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PERFORMANCE EVALUATION OF FOUR OPEN SOURCE DIGITAL ELEVATION MODELS OVER NIGERIA

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ABSTRACT

In earth sciences such as terrain analyses in geomorphology and physical geography, hydrology, terrain correction of gravity measurements in gravimetry and physical geodesy (high precision geoid modelling) and flood modelling to mention but a few, Digital Elevation Models (DEMs) is a very important geospatial data. They are unavoidably free from errors, presumably because of the technique used for generation or the different post-handling steps the models need to experience. It is, in this manner, that basic errors are measured in order to provide users with direct data on the exactness of the DEMs. Therefore, been that the only information regarding any global DEM is the global estimate of Root Mean Square Error (RMSE), it is difficult to ascertain which global DEM best suits an area. Shuttle Radar Topography Mapping Mission (SRTM), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Global Multi-resolution Terrain Elevation Data 2010 (GMTED) and Global 30 Arc-Second Elevation (GTOPO) in validation with Ground Control Points (GCP) data were considered. UNAVCO EGM96 geoids online calculator was used to compute the geoidal height information. The Model validation error matrix such as the Root Mean Square Error (RMSE), Relative Index (RI) and the Normalized Mean Absolute Error (NMAE) are used to assess the performance of the DEMs. From the correlation test result, among the four elevation data sets and the 52 GCPs, the SRTM had a stronger correlation with the GCPs. Several topographic attributes, such as elevation, slope and aspect are also analyzed. The study area is found to have the same slope and aspect values in degree for the four DEMs, and a flat of -1 in just two areas. In terms of the vertical accuracy, the SRTM shows relatively higher vertical accuracy (RMSE 5.413m) compared to ASTER (RMSE 8.413), GMTED (RMSE 13.963) and GTOPO (RMSE 56.853).

Keywords: ASTER**,** DEMs, GMTED**,** GTOPO**,** Nigeria**,** SRTM.

1.0 INTRODUCTION

In representation of topography, terrain analyses in geomorphology and physical geography, line-of-sight analysis, flight simulation, hydrology, terrain correction of gravity measurements in gravimetry and physical geodesy (high precision geoid modelling), flood modelling and assimilation, amongst others, Digital Elevation Models (DEMs) have gained significant popularity (Forkuor and Maathuis, 2012; Gorokhovich and Voustianiouk, 2006; Isioye and Obarafo, 2010; Mason et al. 2016; Patel, et al. 2016; Wiki.GIS, 2018). DEMs are arrays of pixel in grid (usually regular squares) formats in which each pixel have a particular value specific to it (Fisher and Tate, 2006). Methods from which DEMs are generated include topographic maps, conventional field surveys (e.g. Global Navigation Satellite System (GNSS) and total stations), photogrammetry techniques, Light Detection and Ranging (LIDAR), and laser altimetry, amongst others. These are with varying degrees of accuracy, pre-processing requirements, sampling density, and cost (Florinsky, 1998; Manuel, 2004; Amans, et al. 2013; Arun, 2013; Fernandez, et al. 2016). An assortment of DEMs including Shuttle Radar Topography Mission SRTM), Advanced Spaceborne Thermal Emission and Reflection Radiometer-Global Digital Elevation Model (ASTER GDEM), Global Topographic 30 seconds resolution (GTOPO30) and Global Multi-goals Terrain Elevation Data 2010 (GMTED2010) are uninhibitedly accessible for established researchers around the world. Additional details about these DEMs can be found in (Athmania and Achour, 2014; Thomas, et al. 2014; Pakoksung and Takagi, 2015; Elkhrachy, 2018) amongst others.

For the most part, DEMs are unavoidably free from errors, presumably because of the system pursued or the different post-handling steps the models need to experience. It is, in this manner, that basic errors are measured in order to furnish user with direct data on the exactness of the DEMs (Forkuor and Maathuis, 2012). As in many disciplines such as Geomatics, gross error sometimes called blunders (which occur through carelessness resulting from machinery, weather conditions, amongst others), random errors (mostly resulting from statistical behaviour and therefore can be dealt with by statistical methods) and systematic errors (caused by mathematical models adopted e.g. models used for interpolation) are the three classes of errors identifiable in DEMs (GS/CE400, 2001; Fisher and Tate, 2006). The quality of DEMs is dependent on the class of error found in it. Therefore, acquisition system, methodology and algorithms, complexity of the terrain grid spacing and data characteristics all fall within these classes of errors (Athmania and Achour, 2014). Be that as it may, in as much as DEMs harbour these errors, it is prudent to approve their exactnesses and sensibility and to comprehend the potential and confinements of utilizing these datasets for an explicit territory before utilizing them for any reason (Athmania and Achour, 2014; Pakoksung and Takagi, 2015).

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A variety of approaches exist for DEMs validation, among which can be found in the study of (Gonga-Saholiariliva, et al. 2011). In many regions of the world, numerous studies have been carried out to assess the accuracy of DEMS e.g. (Gorokhovich and Voustianiouk, 2006; Forkuor and Maathuis, 2012; Li et al. 2012; Kolecka and Kozak, 2013; Thomas *et al.* 2014; Pakoksung and Takagi, 2015; Krishnan, Sajikumar, and Sumam, 2016; Patel et al. 2016; Elkhrachy, 2018). However, in Nigeria, studies of (Isioye and Obarafo, 2010; Amans et al. 2013; Isioye and Yang, 2013; Ejikeme, et al. 2017) are among the few available on DEMs validation or accuracy assessment. These studies are regional in nature and not at national scale. Therefore, been that the only information regarding any global DEM is the global estimate of root mean square error (RMSE) (Thomas et al. 2014), it will be very difficult to ascertain which global DEM best suits Nigeria for various applications as earlier highlighted.

Therefore, this study evaluates the performances of space borne digital elevation models (DEMs), for terrain representation. Shuttle Radar Topography Mapping Mission (SRTM), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) and Global 30 Arc-Second Elevation (GTOPO) in comparison with GNSS data are considered.

2.0 TEST AREA AND DATASETS

2.1 TEST AREA

The scope of this study covers the entire Nigeria (Figure 1) located on the Western part of Africa, between latitudes 4° and 14° North of the Equator and longitude 3° and 15° East of the Greenwich Meridian. It shares boundaries with The Republics of Benin and Niger in the west, Cameroon in the East, Niger and Chad in the north and the Gulf of Guinea in the South. The terrain of Nigeria is mostly dominated by plains in the northern and southern regions while the remaining centre of the country by plateaus and hills.

2.1.1 DATASETS

For the purpose of this study, four open source DEMs (Table 2) comprising of Shuttle Radar Topography Mapping Mission (SRTM), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Global Multi-resolution Terrain Elevation Data 2010 (GMTED) and Global 30 Arc-Second Elevation (GTOPO) are considered. The accuracy assessment of the DEMs requires an external source of high accuracy to obtain reliable measures (Isioye and Obarafo, 2010; Athmania and Achour, 2014; Pakoksung and Takagi, 2015; Elkhrachy, 2018). Therefore, the study utilizes the Nigerian first order control stations (see Figure 2 and Table 1) obtained from the Office of the Surveyor General of the Federation (OSGoF).

Figure 1. Map of the test area (source: DMAPS, 2019)

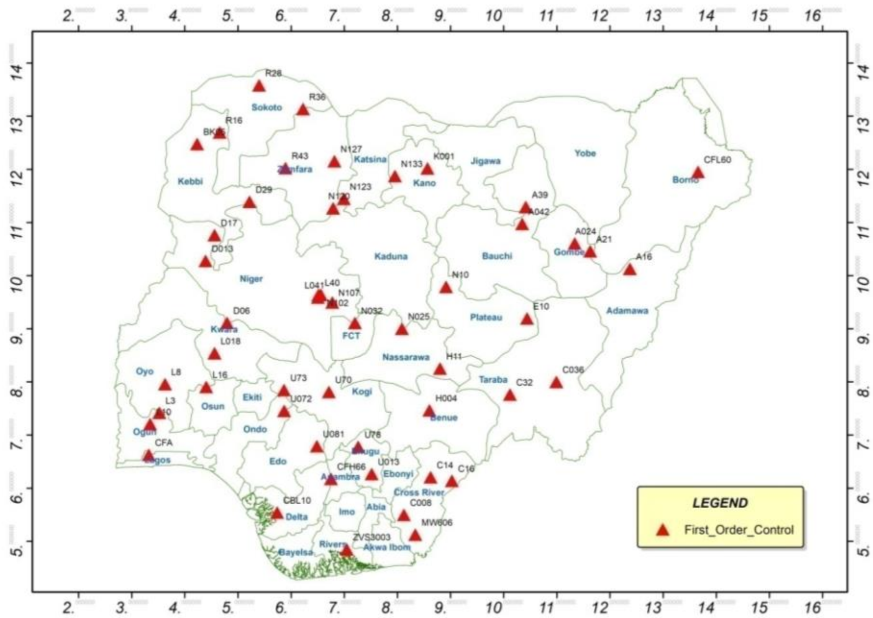

Figure 2. Spatial location of the GNSS stations used for validation

Table 1. First order Controls of Nigeria Serving as Ground Control Points (GCPs)

Station	lat(°)	lon(°)	EGM96(m)	Station	lat(°)	lon(°)	EGM96(m)	Station	lat(°)	lon(°)	EGM96(m)
R43	12.021	5.895	456.529	N123	11.442	6.992	748.141	CBL10	5.539	5.738	7.404
R16	12.693	4.656	335.212	BK05	12.475	4.232	221.239	U081	6.787	6.486	194.817
R28	13.579	5.396	350.331	D29	11.388	5.217	505.926	U78	6.776	7.263	402.515
R36	13.134	6.225	411.697	D17	10.761	4.560	328.344	U70	7.808	6.713	414.158
N127	12.149	6.816	755.286	D013	10.276	4.391	267.888	U73	7.844	5.868	651.949
K001	12.014	8.566	482.553	N102	9.639	6.559	443.787	N107	9.493	6.775	537.486
A042	10.970	10.350	524.700	L40	9.636	6.516	273.641	L041	9.586	6.506	228.273
A39	11.289	10.417	475.249	N032	9.106	7.202	683.946	U072	7.454	5.871	634.755
CFL60	11.952	13.658	298.602	N025	8.999	8.087	569.065	L16	7.904	4.404	498.528
A024	10.604	11.340	605.835	N10	9.785	8.916	1371.689	CFA	6.627	3.323	46.606
A21	10.455	11.628	740.266	C16	6.137	9.027	606.764	L3	7.417	3.521	264.922
A16	10.125	12.376	768.527	H004	7.463	8.603	341.46	L10	7.204	3.345	172.985
E10	9.191	10.440	312.793	C14	6.203	8.624	126.898	L8	7.956	3.627	439.417
C036	7.999	10.993	524.234	C008	5.496	8.123	257.956	L018	8.537	4.558	405.378
C32	7.758	10.121	371.912	MW606	5.122	8.339	81.020	D06	9.109	4.796	294.959
N120	11.265	6.791	572.618	U013	6.264	7.518	299.561				

N133	11.872	7.955	617.650	ZVS3003	4.848	7.048	16.444
H11	8.247	8.804	218.685	CFH66	6.173	6.750	37.306

Table 2. Summary of the Datasets Adopted for the Study

Data	**ASTER**	**SRTM**	**GTOPO30**	**GMTED2010**
Acquisition technique	Satellite stereo image	Shuttle radar	Fusion of multisource	Fusion of Multisource
Format	Geotiff	Geotiff	Geotiff	Geotiff
Vertical datum	EGM96	EGM96	EGM96	EGM96
Horizontal datum	WGS84	WGS84	WGS84	WGS84
Spatial resolution	90 m	1 arc-second	30 arc-second	30 arc-second
Projection system	Geographic	Geographic	Geographic	Geographic
Source	http://earthexplorer.usgs.gov/	http://srtm.csi.cgiar.org/	https://earthexplorer.usgs.gov/	https://earthexplorer.usgs.gov/

3.0 METHODOLOGY

3.1 DATA PREPARATION AND PROCESSING

After download, the four DEMs adopted for the study were clipped to the extent of the study area, there by forming a raster data set. The raster datasets are compared by rescaling the DEMs whereby the DEMs are resample to a common spatial resolution. This was achieved by using bilinear interpolation technique. It is a technique for calculating values of a grid location based on four nearby grid cells. It assigns the output cell values by taking the weight average of the four neighbouring cells in an image to generate new values. Co-registration of the DEMs was performed to remove the potential horizontal and vertical shifts between input DEMs before analysis. A low pass filter with 3 x 3 kernel neighbourhood is applied to all the resample DEMs to improve the quality by removing spurious data/outliers in the data. The kernel neighbourhood multiplies each value in the neighbourhood by a specific weight. GNSS heights are with respect to the ellipsoid (Figure 3). Therefore, to make the height compatible with the DEMs, UNAVCO EGM96 calculator is used, accessible via the link:

https://www.unavco.org/software/geodetic-utilities/geoid-height-calculator/geoid-height-calculator.html.

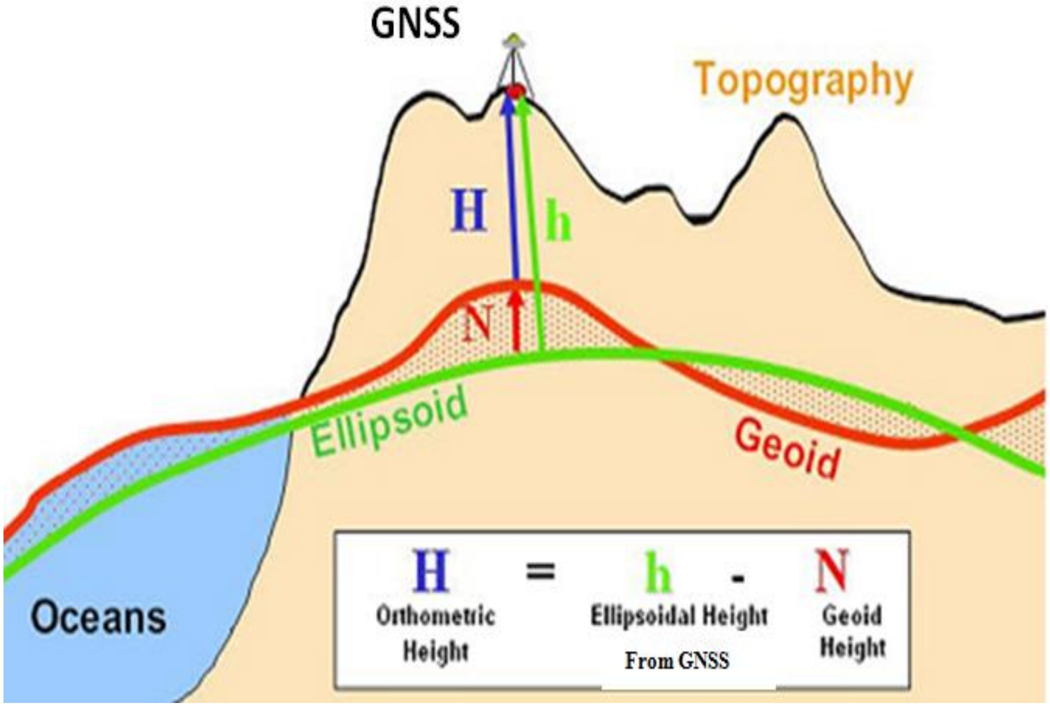

Figure 3. Relationship between Orthometric, GNSS ellipsoidal and geoid height (Elkhrachy, 2018)

3.2 VALIDATION METHOD

Quantitative method based on statistics (performance indicators) and qualitative based on visual analysis were used for accuracy measures. For the quantitative measure, the slope map, aspect map and Triangulated Irregular Network (TIN) were adopted.

The Normalized Mean Absolute Error (NMEA) (Shcherbakov et al. 2013), Root Mean Square Error (RMSE), Reliability Index (RI) (Leggett and Williams, 1981) and Correlation coefficient (r), performance indicators were adopted for the statistical evaluation.

$$NMAE = \frac{\sum_{i=1}^{n}\left(|residuals_i|\right)}{n\bar{o}} \qquad (1)$$

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$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(residuals_i)^2}{n}} \quad (2)$$

$$RI = \sqrt[\exp]{\frac{\sum_{i=n}^{n}\left(\log\frac{o_i}{p_i}\right)^2}{n}} \quad (3)$$

$$r = \frac{\sum_{i=1}^{n}(p_i - \bar{p})(o_i - \bar{o})}{\left[\sum_{i=n}^{n}(p_i - \bar{p})^2 \sum_{i=1}^{n}(o_i - \bar{o})^2\right]^{1/2}} \quad (4)$$

Where n is the number of sample points, $residuals = p_i - o_i, o_i$ and p_i are the ith computed and model estimated. Similarly, $\bar{o}$ and $\bar{p}$ are the mean computed and model estimates.

The NMAE measures the absolute deviation of the simulated values. A value of zero indicates perfect agreement and greater than zero an average fraction of the discrepancy normalised to the mean (Isioye et al. 2015). RMSE measures the average square error with values near zero indicating a close match. RI quantifies the average factor by which a DEM differ from the GNSS value.

4.0 RESULTS AND DISCUSSION

4.1 QUANTITATIVE METHOD

4.1.1 SPATIAL VARIATION OF SLOPE MAP

Slope maps generally depict the rate of change of elevation in the direction of steepest descent. Relatively, it has influence on erosion potential, velocity of surface and subsurface flow, soil formation soil water content and several other earth surface processes (Thomas *et al.* 2014). Figure 4 depicts the slope (in degree) over Nigeria derived from (a) SRTM (0.00-89.99884033); (b) ASTER (0.00-89.99887085); (c) GMTED (0.00-89.99887848) and (d) GTOPO (0.00–89.99872589). The steepest slope map generated from all the DEMs sources

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is from GTOPO. This is likely due to its low spatial resolution. The spatial coverage of slope classes as depicted in Figure 5 (cumulative frequency curve) is more or less uniform for the ASTER, GMTED and SRTM.

4.1.2 SPATIAL VARIATION OF ASPECT MAP

The compass direction a slope faces can be referred to aspect (Aspect Maps, 2016). It can identify the down slope direction of the maximum rate of change in values and it is measured clockwise in degree from 0^o (due north) to 360^o (again due north). Flat areas having no direction and so, are given a values of -1. This is represented by gray cells. Figure 6 shows the aspect of the four digital elevation model used for the study. Base on the cumulative frequency curve of Figure 7, the aspect maps are more or less uniform for the entire DEMs sources. However, the aspect map of GTOPO looks different from the others in terms of smoothness.

4.1.3 SPATIAL VARIATION OF TIN MAP

A triangulated irregular network (TIN) represent continuous surface consisting entirely of triangular facet. It consists of information such as the slope and aspect of each node. Figure 8 shows that all the DEM have the highest point at the central and northeast part of the country. From the Figure 8, SRTM had an elevation value (in meters (m)) of (-8 to 1585.33), ASTER (-116 to 1542), GMTED (-3 to 1568.333) and GTOPO (1 to 1423). This difference can be clearly observed in Figure 9.

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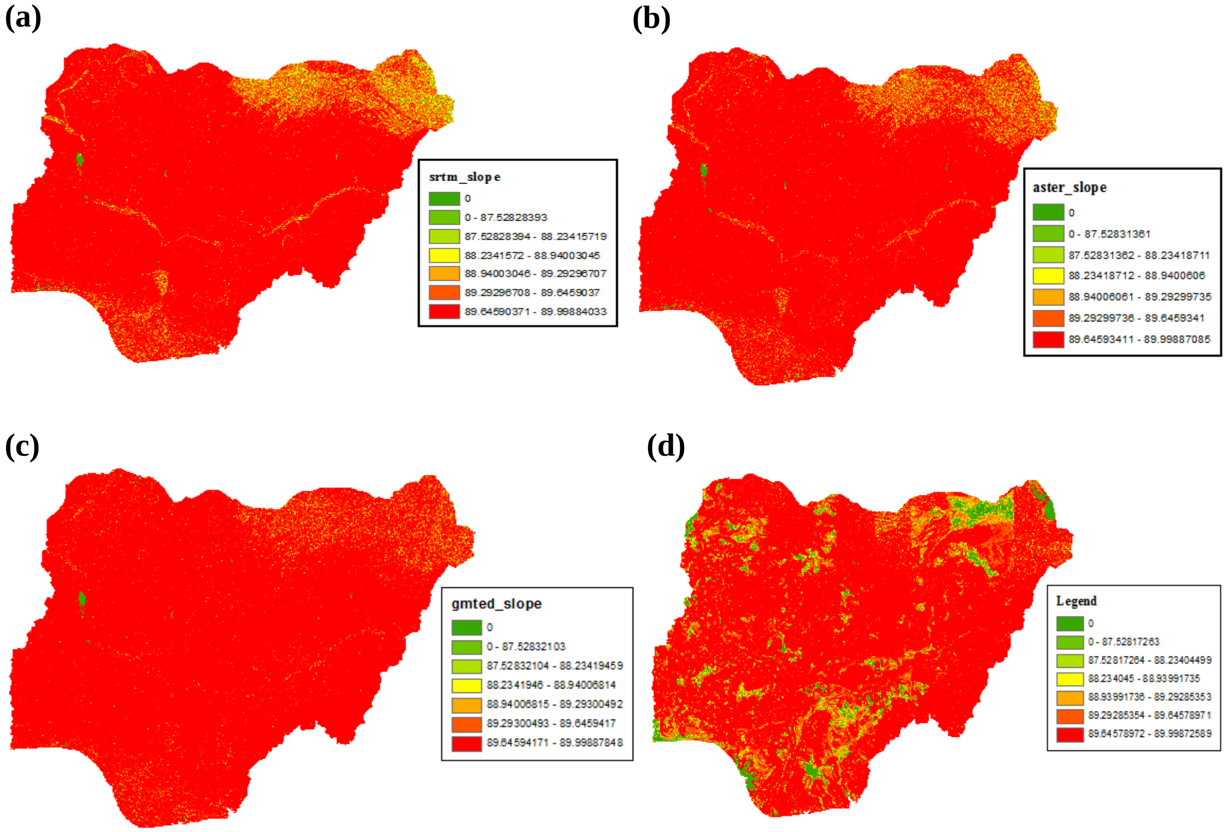

Figure 4. Slope map of Nigeria from (a) SRTM, (b) ASTER, (c) GMTED and (c) GTOPO

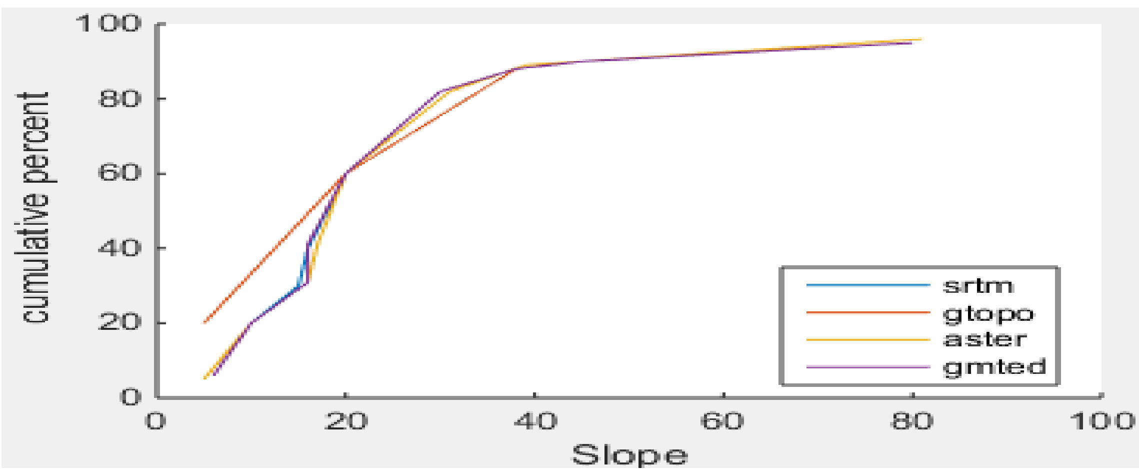

Figure 5. Cumulative frequency distribution of the various classes of slope map

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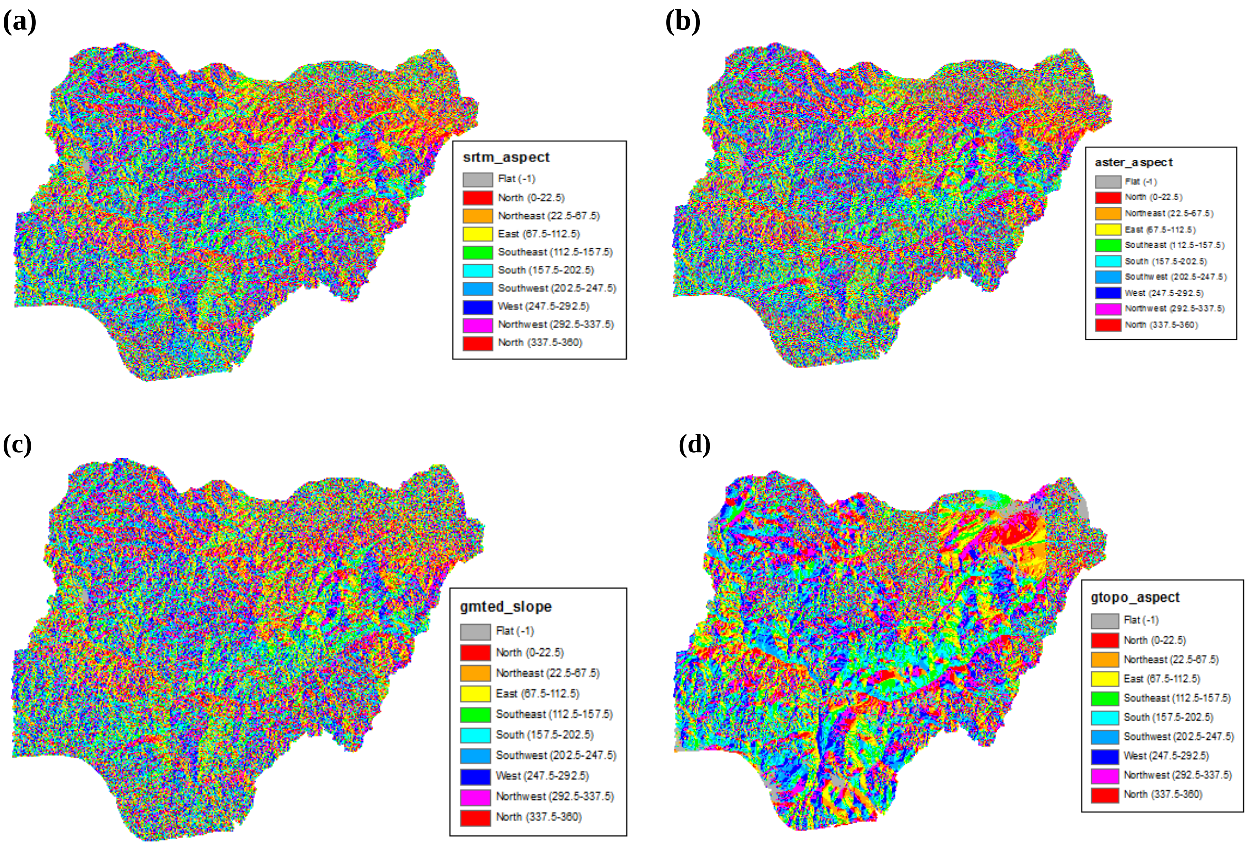

Figure 6. Aspect map of Nigeria from (a) SRTM, (b) ASTER, (c) GMTED and (c) GTOPO

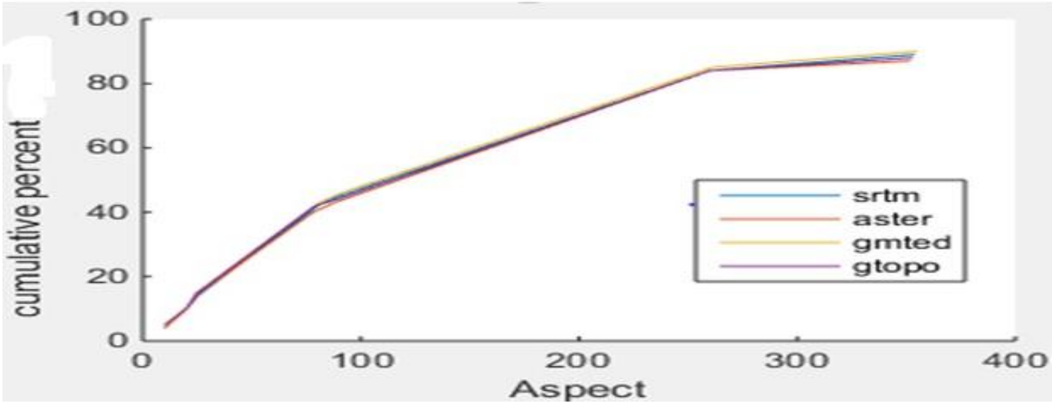

Figure 7. Cumulative frequency distribution of the various classes of aspect map

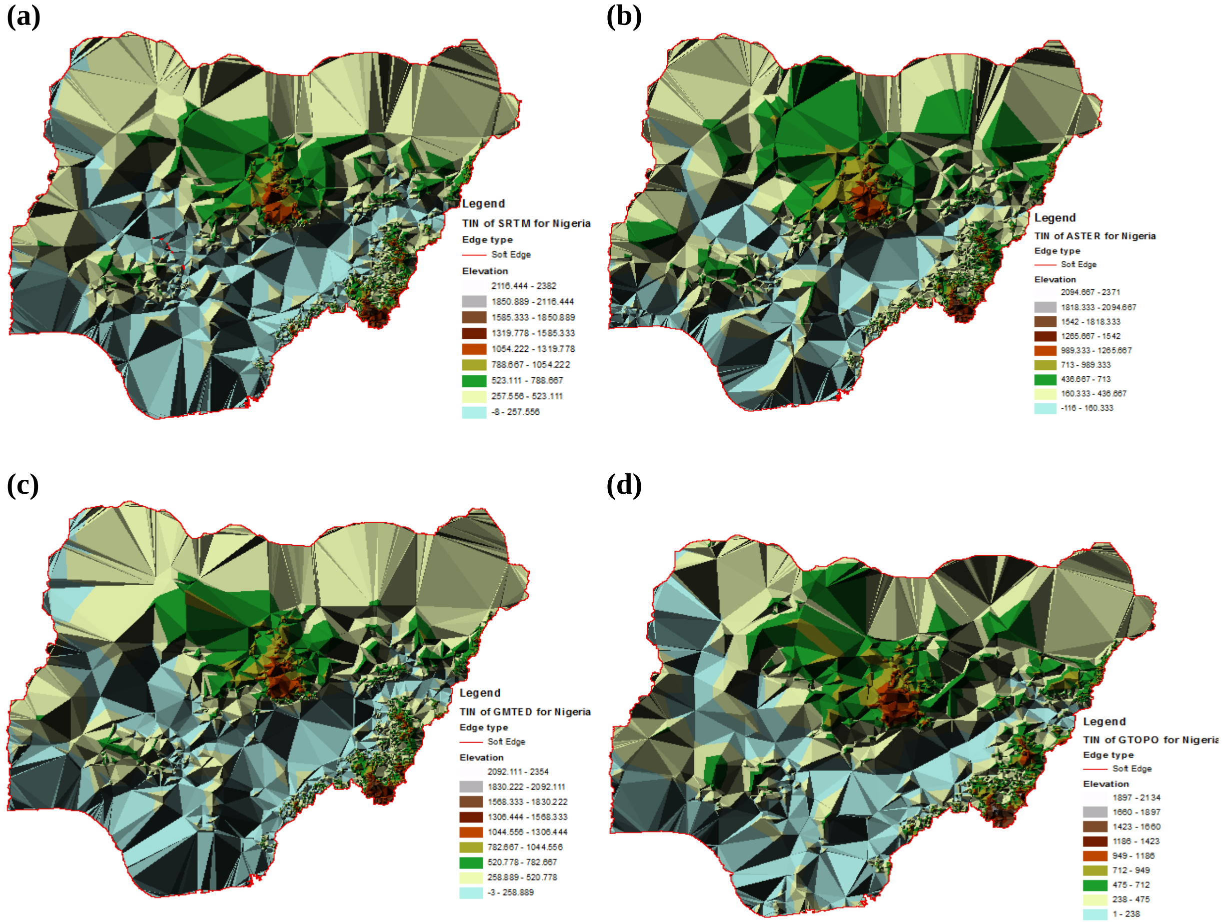

Figure 8. TIN Map of Nigeria from (a) SRTM, (b) ASTER, (c) GMTED and (c) GTOPO

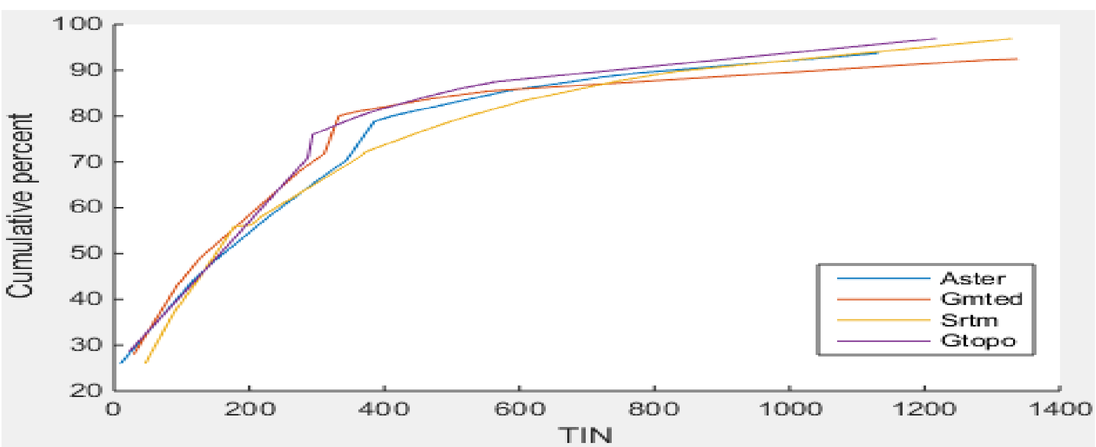

Figure 9. Cumulative frequency distribution of the various classes of TIN map

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4.2 QUALITATIVE METHOD

First, differences in elevation (Gonga-Saholiariliva et al. 2011) between the different DEMs (GTOPO, ASTER, SRTM and GMTED) is computed so that elevation error can be assessed such that the differences describes how the values of variables are distributed normally (Jim, 2018) (see Figure 12). Figure 12 shows the distributions of the elevation differences between the reference surface and the DEMs. The summary of the histograms presented in Figure 12 are presented in Table 3. The mean differences of the whole DEMs, shows shift towards positive values. This indicates that elevation of the SRTM, GMTED, GTOPO, and ASTER DEMs were greater than that of the reference DEM, which is an indication of the presence of vertical offset. Furthermore, the standard deviation presented in Table 3 reveals that SRTM has the least vertical offset, followed by ASTER, GMTED and then GTOPO.

Table 3. Summary of statistics of the elevation differences

Variable	Min	Max	Mean	Standard deviation
GNSS-SRTM	-4.980	31.234	5.586	7.576
GNSS-GMTED	-7.183	60.527	16.743	17.160
GNSS-GTOPO	-437.556	358.764	57.645	103.525
GNSS-ASTER	-31.394	57.234	14.312	13.625

Table 4. Summary of performance indicators

	SRTM	ASTER	GMTED	GTOPO
RMSE	5.413	8.413	13.963	56.853
NMAE	0.016	0.037	0.042	0.019
RI	1.014	1.042	1.025	1.290
R	0.999	0.997	0.996	0.819

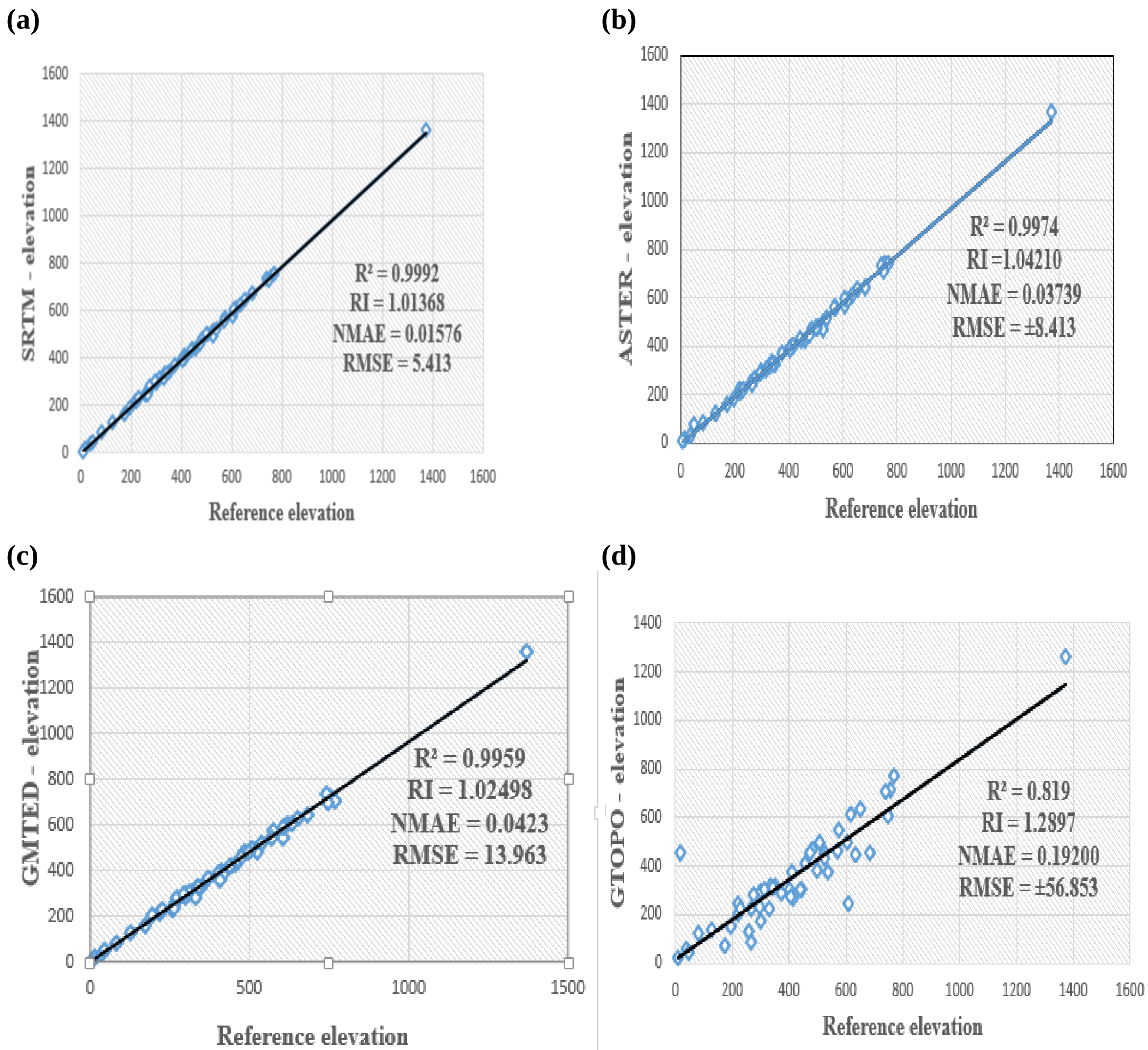

Figure 10. Scatter Plot of Reference Elevation vs. Elevation from (a) SRTM, (b) ASTER, (c) GMTED, (d) GTOPO

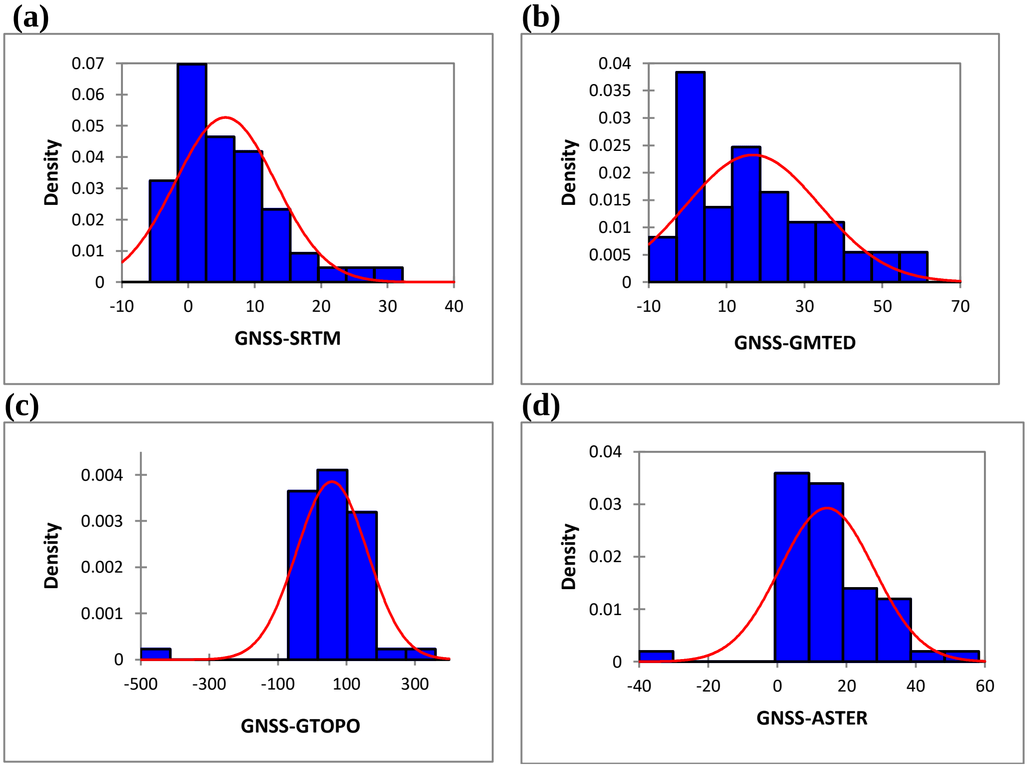

Figure 11. Histograms of the elevation differences: (a) GNSS-SRTM; (b) GNSS-GMTED; (c) GNSS-GTOPO; (d) GNSS-ASTER

The performance indicators, Normalized mean absolute error (NMAE) (Equation 1), root mean square error (RMSE) (Equation 2) and Relative index (RI) (Equation 3) were used for accuracy, and reliability assessment. The summary of the test statistics is presented in Table 4.

Ideally, RMSE values near zero indicate a close match. Therefore, over Nigeria SRTM data shows a perfect match with the reference elevation because it had the lowest RMSE of ±5.413. In addition, all the DEMs have a close match based on NMAE but the SRTM had the smallest NMAE, which is more close to zero (0.016). This indicates that SRTM has the closest agreement with reference data. More so, based on the RI (1.014) of SRTM which is the least as shown in Figure 11 and Table 4 it is clear that SRTM best describes height over Nigeria. Finally, SRTM data is said to have a close correlation with the GPS data because it has a value more closely to 1 (0.999) than any other DEM data in the analysis, followed by the ASTER (0.997) and GMTED (0.996) respectively. Figure 11 (d) shows the correlation of GTOPO and the reference data where by its value, it has the poorest correlation with the GPS data compared with SRTM, ASTER and GMTED. Height accuracy assessment of the four

DEMs adopted in this study reveal that the SRTM data shows a better vertical accuracy than ASTER GDEM, GTOPO and GMTED2010.

However, the better performance of STRM in this study corroborate studies of Athmania and Achour, (2014); Ioannidis et al. 2014) in Tunisia and Algeria and Greece respectively. It is commensurate with (Srivastava and Mondal, 2012). But also contradicts the study of Mukherjee et al. (2013) in Shiwalik Himalaya India, Li et al. (2012) in China, Elkhrachy, (2018) in Najran city, Saudi Arabia, who reported that ASTER performed better in their region of interest. Location, reference data errors, terrain characteristics and surface feature properties have been reported to hinder the vertical precision of DEMs (Athmania and Achour, 2014).

The histograms of elevation differences present a positive skew (see Figure 12) for both examined data, which is an indication that the DEMs are over-estimates of the spatial distribution of terrain elevation over Nigeria. This indicates a clear positive bias for the DEMs on GNSS elevations.

5. CONCLUSIONS

An accuracy assessment of freely available ASTER, GMTED, GTOPO and SRTM data seamlessly available as global DEMs have been conducted for Nigeria using GCPs as reference data. First, the basic characteristic of the models is described. Then, comparisons among the four DEMs presented and their respective vertical accuracy estimated by means of comparisons against GCPs. Finally, model differences are discussed from statistical viewpoint. From the analysis, it is clear that SRTM which is 1arc sec resolution is better than ASTER, GMTED and GTOPO DEM. It had produced the lowest RMSE of 5.413m. Also the SRTM is seen to have a better correlation with the reference data because of its correlation value tending to 1. The GTOPO performed poorer in all the analysis conducted because of its pattern been different from other digital elevation model of better resolution.

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