Determination of the Impacts of Landscape Offsets on the 30-metre SRTM DEM Through a Comparative Analysis with Bare-Earth Elevations

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Key words: Bare-Earth Elevation, Digital Elevation Model, SRTM, Landscape Offset, Land Cover

SUMMARY

Digital elevation models (DEMs) are fundamental spatial data infrastructure that support a wide range of applications in environmental modelling. However, in landscapes covered by vegetation and man-made structures, the DEMs record systematically too-high heights. This is because these obstructing features on the landscape tend to block a portion of the satellite pulses from reaching the ground, thus introducing gaps in the data. This effect also masks the true performance of the DEM in measuring the elevations in open-terrain conditions adjacent to such areas. On DEMs, these features manifest as abrupt transitions in-between open-terrains. The presence of these offsets limits the use of DEMs for many analytical operations where height of the bare-earth is a requirement. Extracting the terrain height component from the data in areas influenced by such cover is a challenging task. This paper investigates the effects of these vertical offsets on the 30-metre DEM from SRTM (Shuttle Radar Topography Mission) in three study sites located in Lagos and Ogun States of South-West Nigeria. The offsets were determined by comparing the SRTM heights with a reference DEM interpolated from local topographic maps of the area. The results showed varying misrepresentations in SRTM elevations with significant differences in the different landscape categories such as bare lands and built-up areas. However, a strong positive correlation was observed between the SRTM DEM and reference DEM with the highest correlation in bare lands (R^2 - 0.98) and lowest in wetland forests (R^2 – 0.85). The study also showed that a significant portion of absolute offsets (47 - 70%) in all landscape categories were in the 1-5m range. This information serves as a valuable resource in efforts directed at developing a bare-earth DEM from satellite-derived elevation datasets, and thus a justification for further research on the impacts of landscape offsets on the SRTM DEM to improve the accuracy and reliability of the data.

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1. INTRODUCTION

A Digital Elevation Model (DEM) is one of the fundamental pieces of information needed to understand and manage the environment. DEMs are gradually replacing topographic maps as the primary and authoritative source of terrain information across the world (Gallant, 2011). Aguilar *et al.*, (2005) citing Maune *et al.*, (2001) emphasized that the generic DEM normally implies elevations of the terrain (bare-earth z-values) void of vegetation and manmade features. This bare-earth DEM simulates true earth-surface elevations minus landscape (land cover) obstructions such as trees, buildings and above-ground obstructions (Podobnikar, 2009 cited in Tighe *et al.*, 2009). DEMs have become important sources of topographical data for many scientific and engineering applications such as - hydrological and geological studies, infrastructure planning and environmental management (Yu and Ge, 2010). Where local topographical data is unavailable, incomplete or out-dated, DEMs from remotely sensed data can be the main source of information. Today, there are several DEMs with world-wide coverage available to the global user community. However, many of these datasets suffer from the shadowing effect of landscape obstructions which block the satellite pulses from reaching the ground. For example, Gallant (2011) noted that the radar used to collect the SRTM (Shuttle Radar Topography Mission) data could not penetrate trees to measure ground heights so elevation offsets occur wherever there is sufficiently dense tree cover. These landscape obstructions constitute noise in the DEMs by masking the actual height of the bare-earth surface. Figure 1 illustrates the tree canopy effect on DEM elevations. The figure shows that the canopy effect is a function of the tree heights as observed from the DEM. Currently, methods such as remote sensing techniques, field surveys and/or digitizing of topographic maps are used to generate DEMs (Nwilo *et al.*, 2012). However, critical to the development of a bare-earth DEM is the necessity for accurate estimates of vertical offsets caused by landscape features (or land cover).

There are two techniques (manual and semi-automated) for filtering these offsets from DEMs. The manual method involves in-situ measurements of heights of landscape features for separation from the DEM. For example, using the manual technique, building and tree canopy heights measured on field can be subtracted directly from the DEM heights. However, it is impractical and expensive to implement such a manually-assisted technique across an entire country or continent. In the semi-automated approach, the heights of landscape structures can be estimated by interpolation algorithms and then subtracted from the DEM heights. For example, the tree offsets can be smoothed out by interpolation of canopy heights across forest patches and subsequent subtraction of the interpolated surface from the DEM (e.g. Gallant, 2011; Gallant *et al.*, 2012). Also, with available GPS control points, trend surfaces can be used to interpolate missing elevation values near the available points (e.g. Maguya *et al.*, 2014). However, the gaps left after forest removal can be very large (up to tens or hundreds of square kilometres) thus limiting the effectiveness and certainty of interpolation algorithms. Currently there is gap in knowledge in addressing this problem, therefore requiring further studies. The literature review shows that much of the focus is on tree covered areas only. Also, there is limited information regarding the spatial variation in DEMs over the entire landscape. This study contributes to existing knowledge by evaluating the impacts of these landscape obstructions on the spatial variation of the 30-metre SRTM DEM's accuracy over three sites covering 477 square km. By differencing the SRTM elevations from that of a reference surface derived from local topographic maps, the vertical offsets of these landscape features was determined. The elevation surface generated from the topographic maps is referred to as the "reference DEM" in this study. The estimation of the landscape offsets also serves as an accuracy measure for the SRTM DEM by evaluating the degree of closeness between the two datasets.

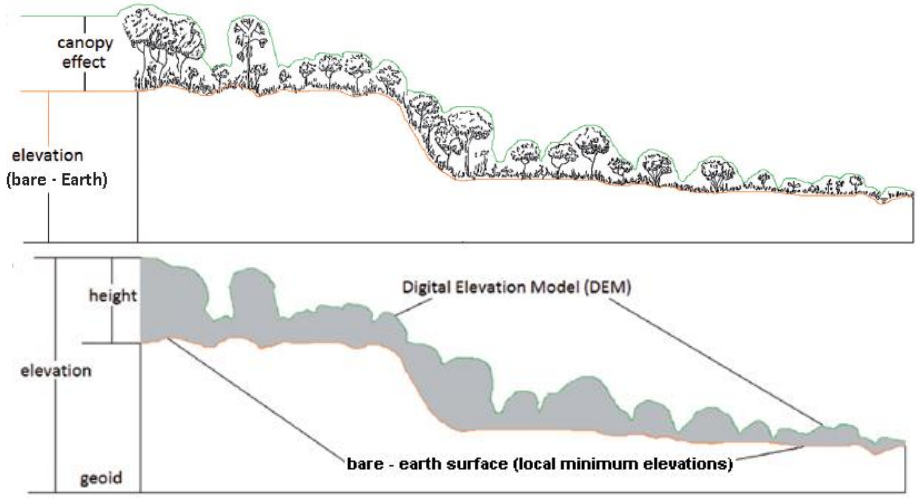

Figure 1: Tree canopy effect on Digital Elevation Models (modified from Munoz *et al.,* 2013)

2. LITERATURE REVIEW

The Shuttle Radar Topography Mission (SRTM) was co-sponsored by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA) (Dowding *et al.,* 2004). SRTM used a radar interferometer to generate a globally consistent digital elevation map for latitudes smaller than 60° (Rodriguez and Martin, 1992, Rosen *et al.,* 2000). The extent of the coverage means that Nigeria, lying between latitudes 4° and 14°N is covered by this mission. As part of the SRTM mission, an extensive ground campaign was conducted by NGA and NASA to collect ground-truth data that would allow for the global validation of this unique data set. The guidelines of the SRTM mission specified an accuracy requirement of 16m absolute vertical error (90% linear error) (Karwel and Ewiak, 2008). SRTM elevation data is derived from X-band (wavelength – 3.1cm) and C-band (wavelength – 5.6cm) Interferometric Synthetic Aperture Radar (Hoffman and Walter, 2006). The operational goal of the C-band system was to generate contiguous mapping coverage as called for by the mission objectives while the X-band system generated data along discrete swaths 50 km wide (Farr *et al., 2007*). These swaths offered nearly contiguous coverage at higher latitudes. The data was acquired from 11 – 22 February, 2000. Interferometric

Synthetic Aperture (InSAR) measures the distance between two known points (the interferometric antennas) and the surface point for each point on the earth's surface. Given that the vector between the two antennas (the "interferometric baseline") and their absolute position is known through in-situ measurements, the range to the point and the range difference can be used to triangulate the location of the surface point in space (Rodriguez, Morris and Belz, 2006). The surface height can then be inferred by relating this location to the appropriate datum. The radar wavelengths furnish signal returns from the landscape such as bare ground, rough water, and vegetation. These surfaces are what are represented by the DEM. Due to SRTM's relatively short wavelength, the majority of incoming electromagnetic energy is reflected by scatterers located within the vegetation canopy at heights well above the bare-earth surface (Kellndorfer *et al.,* 2004). Heavy vegetation canopies may not be penetrated significantly and the topographic map will not correspond to the ground surface in those areas (Farr *et al.,* 2007). Also, smooth surfaces such as calm water may not scatter enough radar energy back to the sensor and thus may not yield a height measurement.

Researchers have evaluated the performance of the SRTM dataset for different studies all over the world. In particular, the SRTM v4.1 which is an enhancement by the Consultative Group for International Agricultural Research – Consortium for Spatial Information (CGIAR-CSI) of the original SRTM product. For example, Nwilo *et al.,* (2012) performed an accuracy assessment of the 90m SRTM version 4.1 against twenty-two (22) GPS control points at a test site in Lagos, Nigeria. The DEM was shown to have an average absolute error of ±0.2m at the site. Kellndorfer *et al.,* (2004) quantified the magnitude of the vertical error component in SRTM data for two vegetation-free areas in Iowa and North Dakota of USA and obtained absolute errors of 4.0m and 1.1m, respectively. Ozah and Kufoniyi (2008) assessed the accuracy of the 90m SRTM v4.1 product in a section of Ondo State, Nigeria. The results showed an absolute vertical accuracy of ± 7.748m which is much better than the absolute vertical accuracy value of ±16m published in the SRTM data specifications. Similarly, Isioye and Obarafo (2010) evaluated the performance of the same CGIAR-CSI SRTM dataset against GPS check points in Zaria, Kaduna State, Nigeria. The results showed an absolute average vertical error of 5.586 ± 1.001m for the SRTM dataset. In another investigation of the quality of the SRTM v4.1 over Australia, Hirt *et al.,* (2010) reported a vertical accuracy of ~6m. Gorokhovich and Voustianiouk (2006) assessed the accuracy of SRTM v4.1-based elevations with that of two independent datasets collected with the same GPS system in the Catskill Mountains (New York, USA) and in Phuket (Thailand). The results of their study showed that the absolute average vertical errors from SRTM v4.1 ranged from 7.58 ± 0.60m in Phuket to 4.07 ± 0.47m in Catskills. They also noted a strong correlation of the error values with slope and aspect. The analysis revealed significant decrease in accuracy when measurements were performed on terrain characterized by slope values greater than 10°. In the analysis of aspect for Phuket, the highest magnitude of errors was observed for measurements made on slopes facing North-West (NW) and South-East (SE). Correspondingly, SRTM v4.1 under-estimated elevations of slopes facing NW and over-estimated elevations of slopes facing SE. In a more recent study, Santillan and Makinano-Santillan (2016) conducted a vertical accuracy assessment of three DEMs including the 30m SRTM v3.0 through a comparison with the elevations of 274 ground control points scattered over various sites in North-Eastern Mindanao, Philippines. The results of their study showed that

SRTM v3.0 had mean error and RMSE (Root Mean Square Error) values of 6.91m and 8.28m respectively. Also, majority of the SRTM's errors were within the 0 - 20m range.

Going further, Miliaresis (2008) evaluated the effects of land cover on the aspect/slope accuracy dependence of the SRTM-1 Elevation Data for the Humboldt Range in the North-West portion of Nevada, USA. The SRTM data was compared with bare-earth elevations from the U.S. National Land Cover Dataset (NLCD) and the U.S National Elevation Dataset (NED). Four land cover classes: forests, shrubs, grass and snow cover, were included in the study area. The decomposition of elevation differences on the basis of aspect and slope terrain classes identified an over-estimation of elevation by the SRTM instrument along the East, North-East and North directions (negative elevation difference that decreases linearly with slope). Conversely, there was an under-estimation evident towards the West, South-West and South directions (positive elevation difference increasing with slope). In implementing a geomorphology-based approach for fusing the SRTM and ASTER (Advanced Space-borne Thermal Emission and Reflection Radiometer) DEM, Tran *et al.,* (2014) also considered land cover units in correcting the elevation of SRTM with respect to the bare-earth surface in a case study of Danang City, Vietnam. A weighted average method was used to fuse both DEMs based on a landform classification map.

These performance assessments of the SRTM elevation products, and especially the accuracy correlation with terrain derivatives such as slope and aspect has provided valuable information to the global user community on its limitations in variable terrain configurations across the world. The accuracy measures are usually determined through comparisons of the SRTM DEMs with reference elevations from GPS check points or national topographic databases. However, it is well known that landscape features constitute obstructions to satellite signal penetration and appear as vertical offsets on DEMs. The presence of these obstructive land cover limits the DEM functionality and its applications scope. Also, the interaction of SRTM's radar pulses with different landscape features varies and this affects the accuracy of its height estimates. The predictable nature of these offsets (e.g. buildings with regular heights and tree species/canopies with uniform vertical structure) can serve as a modelling strategy for a more informative description of the DEMs performance across variable landscapes. It will also provide critical information in the development of a credible bare-earth DEM which will have more functional applications in environmental modelling, hydrologic processing and water resources management. Currently there is a gap in knowledge in addressing this problem, therefore requiring further studies. Also, the literature review shows that much of the focus in separation of landscape offsets from DEMs is on tree covered areas only. This study fills this gap by evaluating the impacts of the entirety of these landscape obstructions on the spatial variation of accuracy in the 30-metre SRTM DEM product in the study area.

3. THE STUDY AREA

A total of three sites spread over six Local Government Areas (LGAs) in Lagos and Ogun States were selected for this study. These sites were selected given the massive urban expansion and luxuriant vegetation type of the states. The two states are in the tropical rainforest belt of South-West Nigeria. The prolonged rainy season in the rainforest supports perennial tree growth. Site 1 is the largest covering part of Lagos and Ogun States with a coverage of 381.90km^2 along the corridor of the Lagos-Sagamu Expressway. The second site (Site 2) is at Ijebu-Ode town in Ogun State while the third site (Site 3) is located at Epe town in Lagos State. Sites 2 and 3 each have a coverage of 47.70km^2. Figure 2 presents the map of the study sites, while Table 1 shows the geographic extent and distribution of the sites by LGA. These sites are among the most developed regions in South-West Nigeria. The characteristics of these sites present a wide diversity of landscape features for this investigation. For example, Lagos State has a very diverse and fast-growing population, resulting from heavy and ongoing migration to the city from all parts of Nigeria as well as neighbouring countries. The state is a low-lying coastal state and the centre of commerce for Nigeria. The land surface in the state generally slopes gently downwards from north to south, and is naturally made up of depositional landforms which include: wetlands, barrier islands, beaches, low-lying tidal flats and estuaries (Iwugo *et al.*, 2003). Two main vegetation types are identifiable in Lagos State: swamp forest of the coastal belt and dry lowland rain forest. The swamp forests in the state are a combination of mangroves, wetland forests and coastal vegetation developed under the brackish conditions of the coastal areas and the swamp of the freshwater lagoons and estuaries. Figure 3 shows a picture taken during a field visit to Site 1 of a wetland forested area along the Ikorodu - Epe road. Ogun State is located to the north of Lagos State. The northern part of the state is mainly of derived savannah vegetation, while the central part falls in the rain forest belt (Ogunde, 2013). The landscape of the state comprises extensive fertile soils and savannah land in the north-western parts, forest reserves, rivers, lagoons, rocks and mineral deposits. Ogun State is characterized by highlands to the north which slope downwards to the south. The highest region (North-West) rises over 300 metres above sea level while the lowest levels are in the southern parts (Ogunde, 2013).

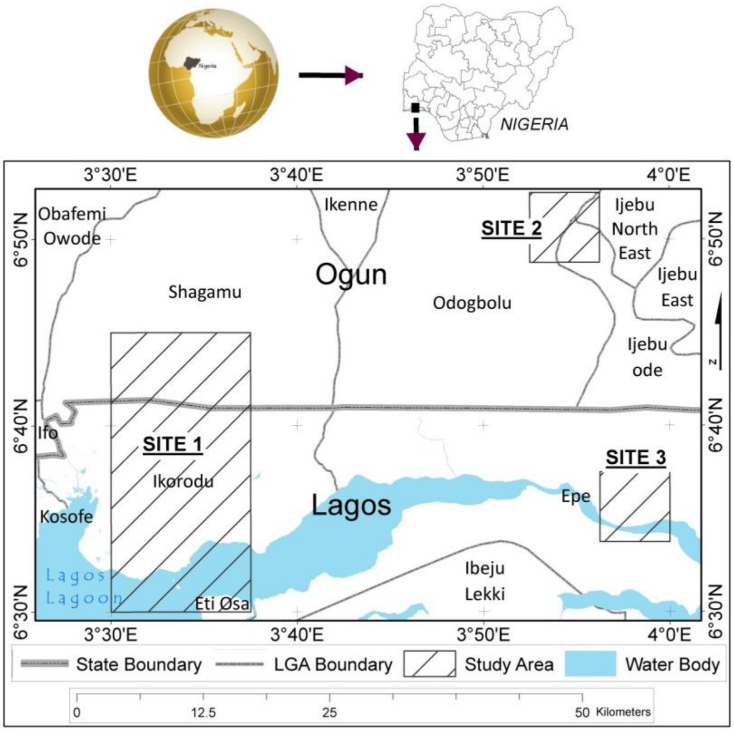

Figure 2: Map of the study area

Table 1: geographic extent and distribution of the study sites by LGA

	Geographic Extent	**Local Government Area (LGA)**
Site 1	3°30′– 3°37.5′E; 6°30′ – 6°45′ N (381.90km^2)	Ikorodu and Sagamu
Site 2	3°52.5′– 3°56.25′E; 6°48.75′– 6°52.5′N (47.70 km^2)	Ijebu-Ode, Odogbolu and Ijebu North-East
Site 3	3°56.25′– 4°00′E; 6°33.75′– 6°37.5′N (47.70 km^2)	Epe

Figure 3: Typical scene of wetland forests at Site 1 along Ikorodu - Epe Road

4. METHODOLOGY

The methodology adopted in this research consisted of the following steps:

1. Acquisition and compilation of the required data
2. Datum Harmonization
3. Interpolation of Reference DEM from topographic maps
4. Extraction of land cover from Landsat imagery; and
5. Separation of landscape offsets from the SRTM DEM

4.1 Data Acquisition and Compilation

4.1.1 30-metre SRTM DEM

The SRTM version 3.0 Global dataset is an enhancement to the initial SRTM 90m dataset. Previously SRTM data at this resolution have only been available for the United States and its territories. Before this release, the best available 90m SRTM DEMs for regions outside the USA are: (i) SRTM v3 released by NASA in November 2013 (NASA LP DAAC, 2013), and (ii) SRTM v4.1 released by CGIAR-CSI in 2008 (Jarvis *et al.*, 2008). SRTM v3.0 was downloaded from the USGS (United States Geological Surveys) EarthExplorer online portal (http://earthexplorer.usgs.gov/). SRTM v3.0 is provided in 1° x 1° tiles at 30m resolution on WGS84 datum. Also, it is referenced to mean sea level realized by the EGM 96 geoid model.

4.1.2 Topographic Maps

The reference elevation data used in this study are from a DEM generated from contours and spot heights vectorized from 1:25,000 topographic maps of the study sites. The map contours are spaced at 5m interval. The topographic maps include sheets 280SW1, 280SW3, 280SE4 and 280NE4 acquired from the Office of the Surveyor General of the Federation (OSGoF). A major advantage of the orthometric heights on the maps is its consistency with the height system of the SRTM DEM, which makes the heights readily usable due to compatibility.

4.1.3 Landsat Imagery

The LandSat mission is a joint initiative between USGS and NASA It represents the world's longest continuously acquired collection of space-based medium-resolution land remote sensing data. A single Landsat 7 Enhanced Thematic Mapper (ETM+) imagery with Path/Row No of 191/55 was downloaded from the USGS Global Visualization portal (http://glovis.usgs.gov/). Since the SRTM mission was flown in February 2000, the Landsat image for a period in year 2000 was downloaded. Table 2 summarises the characteristics of the elevation data sources while Table 3 shows the characteristics of the Landsat image.

Table 2: Characteristics of Elevation data sources

Data	**Source**	**Coordinate System**	**Geoid Reference**	**Height System/ Vertical Units**	**Scale/ Resolution**	**Date Produced**
SRTM Global v3.0	NASA/ NGA	Geodetic Longitude – φ Latitude - λ Height - H	WGS84 datum/ EGM96	Orthometric (meres)	1 arc-second (30m)	February 2000
Topographic maps	OSGoF		Minna datum		1:25,000	1987

Table 3: Characteristics of the Landsat Dataset

LandSat Data	**Source**	**Path/Row**	**Resolution**	**Acquisition Date**
Landsat 7 ETM+	USGS	191/55	30m	February 2000

4.2 Datum Harmonization

Since the SRTM dataset is provided in a geographic coordinate system in WGS84, it was reprojected in ArcGIS 10.1 to a Universal Transverse Mercator (UTM) projection referenced to Nigeria’s local Minna datum. Minna datum is based on the Clarke 1880 ellipsoid. This transformation helped to overcome linear measurement difficulties and preserve geometric properties of the DEM. For conformity, the Landsat data on WGS84 in the UTM system was transformed to Minna datum, the local reference datum.

4.3 Interpolation of Reference DEM

The topographic maps were georeferenced using the coordinates of the corner points. Next, the hypsometry layers (contours and spot heights) were vectorized as ESRI shapefiles and the height values inputted as attributes. The contours and spot heights were then interpolated into a DEM using the ArcGIS *Topo To Raster* interpolation method which is based on the ANUDEM program version 5.3. The ANUDEM program is distributed by the Australian National University (ANU) Fenner School of Environment and Society. It has been designed to produce regular grid DEMs with sensible shape and drainage structure from arbitrarily large topographic data sets (Hutchinson, 2011). The cell size of this reference DEM was set to 30m in order to conform to the spatial resolution of the SRTM DEM.

4.4 Land Cover Extraction

The first step of the extraction involved a preliminary interpretation of the Landsat image. This interpretation categorized the study area land cover into six classes - bare lands, built up areas, grasslands (including shrubs and croplands), wetland forests, mixed forests and water bodies. Next, a step-by-step process of training class selection based on the spectral signatures of each class was done on ENVI 5.0 software. In the training class selection, care was taken to avoid inclusion of mixed pixels which could compromise the fidelity of the output classes. Then, the image was subjected to supervised classification by the parallelepiped technique. The parallelepiped algorithm is a computationally efficient method of classifying remote sensor data. It uses a simple decision rule to classify multispectral data. The decision boundaries form an n-dimensional parallelepiped in feature space (Kumar, 2003). If a pixel value lies above the low threshold and below the high threshold for all n bands being classified, it is assigned to that class. If the pixel value falls in multiple classes, ENVI assigns the pixel to the first class matched. After classification, the feature classes were transferred to ArcGIS for editing, elimination of spurious clusters and refinement of the output.

4.5 Separation of Landscape Offsets

By zooming in and identifying individual pixels on the SRTM DEM, it was revealed that the heights on water bodies in the study area were already levelled out in the product before delivery. Hence, the water bodies were excluded from subsequent analysis. The offsets attributable to the other land cover features were calculated based on the difference elevation map of SRTM with respect to the reference DEM. First, a dense grid of 424,521 points was extracted from the SRTM DEM with the location of each point being the geometric centre of each 30m pixel. This grid was overlaid on the reference DEM for the extraction of elevations at coincident points. Next, the point grids were separated by location into five clusters corresponding with the land cover classes retained for analysis. The SRTM point elevations were then subtracted from the point elevations of the reference DEM. These differences ($\Delta H_{TOPO\text{-}SRTM}$) in each of the five land cover patches were computed and tabulated separately. The differences were subsequently used to compute accuracy statistics categorized according to land cover in the sites.

5. RESULTS

The elevation surfaces from the SRTM DEM and topographic map are shown in Figures 4 and 5 respectively. For both surfaces, the elevation ranges at all sites are – Site 1 (SRTM: 0 - 103m; Topo: 0 - 91m), Site 2 (SRTM: 0 - 122m; Topo: 15 - 126m) and Site 3 (SRTM: 0 - 49m; Topo: 0 - 45m). The land cover information extracted by parallelepiped classification is shown in Figure 6. In the land cover distribution at the three sites, bare lands account for 2.62km^2 (0.55%), built-up areas account for 57.02km^2 (11.92%), grasses, shrubs and croplands account for 162.05km^2 (33.88%), wetland forests account for 97.30km^2 (20.34%), mixed forests account for 91.33km^2 (19.09%) while 68.01km^2 (14.22%) of the area is covered by waters of the Lagos lagoon. A total of 424,521 points were compared on both surfaces at coincident locations – 2,777 points in bare lands, 57,740 points in built-up areas, 166,341 points in grasses, shrubs and cropland areas, 101,043 points in wetland forests and 96,620 points in mixed forests. Table 4 shows the descriptive statistics of point elevations at the compared points on bare lands and built-up areas while Table 5 shows statistics for vegetation covered areas.

The point elevations from the SRTM DEM and reference DEM are denoted by H_{SRTM} and H_{TOPO} respectively. The difference between the SRTM point elevations and reference surface is denoted as $\Delta H_{TOPO\text{-}SRTM}$.

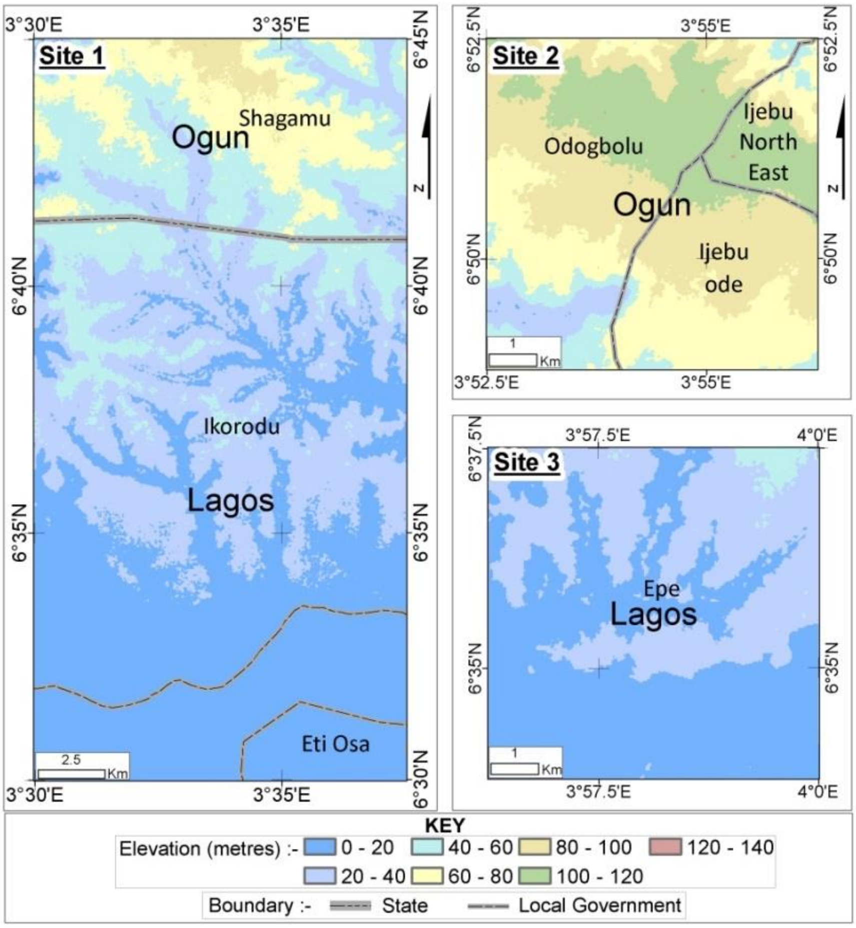

Figure 4: Elevation surface from SRTM DEM

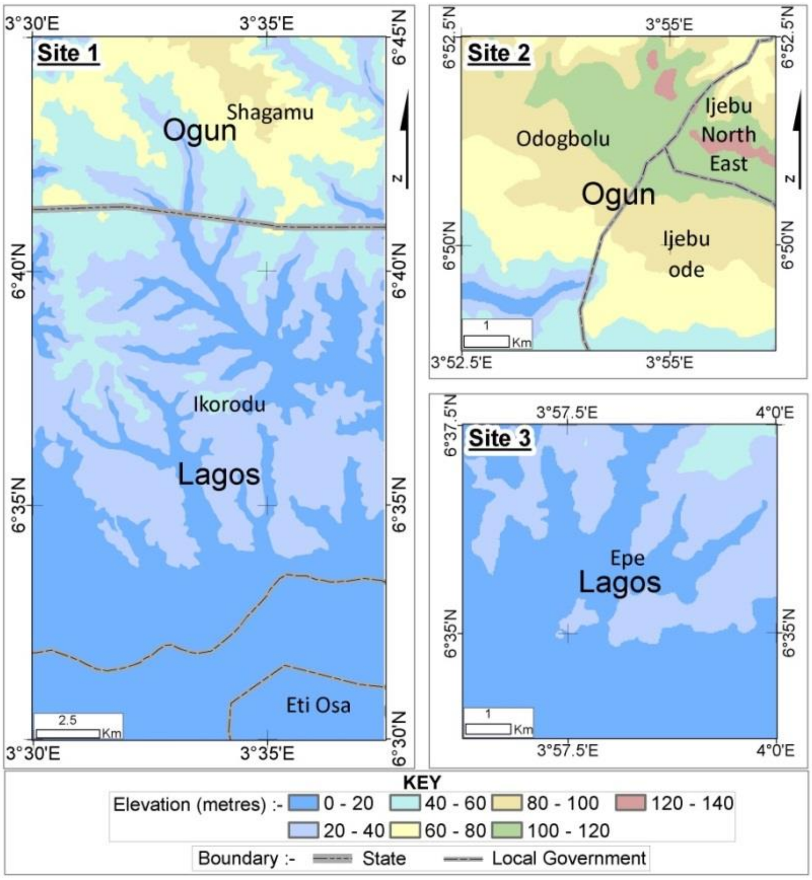

Figure 5: Reference DEM interpolated from Topographic maps

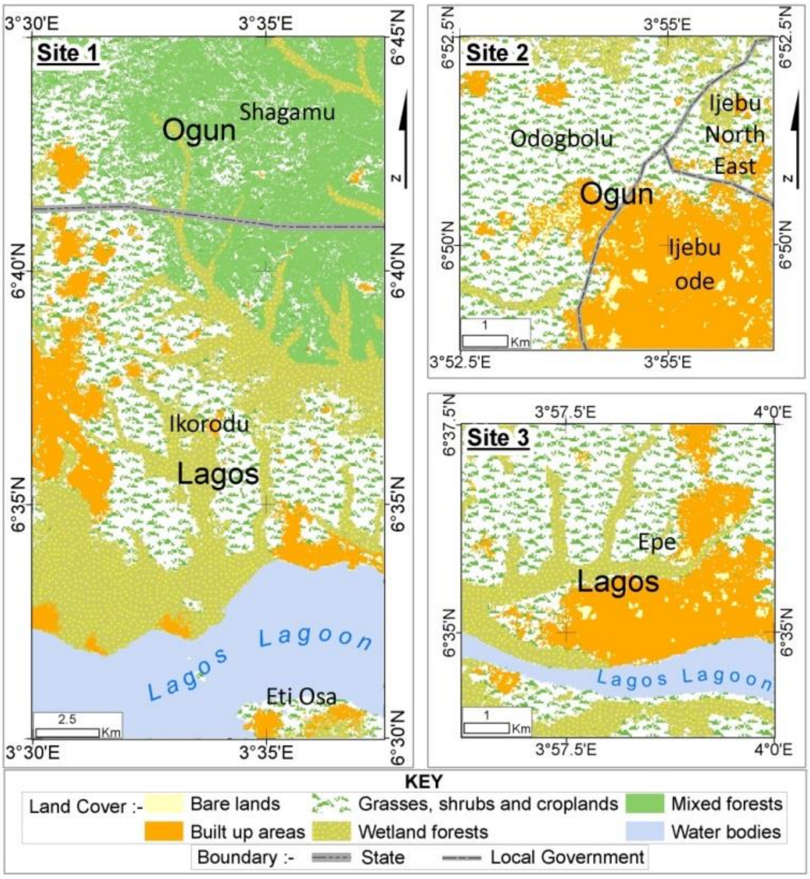

Figure 6: Spatial distribution of Land cover derived by supervised classification

The summary of landscape offsets (elevation differences) is shown in Table 6. The mean elevations derived from both surfaces are as follows: bare lands (H_{SRTM} - 61.64m; H_{TOPO} - 59.34m), built-up areas (H_{SRTM} - 42.94m; H_{TOPO} - 41.89m), grasses, shrubs and croplands (H_{SRTM} - 42.69m; H_{TOPO} - 42.76m), wetland forests (H_{SRTM} - 17.99m; H_{TOPO} - 13.12m) and mixed forests (H_{SRTM} - 51.25m; H_{TOPO} - 49.11m). On the landscape offsets ($\Delta H_{TOPO-SRTM}$), the mean differences are as follows: bare lands (-2.30m), built-up areas (-1.05m), grasses, shrubs and croplands (0.07m), wetland forests (-4.87m) and mixed forests (-2.14m). Negative offsets indicate areas in which SRTM over-estimated the elevations of the reference DEM while positive offsets indicate an under-estimation of the reference DEM elevations by SRTM.

Table 4: Descriptive statistics of point elevations in bare lands and built-up areas

	Bare lands		**Built up areas**	
	H_{SRTM} (m)	**H_{TOPO} (m)**	**H_{SRTM} (m)**	**H_{TOPO} (m)**
No. of points	2,777		57,740	
Min.	0	0	0	0
Max.	116	123	119	123

Mean	61.64	59.34	42.94	41.89
S.D	28.27	28.04	28.14	27.77

The goodness of fit of the SRTM with the reference DEM was evaluated by using the standard errors (S.E) and coefficient of determination (R^2). Table 7 presents the goodness of fit statistics while Figure 7 presents the scatter plots of H_{SRTM} against H_{TOPO} fitted with 95% confidence bounds (shown by the red dotted lines). The results are as follows: bare lands (S.E – 4.023m; R^2 – 0.980), built-up areas S.E – 4.359m; R^2 – 0.976), grasses, shrubs and croplands (S.E – 4.606m; R^2 – 0.971), wetland forests (S.E – 5.858m; R^2 – 0.851) and mixed forests (S.E – 5.340m; R^2 – 0.909).

Table 5: Descriptive statistics of point elevations in Vegetation covered areas

	Grasses, shrubs and croplands		**Wetland forests**		**Mixed forests**	
	H_{SRTM} (m)	**H_{TOPO} (m)**	**H_{SRTM} (m)**	**H_{TOPO} (m)**	**H_{SRTM} (m)**	**H_{TOPO} (m)**
No. of points	166,341		101,043		96,620	
Min.	0	0	0	0	5	1
Max.	122	126	121	122	103	91
Mean	42.69	42.76	17.99	13.12	51.25	49.11
S.D	26.80	27.42	15.15	15.85	17.72	19.59

Table 6: Descriptive statistics of landscape offsets for different land cover

	$\Delta H_{TOPO-SRTM}$ (m)				
	Bare lands	**Built up areas**	**Grasses, shrubs and croplands**	**Wetland forests**	**Mixed forests**
No. of points	2,777	57,740	166,341	101,043	96,620
Min.	-16	-23	-26	-28	-29
Max.	12	17	27	26	21
Mean	-2.30	-1.05	0.07	-4.87	-2.14

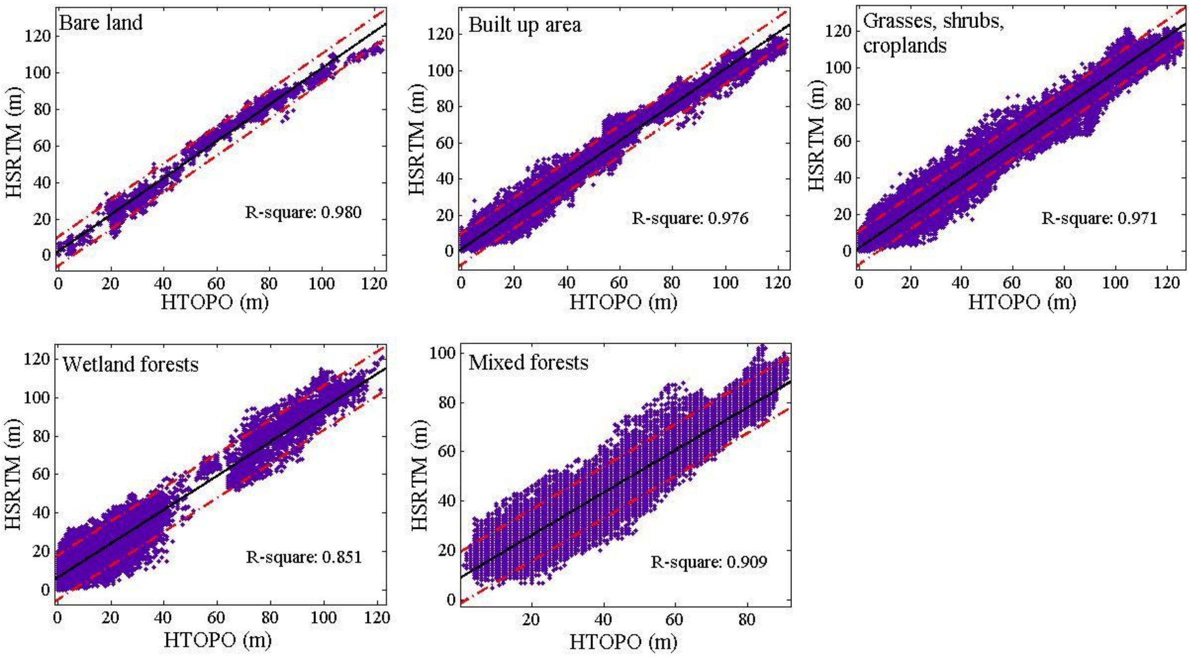

Figure 7: H_{SRTM} vs. H_{TOPO} categorized by land cover and shown at 95% confidence bounds

The linear regression of SRTM with the reference DEM yielded the following relations:

Bare lands:	$H_{SRTM} = 0.998H_{TOPO} + 2.421$	Eq. 1
Built-up areas:	$H_{SRTM} = 1.001H_{TOPO} + 1.013$	Eq. 2
Grasses, shrubs, croplands:	$H_{SRTM} = 0.963H_{TOPO} + 1.517$	Eq. 3
Wetland forests:	$H_{SRTM} = 0.882H_{TOPO} + 6.415$	Eq. 4
Mixed forests:	$H_{SRTM} = 0.863H_{TOPO} + 8.893$	Eq. 5

Table 7: Goodness of fit statistics between H_{SRTM} and reference DEM

	Bare lands	**Built up areas**	**Grasses, shrubs and croplands**	**Wetland forests**	**Mixed forests**
S.E	4.023	4.359	4.606	5.858	5.340
R^2	0.980	0.976	0.971	0.851	0.909

Table 8: Percentage offset magnitudes in SRTM with respect to reference DEM

	Percentage (%)				
$\Delta H_{TOPO-SRTM}$ (m)	**Bare lands**	**Built up areas**	**Grasses, shrubs and croplands**	**Wetland forests**	**Mixed forests**
> -20	0.00	0.01	0.02	0.66	0.49
-20 → -16	0.04	0.32	0.16	4.39	2.36
-15 → -11	1.08	1.53	1.32	13.49	6.49
-10 → -6	20.67	12.63	9.34	25.01	16.21
-5 → -1	46.96	40.33	34.06	31.58	31.08

0	7.99	9.53	8.82	6.21	7.51
1 → 5	19.37	29.64	35.09	15.51	28.68
6 → 10	3.64	5.54	9.60	2.44	6.56
11 → 15	0.25	0.47	1.32	0.58	0.57
16 → 20	0.00	0.01	0.22	0.13	0.05
> 20	0.00	0.00	0.04	0.01	0.00
Total	100	100	100	100	100

In Table 8, the percentage offset magnitudes in SRTM with respect to the reference DEM are categorised by land cover distribution into error bounds. These errors correspond to the vertical offsets attributable to the land cover. Within this continuum of offsets, 7.99% of the height points are observed to coincide on bare lands, 9.53% on built up areas, 8.82% on grasses, shrubs and croplands, 6.215 on wetland forests and 7.515 on mixed forests. A greater percentage of the absolute offsets are within the range of 1 - 5m for all land cover classes.

6. DISCUSSION

The non-homogeneity in the surface characterization by the SRTM DEM across the study sites can be attributed to the influence of the landscape features on the DEM which constitutes noise in the dataset. This noise produces misrepresentations in elevations. In the estimation of standard error in the SRTM DEM with respect to the reference DEM, it can be seen that bare lands have the lowest discrepancy (S.E – 4.023m) while wetland forests have the highest (S.E – 5.340m). Similarly, the linear regression between SRTM DEM and the reference DEM shows significant correlation on all sites with bare lands having the highest agreement (R^2 – 0.980) and wetland forests the lowest (R^2 – 0.851). Virtually all points in bare lands fitted within the 95% confidence bounds. The occurrence of points at the outermost fringes of the 95% bounds in the vegetation covered areas can be attributed to irregularly spaced tall tree canopies and random spikes in the SRTM surface. It is seen that the height offsets are greatest in forested areas and lowest in areas with marginal cover such as bare lands. The high offsets in forested areas and especially in the wetland forests can be attributed to the inability of SRTM's radar pulses to effectively penetrate the dense vegetation canopy. The highest occurrences of above-ground offsets in the wetland forests (31.58%) and mixed forests (31.08%) are in the range of 1 - 5m. Also, these forests record the lowest occurrences of SRTM elevations coinciding with the reference DEM (wetland forests – 6.21%; mixed forests – 7.51%). Conversely, the highest occurrences of SRTM elevations coinciding with the reference DEM are observed in bare lands and built-up areas (bare lands – 7.99%; built-up areas – 9.53%). This can be attributed to the gaps in open terrain and in-between buildings through which radar pulses are able to penetrate.

The offsets in bare lands are generally of a minor amplitude when compared to that of built-up areas and vegetation-covered areas. About 47 – 70% of the absolute offsets in all landscape categories are within the range of 1 - 5m range. It is also observed that most of the SRTM heights on the landscape tend to over-estimate the ground elevations. The water courses draining the wetland forests makes its trees to be generally higher and more luxuriant than the surrounding mixed forests. For example, Table 8 shows that 31.58% of the wetland trees are 1 – 5m in height, 25.01% are 6 –

10m in height while 13.49% are 11 - 15m in height. In contrast, 31.08% of trees in the mixed forests are 1 - 5m in height, 16.21% are 6 - 10m in height and just 6.49% are 11 - 15m in height. Grasses, shrubs and croplands contribute least to the SRTM over-estimation among vegetation covered areas. From Table 8, only 9.34% of grasses accounted for above-ground offsets in the 6 - 10m range and even a smaller portion (1.32%) accounted for above-ground offsets in the 11 - 15m range. Generally, the DEM is more reliable in built-up areas, bare lands and areas with short vegetation growth such as grasses, shrubs and crop cultivated lands. The vertical accuracy of SRTM v3.0 across the full landscape in the three sites still surpasses the 16m accuracy requirement presented in the original SRTM specifications.

7. CONCLUSION

This research has evaluated landscape offsets in the 30-metre DEM from SRTM against those obtained from reference topographic maps. It has been shown that the DEM product tends to over-estimate the terrain height in forested areas much more than in built-up areas and open terrain with marginal cover. Nonetheless, SRTM v3.0 exhibited a good level of dependency in comparison with the reference elevation data and can be regarded as a good elevation database over areas that lack adequate cover from national topographic databases. More importantly, this study has shown that the pattern and spread of landscape features exhibits predictable trends which can form part of a modelling strategy for derivation of the bare-earth surface from satellite DEMs. Efforts are in progress by the research team to automate the filtering of offsets and derivation of bare-earth heights in areas shadowed by forest cover by fusing DEMs with space-borne LIDAR (Light Detection and Ranging) which has the capability to penetrate dense vegetation canopies.

8. RECOMMENDATIONS

The following recommendations are put forward:

- Going further, landscape offsets in forested areas can serve as an input in creating a Canopy Height Model for use as a modelling strategy designed to filter out vertical errors from the SRTM and other global DEM datasets.
- The approach of this study can be replicated in other topographic regions and vegetation belts of Nigeria to provide more insight on the influence of the country’s variable landscape on SRTM’s accuracy.
- The effects of landscape offsets on terrain derivatives such as slope, aspects and watersheds is an interesting area for future research.
- Where economically feasible, airborne LIDAR (Light Detection and Ranging) should be used in place of InSAR DEMs. The capability of LIDAR for mapping forest vertical structure makes it an invaluable additive in the development of techniques to filter out tree canopy offsets.
- Also, the utility of the space-borne Geoscience Laser Altimeter System (GLAS) aboard the Ice, Cloud and Land Elevation Satellite (ICESat) in automated filtering of tree canopy offsets should be explored. GLAS is freely available unlike most LIDAR sensors and its coverage spans the globe.

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