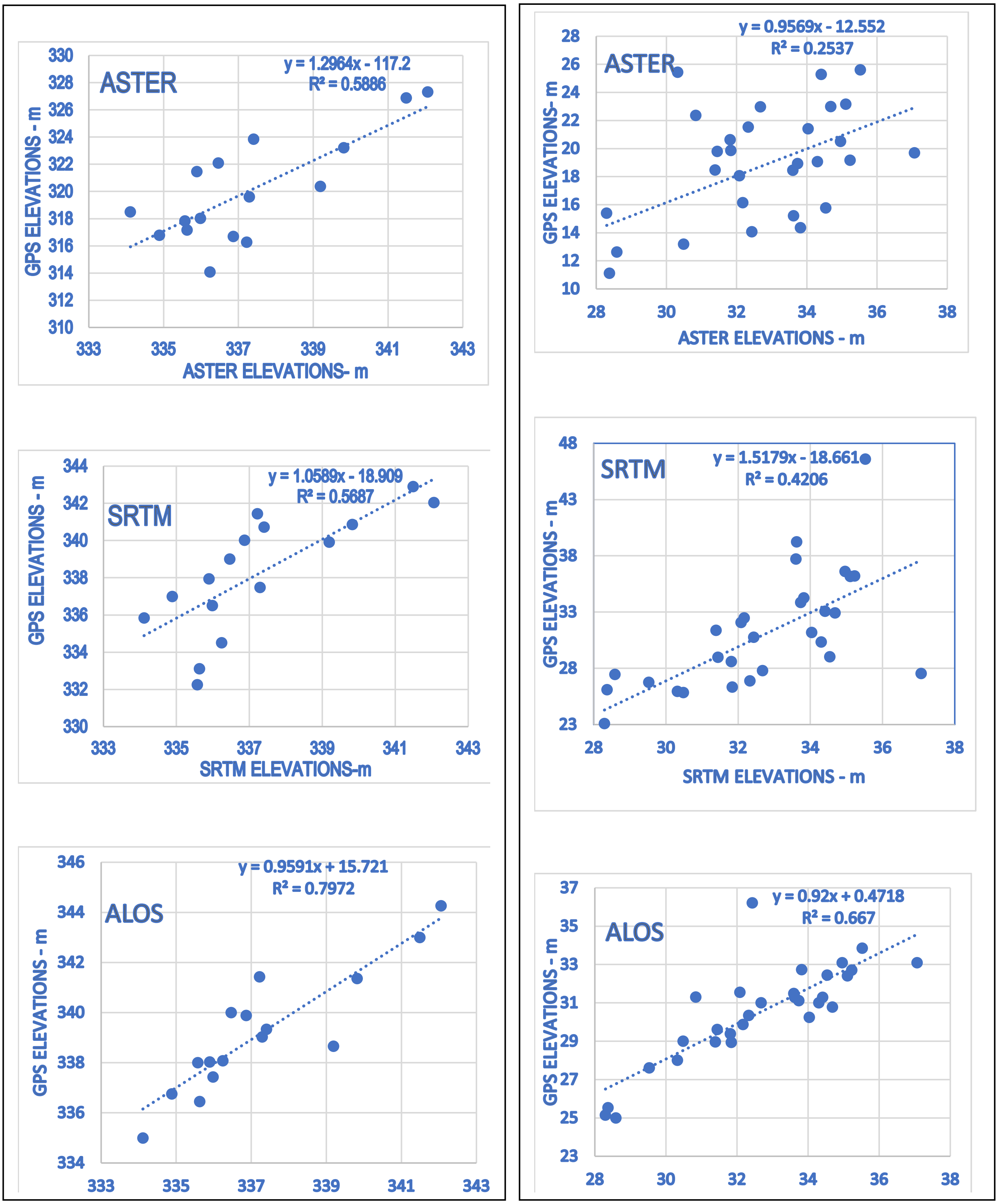


Fig. 6. Relationship between estimated elevations and GPS elevations. In the left is the ASTER, SRTM, and ALOS DEM for the 3rd study area (ASEMA), in the right is the ASTER, SRTM, and ALOS DEM for the 4th study area (SADAT). The dotted line in each case represents 1:1 prediction line.

Conclusion

The RMSE of the ALOS DEM was significantly lower compared to the ASTER and SRTM DEMs across the study areas. Specifically, the RMSE of ALOS decreased by 85% and 67% compared to ASTER and SRTM respectively in the 1st study area. Similarly, the RMSE decreases were 80% and 83%, 87% and 88%, and 82% and 69% for the 2nd, 3rd, and 4th study areas respectively. The mean elevation differences between the actual GPS measurements and the estimated elevations from the ALOS and SRTM DEMs were close to 1 m. In contrast, the ASTER DEM exhibited much larger mean elevation differences. The large negative mean elevation differences for the ASTER DEM, reaching up to 6 m, 12 m, 17 m, and 14 m in the 1st, 2nd, 3rd, and 4th study areas respectively, indicate a clear downward bias in the ASTER elevation data compared to the GPS measurements. This downward bias is further corroborated by the terrain profile analysis and low correlation coefficients between the GPS and ASTER DEM elevations. The ASTER DEM appears to require co-registration to correct the pseudo heights included in the elevation data. Conversely, the ALOS DEM demonstrated excellent vertical accuracy across all study areas, with mean elevation differences of 0.95 m, 1.26 m, 2.19 m, and 2.59 m for the 4 study areas located in different parts of Egypt. This high level of vertical accuracy and completeness makes the ALOS DEM a reliable and trusted source for many applications like map production. ALOS DEM can be used to produce 1:50,000 topographic maps based on the checked accuracy as the RMSE is less than half of the contour interval used in such maps.

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