IFE
RESEARCH PUBLICATIONS
IN GEOGRAPHY

Shuttle Radar Topography Mission (SRTM) Elevation Data: A Contemporary Global Elevation Model for describing the topography in Zaria and its environs

Isioye[1], O.A., and Obafaro[2], E. O.
Department of Geomatics Engineering, Ahmadu Bello University, Zaria-Nigeria
[1] lekkyside4u@yahoo.com, [2] emmireel@yahoo.com

Abstract

Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) has created an unparallel data set of global elevations that is freely available for modeling and environmental applications. The global availability (almost 80% of the Earth surface) of SRTM data provides baseline information for many type of the worldwide researches. This product presents a great value in the production of topographic map, analysis in ecology, accuracy of precise gravimetric geoid, agriculture, climatology, geology, pedology, geomorphology, environmental modeling, rainfall-runoff studies, landslide hazard zonation, seismic source modeling and hydrological modeling. However, overall assessment of the accuracy of this product requires additional regional studies involving ground truth control and accuracy verification methods with higher level of precision, such as the Global Positioning System (GPS). The study presented in this report is based on two independent datasets collected with GPS system and Topographic map. Statistical analysis included estimation of absolute errors. Data from the various dataset were analyzed independently and in combination. Differences in terrain enabled a good interpretation of results. The results of this study showed that absolute average vertical errors of the SRTM dataset is 5.586 ± 1.001m in Zaria (mean ± S.E.M.). This is significantly better than a standard SRTM accuracy value indicated in its specification (i.e. 16 m). The error values have strong correlation with slope and certain aspect values. The result show good contour and terrain harmonization at contour interval greater than 15m. It was recommended that SRTM dataset and other global elevation datasets be evaluated before put to use. Also, it was further recommended that the application of SRTM dataset in providing terrain correction for the Nigerian Gravimetric Geoid Model will help improve the accuracy of the model which is for now being questioned.

Keywords: SRTM, GPS, Digital Elevation Model (DEM), Slope, Aspect.

IRPG Vol 9., No 1. pp.221-245, 2010.

Introduction

Digital Elevation Models (DEMs) are becoming more and more important in the production of topographic map, analysis in ecology, agriculture, climatology, geology, pedology, geomorphology, environmental modeling, rainfall-runoff studies, landslide hazard zonation, seismic source modeling, hydrological modeling and in water resources management (because they can provide many hydrological relevant parameters, such as drainage networks and catchment boundaries). Digital elevation models also play an important role in the accuracy of precise gravimetric geoid; they are used to compute terrain corrections, direct topographical effects on gravity and indirect effects on geoid, and also to generate mean gravity anomalies (Featherstone and Kirby, 2000). Most of the disciplines of scientific research involving the Earth's land surface require topographic data and derived slope, slope aspect, and ortho-image cartographic products (Hohle, 1996). Our capacity to understand and model earth surface processes depends on the quality of the topographic data that are available in a digital format called Digital Elevation Model (DEM). A DEM is a computerized representation of the Earth's terrain (Burrough and McDonnell, 1998), and can be described by a wire frame model or an image matrix in which the value of each pixel is associated with a specific topographic height (Evans, 1980).

The Shuttle Radar Topography Mission (SRTM) 3-arc second DEM is the result of a collaborative effort by the National Aeronautics and Space Administration (NASA), the National Imagery and Mapping Agency (NIMA), the German space agency, and Italian space agency (Rabus *et al.*, 2003; Foni and Seal, 2004; Van Zyl, 2001). The mission was launched on 11 February 2000 aboard the Space Shuttle *Endeavour*. Using radar interferometry, a 3-arc second (SRTM-3) and a 1-arc second (SRTM-1) DEM were produced for almost the entire globe. The Australian SRTM-3 data were publicly released in July 2004, although the SRTM-1 data are yet to be released. Data were collected using two interferometers, C-band (American) and X-band (German) systems, at 1-arc second (30 m) (Foni and Seal, 2004; Rabus *et al.*, 2003; Van Zyl, 2001). The absolute vertical and horizontal accuracy of the data collected was reported to be ±16 m and ±20 m (Kaab, 2005; Kellndorfer *et al.*, 2004; Miliaresis and Paraschou, 2005; Rabus *et al.*, 2003). The 3-arc second (90 m) DEM was created by 3 × 3 averaging of the 1-arc second data (i.e. 9 data points combined to form a single 3-arc second data point). Elevation data error has features of random noise. Thus the process of averaging is considered to reduce error by approximately a factor of three and reduces random error but not systematic error (USGS, 2003). Each data tile covers an area spanning 1° in latitude and longitude, containing 1201 rows and 1201 columns. Elevation values are given in meters and WGS84 is used as horizontal and vertical datum (Rabus *et al.*, 2003). When corrected to meters, the spacing is 91·666 m by 91·666 m, which in this work is referred to as a 90 m DEM. This giant leap forward in spatial resolution for DEMs with global coverage is likely to change the way in which related research can be performed and applied.

While the data coverage of SRTM is global, the short wavelength C-band and X-band radar cannot penetrate vegetation, that means, not digital elevation models showing the height values of the bare ground, but digital surface models (DSMs) showing the height of the visible surface-top of buildings and vegetation have been generated. By this reason different accuracy has to be expected for open area and forest or cities. Much more importantly, some regions have missing data because of a lack of contrast in the radar image, presence of water, or excessive atmospheric interference. These missing data are especially along rivers, lakes, and steep regions (often on hillsides with a similar aspect due to shadowing). This non-random distribution of the void (missing data), impedes the potential use of SRTM data, and has been subject of a number of algorithms for “filling-in” the voids through various spatial analysis techniques. These include spatial filters, iterative void filling, and interpolation techniques, many of which are still under development and testing.

Although SRTM data produced a number of voids due to lack of contrast in the radar image, a methodology based on spatial filtering was developed to correct this phenomenon (Dowding et al. , 2004; Jarvis et al., 2004). The final seamless data set with voids filled in is available at the website of Consultative Group for International Agriculture Research Consortium for Spatial Information (CGIAR-CSI) via http://srtm.csi.cgiar.org/. However, the accuracy of this product is yet to be assessed. Partial assessment of its accuracy was done by the Centro Internacional de Agricultura Tropical (CIAT) in South America to verify performance of the developed DEM (Jarvis et al., 2004), but global user community would gain more benefits from other regional assessments.

Given the demand for a product such as the SRTM DEM, it is important to examine carefully the quality of the dataset (Smith and Sandwell, 2003; Rabus et al., 2003; Falorni et al., 2005; Kobrick, 2006; Grohman et al., 2006), comparing it with alternative sources of terrain elevation data. In several papers, the accuracy of SRTM X- and C-band DEMs was checked against topographic maps and ground control points measured by differential GPS, (Kocak et al., 2005; Gorokhovic and Voustianiouk, 2006; Hancock et al., 2006; Gorokhovich et al., 2006). Also, Ojigi et al., (2010) attempts a 3-D data validation of the SRTM in Lokoja area of Nigeria with conventional ground survey-based topographic data in order to establish a geospatial resemblance ratio between the two dataset. But the paper has failed to reconcile the different height system between the dataset, it is impossible to obtain the same height by mere super-imposing the two dataset over each other. This however calls for careful and quality approaches on validating the SRTM dataset. Hence, this study will attempt to present the result of an experiment to validate the quality of SRTM DEM data for Zaria and its environs through comparison with GPS Points and topographic DEM. The objectives include; to obtain SRTM DEM data and process it, digitize topographic DEM, extraction of spot heights from the both dataset, GPS observation for ground truthing, process spot height into contour map, superimpose the maps, estimate some topographic attributes e.g. Slope, Elevation, Aspect, e.t.c and perform quantitative analysis using statistical techniques.

Study Area

The scope of this research work covers some areas within the Northern part of Nigeria. The study site is bounded by longitude 07°E to 08°E of the Greenwich Meridian and latitude 10°30'N to 11°30'N of the Equator which form a composite map with standard map sheet name and number: Maska; 101, Zaria; 102, Kaduna; 123, Igabi; 124 (see Figure 1) each at a scale of 1:100,000 with an area of 11,664sqkm. Zaria was chosen as the test site for GPS data Point observations (Figure 2).

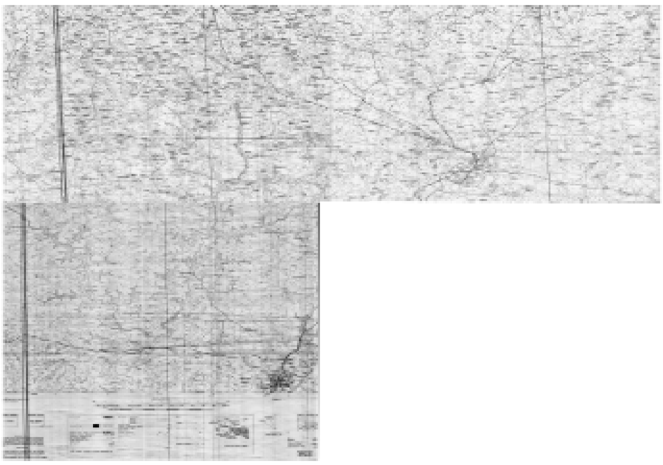

Figure 1: Topographic Map of the Study Area

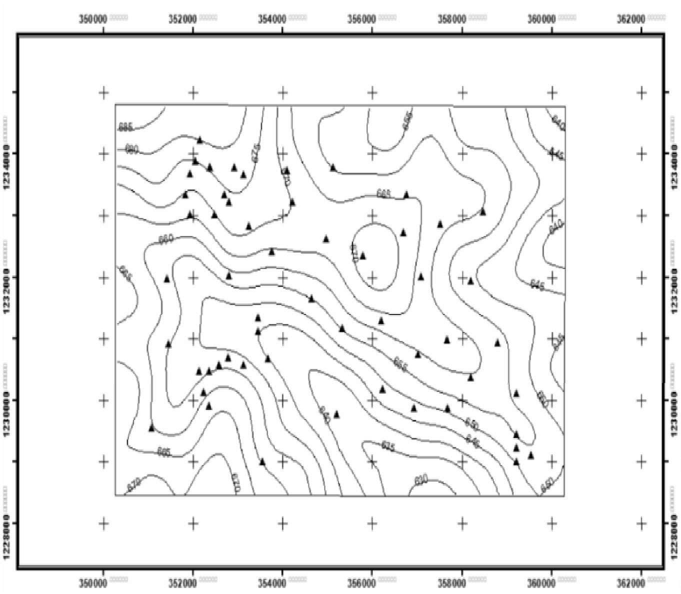

Figure 2: GPS data points over the test site

Materials and Methods

With reference to the schematic diagram (Figure 3), this study comprises four main tasks. The first task is to acquire experimental data; the second task is data processing; the third task is to compare the data and the fourth include analysis and data presentation.

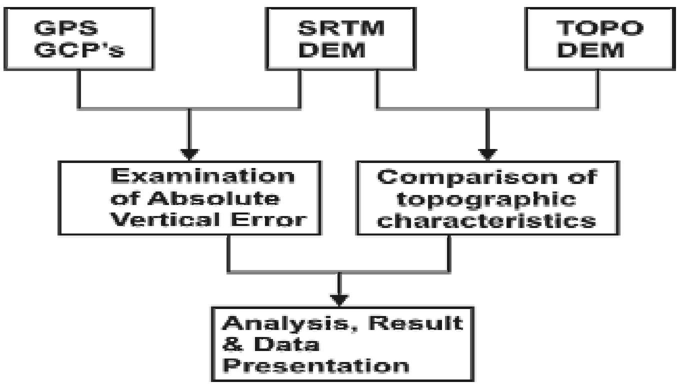

Figure 3: Schematic Diagram of Methodology

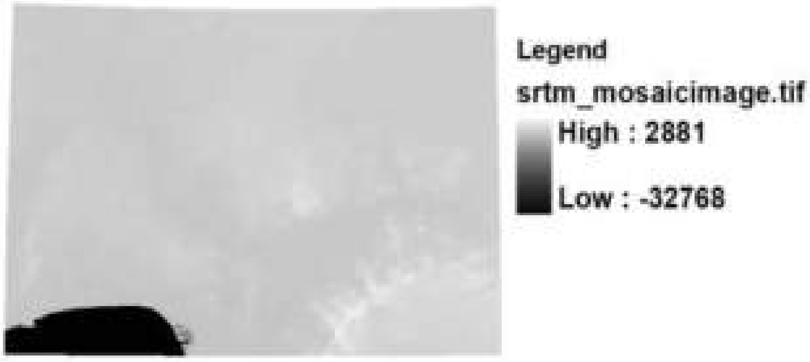

Figure 4: SRTM Mosaic image.tiff

Data description and data acquisition

Shuttle Radar Topographic Mission (SRTM)

Although SRTM data produced a number of voids due to lack of contrast in the radar image, a methodology based on spatial filtering was developed to correct this phenomenon (Dowding et al., 2004; Jarvis et al., 2004). The final seamless data set with voids filled in is available at the website of Consultative Group for International Agriculture Research Consortium for Spatial Information (CGIAR-CSI) via http://srtm.csi.cgiar.org/. SRTM DEM data covering the study area of interest was downloaded from the seamless dataset website of CGIAR-CSI. The downloaded data mosaicked (Figure 4.0) and masked (Figure 5.0) then projected from geographical to Universal Traverse Mercator (UTM) Zone 32N in WGS 84 Datum for absolute vertical error assessment in comparison with GPS Points and then, also reprojected to Universal Traverse Mercator (UTM Zone 32N) coordinate system in Minna Datum for the comparison of topographic characteristics (i.e. relative altitude, slope and aspect) with the topographic map.

SRTM DEM data was converted from raster into a regular polygon dataset with attribute table storing elevation values using the 3D analyst module in ArcInfo 9.2. Thus, each polygon replicated raster pixel (Figure 6.0). These polygon data was used to find the conjugate GPS Points on the SRTM for absolute vertical assessment. From the SRTM DEM data topographic characteristics such as Slope map (Figure 7.0), Aspect map (Figure 8.0) were also created using ArcInfo9.2 software with the 3D analyst module.

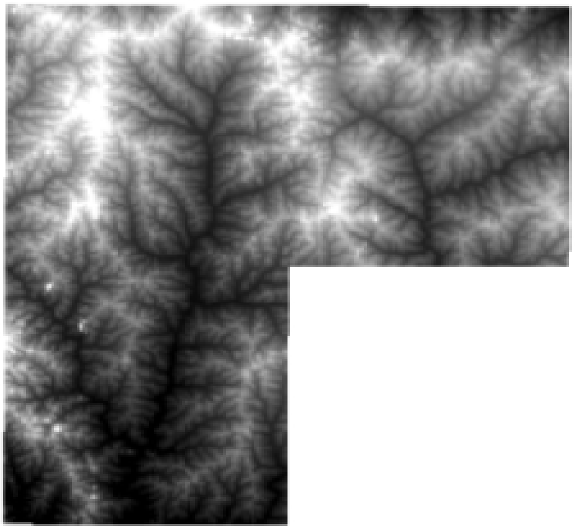

Figure 5.0: Masked SRTM DEM of the Area

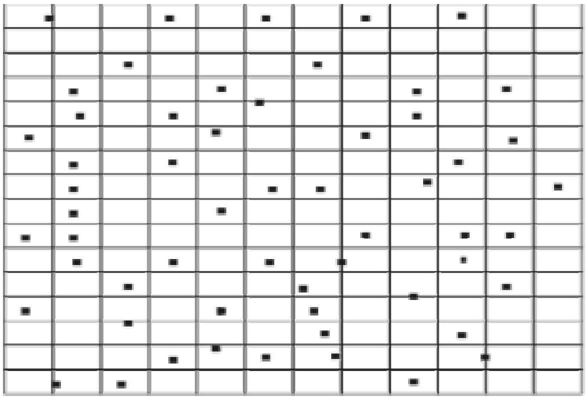

Figure 6.0: GPS data (points) and SRTM pixels (square)

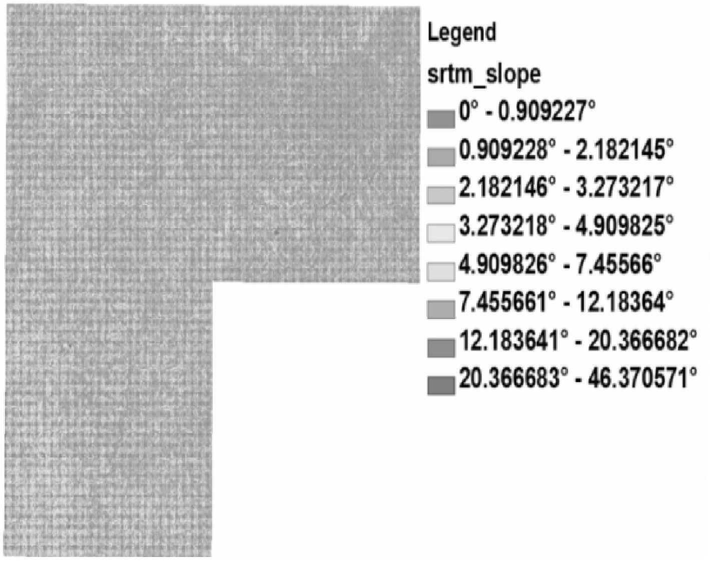

Figure 7.0: Slope map of SRTM

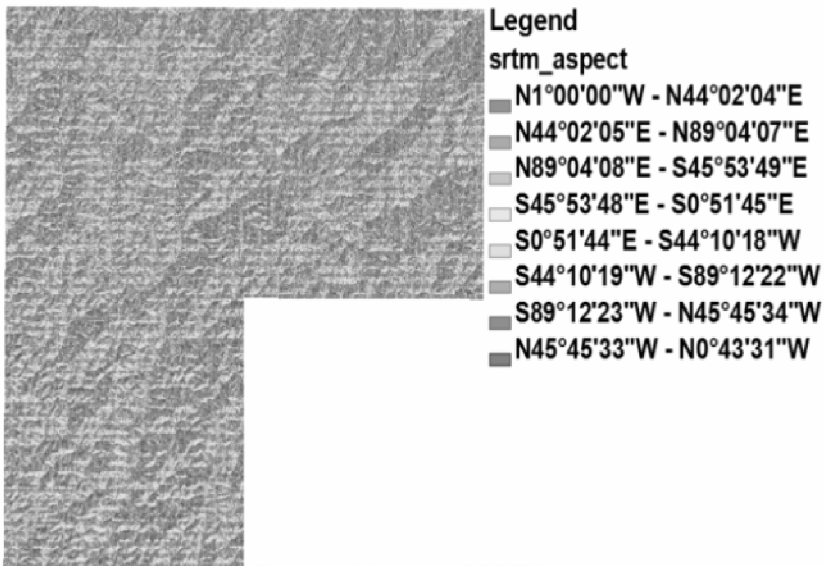

Figure 8.0: Aspect map of SRTM

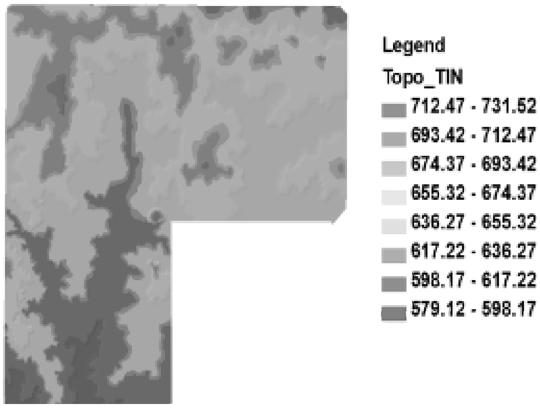

Figure 9.0: TIN map of the Topo Map

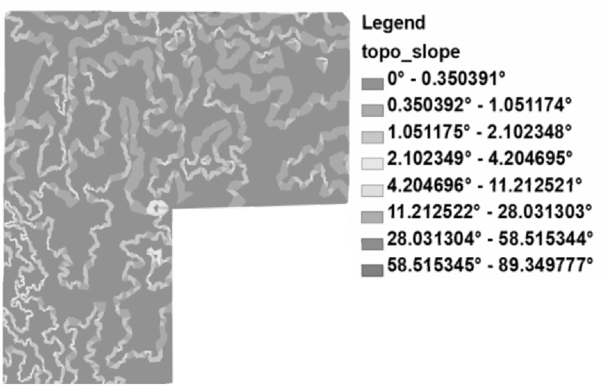

Figure 10.0: Slope map of the Topo Map SRTM

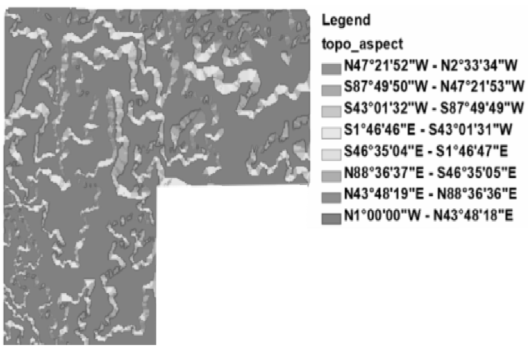

Figure 11.0: Aspect map of the Topo Map SRTM

Topographic Map DEM

Topographic maps (Figure 1.0) covering the area was acquired, mosaicked, vectorized and spot heights extracted. The extracted spot heights from the map in feet was converted to meter and the x,y coordinates projected to Universal Traverse Mercator projection (UTM Zone 32N) system using Minna Datum. The extracted x,y,z was imported into ArcGis 9.2 and used to create a Triangular Irregular Network TIN (Figure 9.0). Slope map (Figure 10.0) and Aspect map (Figure 11.0) were also created.

GPS Ground Control Points Observation

Among various methods of accuracy assessment, GPS survey provides the best way to map features on terrain with high accuracy. GPS Points Data was collected along roads and some locations with specific topographic characteristic (i.e. hill, mountain, water bodies, e.t.c). To establish Points over the study area, two highly accurate GPS reference points were used. The coordinates and heights of these two points was obtained from the Department of Geomatics Engineering, Ahmadu Bello University Zaria. One of the Points was used as base for the measurement of other 57 new Points using Global Positioning System (GPS) (Figure 2.0). The other point was used as a check point.

A pair of Sokkia Stratus GPS System was used for these measurements. When surveying with GPS, the highest possible accuracy of collected data is usually achieved by using a carrier- phase tracking mode (Blomenhofer et al., 1994; Farrell et al., 2003). This mode requires both receivers (remote and reference) to be close enough and maintain tracking carrier phases simultaneously. This limitation might slow down the process of data collection (if remote and reference devices get disconnected) and decrease battery life (waiting for establishing connection and phase carrier mode). Therefore, an alternative is to use post-processing of GPS data with available base station data. This method was used in present study.

Base station data are usually collected by a high end receiver that constantly logs coordinates of its own location and determines an error associated with the satellite position, atmospheric conditions, etc. The base station used in the survey was XSJ37 available at Ahmadu Bello University Zaria. Data from the base station and rover receiver were downloaded and then post-processed with Sokkia Survey 4.0 software.

GIS analysis

The fusion of SRTM-based elevation data from SRTM and GPS data required overlay of two different topological objects: raster pixels and point data. This required converting both data formats into one compatible form. In the present study, SRTM data were converted into a regular polygon dataset with attribute table storing elevation values. Thus, each polygon replicated raster pixel and was overlain with point data from GPS (Figure 6.0). This operation is also known as "spatial join" (Gorokhovich et al., 2006). It transfers attribute table values from polygons to underlying point data. Figure 6.0 shows an example of both datasets. Visualization of vertical errors in GIS revealed lack of uniform distribution of the errors across terrain. Greater error values were associated with rugged terrain, while smaller error values were associated with coastal plain, suggesting that such terrain characteristics as slope and aspect can influence SRTM accuracy. Slope and Aspect grid created as shown above for both topographic map and SRTM data were overlaid. All data with their respective attributes were organized in a spreadsheet table for subsequent statistical analysis (Appendixes A & B).

SRTM data and it conjugate GPS Points were imported into ArcInfo 9.2 as a dbase file and with the 3D Analyst module the contours were produced (Figures 12, 13, and 14) at 5m, 15m and 30m contour interval corresponding to topographic map scale of 1:25000, 1:50000 and 1:100000 respectively. The two dataset in the same height system (ellipsoidal height) were overlaid for the purpose of comparing the contour values over the area.

Statistical analysis

The main goal of statistical analysis was to answer the following questions:

1. Does absolute vertical accuracy of SRTM data exceed the 16 m value specified for the original SRTM dataset?
2. How does slope and aspect influence SRTM data accuracy?
3. How does interpolation of SRTM DEM affect its representation of the earth terrain?

To address these questions, the magnitude of absolute errors in SRTM data was examined. "Errors" were operationally defined as discrepancies between elevation from SRTM data and corresponding GPS measurements which we assumed to be accurate and, thus, used them as reference values. Also analysis was made on the magnitude of absolute errors in the SRTM data with respect to slope and aspect characteristics of the landscape. To this effect, student-t test analysis was conducted on SRTM and GPS data. The same was done on SRTM and TOPO data. All analyses were performed using SPSS statistical package (ver. 16.0, SPSS Inc., Chicago, IL). In all tests, results with probability values less than 0.05 were considered statistically significant. Presented data are shown as mean ± S. E.M. (standard error of the mean), unless otherwise noted.

Results and Discussion

SRTM Data Accuracy

Tables 1.0 show descriptive statistics for SRTM and GPS data for Zaria area. Tables 2.0 show descriptive statistics for relative altitudinal differences for SRTM and TOPO data for the whole study area. Results of the t-tests statistically indicates that there no significant differences between data obtained by the STRM and GPS Measurement in the study area. Table 3.0 summarizes discrepancies between SRTM and GPS measurements. Average absolute error of SRTM data was found to be 5.586 ± 1.001m (Zaria). Table 4.0 shows the discrepancies between TOPO and GPS data measurements. Average absolute error of TOPO data was found to be 1.398 ± 0.453m. Also Table 5.0 summarizes discrepancies between SRTM and TOPO measurements, where average absolute error of SRTM data was found to be 6.755 ± 0.801m.

Table 1: Analysis of SRTM and GPS data for Zaria study area

Statistical parameters	SRTM data	GPS data
Mean	6.661	6.693
S.E.M	1.461	1.746
Minimum	642.00	643.50
Maximum	680.00	696.70
Count	58	58
p Value (independent measures t-test: SRTM vs. GPS) 0.81		

Table 2: Analysis of SRTM and TOPO data for whole study area

Statistical parameters	SRTM data	TOPO data
Mean	49.907	53.122
S.E.M	6.046	6.433
Minimum	1.00	0.93
Maximum	139.00	152.40
Count	54	54

Table 3: Analysis of discrepancies (absolute values) betweeen GPS and SRTM data for Zaria study area

Statistical parameters	Zaria area
Mean	5.586
S.E.M	1.001
Minimum	0
Maximum	42
Count	58
p Value (independent measures t-test: SRTM vs.16)	<0.0001

Table 4: Analysis of discrepancies (absolute values) betweeen GPS and TOPO data for Zaria study area

Statistical parameters	Study area
Mean	1.398
S.E.M	0.453
Minimum	0.2
Maximum	2.74
Count	6
p Value (independent measures t-test: SRTM vs.TOPO)	<0.027

Table 5: Analysis of relative altitudinal discrepancies (absolute values) between SRTM and TOPO data for whole study area

Statistical parameters	Study area
Mean	6.755
S.E.M	0.801
Minimum	0.15
Maximum	29.44
Count	57
p Value (independent measures t-test: SRTM vs.16)	<0.0001

The effect of interpolating SRTM DEM at contour interval less than its spatial resolution (i.e. 90x90 cell size).

Figure 12.0 show overlaid contour of SRTM and GPS Points at 5m contour interval. It reveals that height information at certain location are unknown. This account for the crossing of the contour lines. Figure 13.0 show that 15m contour interval has a better result than the 5m contour interval. Figure 14.0 show a trend of better output as the interval increase to 30m. Table 6.0 gives a statistical report on the relationship between the various contour maps at different contour intervals.

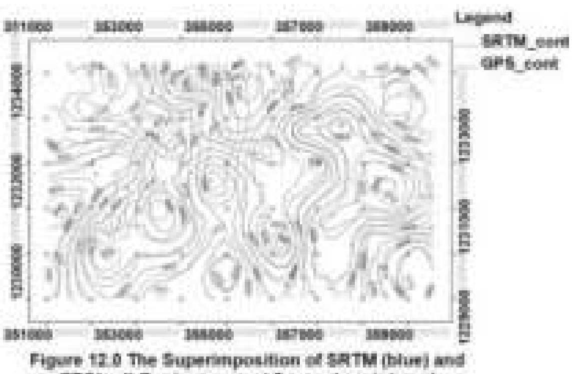

Figure 12.0 The Superimposition of SRTM (blue) and GPS(red) Contour map at 5m contour interval

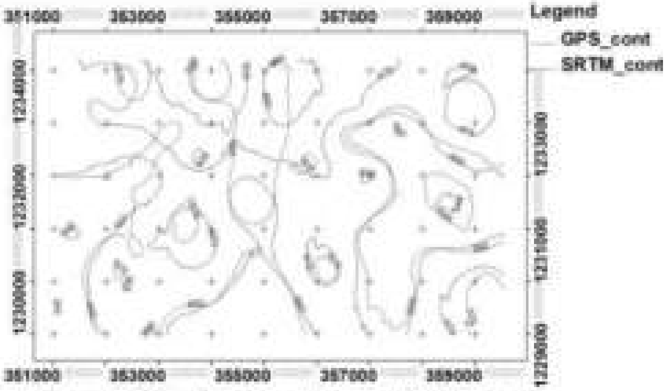

Figure 13.0 The Superimposition of SRTM (blue) and GPS(red) Contour map at 15m contour interval

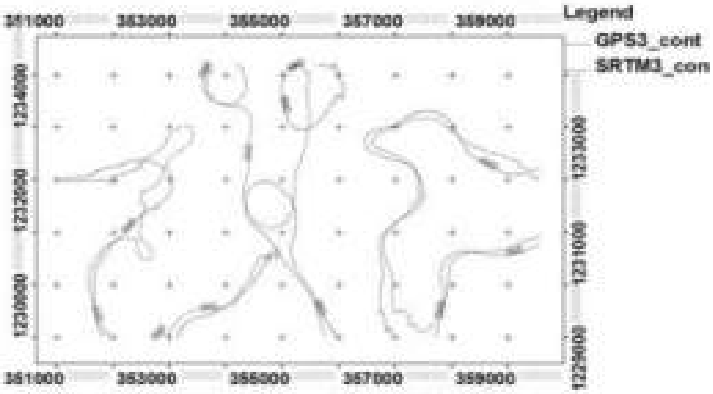

Figure 14.0 The Superimposition of SRTM (blue) and GPS(red) Contour map at 30m contour interval

Table 6.0: Relationship between the various contour maps at different contour intervals

S/No.	Data Source	Contour Interval	Pearson's product moment Correlation coefficient	Independence measure t-test at 99% C.I
1.0	GPS/SRTM	5m	0.110	0.314
2.0	GPS/SRTM	15m	0.350	0.550
3.0	GPS/SRTM	30m	0.580	0.002

The influence Slope and aspect on SRTM data accuracy´

Analysis revealed significant decrease in accuracy of SRTM data when measurements were performed on terrain characterized by slope values greater than 10° (Table 7.0). Indeed, the average magnitude of errors is more than ten times higher for terrains with slope values exceeding 10° compared to areas where slope values are less than 10° in the study area (3.862 ± 2.444m vs. 40.564 ± 2.415m, $p < 0.001$). Aspect of the terrain was classified into 8 classes and found to have influence on both the magnitude and the sign of errors in the SRTM data.

Table 7.0: Analysis of discrepancies (absolute values) between SRTM and TOPO data for terrain with slope values less and greater than 10° in the whole study area

Slope	≤10°	>10°
Mean	3.862	40.564
S.E.M	2.444	2.415
Minimum	0.56	38.15
Maximum	15.85	42.98
Count	6	2
p Value (independent measures t-test, slope ≤10° vs. slope>10°)	<0.001	<0.001

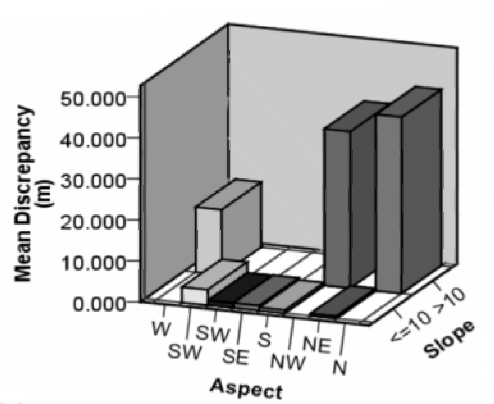

Fig. 15.0 Discrepancy between SRTM and TOPO data as a funtion of slope and aspect characteristics of the terrain; study area

The highest magnitude of errors was observed for measurements made on slopes facing north (N) and north west (NW). Correspondingly, SRTM measurements underestimated elevations of slopes facing NW and overestimated elevations of slopes facing N (Figure 15.0). These differences (SRTM data overestimate for north-facing slopes and underestimate for northwest-facing slopes) correlate to the shuttle flight path directions.

Conclusion and Recommendations
Conclusion

In this study, the quality of the DEM acquired by the Shuttle Radar Topography Mission (SRTM) was evaluated through comparison with GPS readings and cartographically derived DEMs. Comparison was carried out analyzing the difference in elevation, relative altitudinal differences and slope angle. Analyses presented in this project indicate the following:

Absolute vertical accuracy of CGIAR-CSI SRTM data for our datasets proved to be more than two times higher than the value of 16m presented in the original SRTM requirement specification.

Both slope and aspect characteristics of the terrain have significant impact on accuracy of SRTM data. Accuracy particularly suffers on terrains with slope values higher than 10°. Aspect of the terrain influences both the magnitude and the sign of errors in the SRTM data. SRTM data underestimate elevations of slopes facing NW and overestimate elevations of slopes facing N, but the errors are significant only on terrains with slope values exceeding 10°. Quality of collected SRTM data also depends on incidence angles that affect differential distances for ground targets and the accuracy of original data (Jarvis et al., 2004). These angles could be potentially taken into account in studies that use original SRTM data.

Role of vegetation was not fully assessed in this study. It is assumed that in the study area vegetation covers uniformly (height and density) 90 × 90m square (pixel size of CGIAR-CSI SRTM product). In this case, the associated error would be constant.

The results of accuracy assessment also depend on the number of GPS observations per one spatial unit of SRTM data (i.e. 90m). The more GPS readings would be available, the more accurate the final estimation will be. However, implementation of this approach requires special planning of GPS surveys and considerable additional resources, and was not within the scope of the present study.

SRTM DEM show good result as revealed by comparison with field-based measurement of GPS points. The SRTM DEM has an average error of 5.586 ± 1.001m. However, some systematic errors were identified in the SRTM data, related to aspect. The errors are found to be higher in north-facing slopes. This can be attributed to the effect of incidence angle of the original radar images used to produce the SRTM DEM. The result of the contour created from SRTM and GPS Points show that SRTM-3 can give a good representation of the earth terrain at contour interval greater than 15m (Figure 6.0). Finally, the SRTM DEM was found to contain more surface detail and roughness than the TOPO DEM.

Recommendations

The following recommendations are hereby made:

(a). Call on the relevant mapping authorities to create a national elevation database for the country.

(b). Re-defining current height system in Nigeria to enhance capability with systems in use for global elevation datasets.

(c). Although, the SRTM data should be compared with more other DEM data sources (i.e. GTOPO30, GLOBE, ASTER DEM, Altimeter data height, Leica Virtual Explorer etc.) and more analysis should be made to validate SRTM data at different areas.

(d). In view of the results obtained in this study, it is further recommended that the SRTM data be used for refining the gravimetric geoid solution computed for the country by Ezeigbo, et al., (2006). It may be used to compute terrain corrections for the computed model as it will certainly improve the accuracy of the model.

(e). SRTM data should be used on the study area (Zaria) and elsewhere upon proper validation as supplementary data for small-scale map such as Geological map.

(f). Efforts should be put at developing mathematical models that will enable accuracy modeling of SRTM data errors (especially at high undulating terrain regions across the country).

(g). African Geoid Project set up by IAG Committee for Developing Countries, now a project of Commission on Gravity should utilize the advantage of SRTM to meet the need for unified vertical reference frame for Africa to support economic development.

Acknowledgement

This work is supported in part by the Surveyors Registration Council of Nigeria (SURCON) through undergraduate final project sub-grant. This work is also supported by Arinmap Consultant in Abuja, Nigeria. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s).

References

Blomenhofer, H., Hein, G., Blomenhofer, E., and Werner, W. (1994). *Development of a Real-Time DGPS System in the Centimeter Range, IEEE 1994, Position, Location, and Navigation Symposium, Las Vegas NV* (pp. 532–539).

Burrough, P.A. and McDonnell, R.A. (1998). Principles of Geographical Information Systems. 2nd Edition, Oxford University Press.

Dowding, S., Kuuskivi, T. , and Li, X. (2004). Void fill of SRTM elevation data principles, processes and performance. *Proceedings of the conference " ASPRS Images to Decision: Remote Sensing Foundation for GI S Applications" , Kansas City, MO, September 12–16.*

Evans, I. (1980). An integrated system of terrain analysis and slope mapping. *Z. fur Geomorphology*, Suppl. 36, 274- 295.

Ezeigbo, C. U., Fajemirokun, F.A., and Nwilo, P. C. (2006). Determination of an optimum geoid for Nigeria. *A report submitted to National Space Research and Development Agency (NASRDA) Federal Ministry of Science and Technology, Abuja, Nigeria.*

Falorni, G., Teles, V., Vivoni, E. R., Bras, R. L. and Amaratunga, K., (2005), Analysis and characterization of the vertical accuracy of digital elevation models from the Shuttle Radar Topography Mission, *Journal of Geophysical Research - Earth Surface,* 110, 1-20.

Farrell, J. A., Tan, H. -S., and Yang, Y. (2003). Carrier phase GPS-aided INS- based vehicle lateral control. *Journal of Dynamic Systems, Measurement, and Control,* 125(3), 339- 353.

Featherstone, W.E., and Kirby, J.F. (2000). The reduction of aliasing in gravity anomalies and geoid heights using digital terrain data, Geophys. J. Int., 141, 204- 214.

Foni, A., and Seal, D. (2004). Shuttle Radar Topography Mission: an innovative approach to shuttle orbital control. *Acta Astronautica* **54**: 565–570.

Gorokhovich, Y., and Voustianiouk, A. (2006). Accuracy assessment of the processed SRTM-based elevation data by CGIAR using field data from USA and Thailand and its relation to the terrain characteristics, Remote Sensing of Environment, 104 (4), 409-415.

Grohman, G., Kroenung, G. and Strebeck, J. (2006). Filling SRTM voids: the Delta Surface Fill Method. Photogramm. *Eng. Remote Sens,* March, p.213-216.

Hancock, G. R., Martinez, C. K., Evans, G., and Moliere, D. R. (2006). A comparison of SRTM and high-resolution digital elevation models and their use in catchment geomorphology and hydrology: Australian examples. *Earth Surf. Process. Landforms* 31, 1394–1412.

Hohle, J. (1996). Experience with the production of digital orthophotos. Photogramm. Eng. Remote Sens, 62(10), 1189-1194.

Jarvis, A., Rubiano, J., Nelson, A., Farrow, A., and Mulligan, M. (2004). Practical use of SRTM data in the tropics—comparisons with digital elevation models generated from cartographic data. *Working Document, Vol. 198*. Centro Internacional de Agricultura Tropical (C IAT) 32 pp .

Kaab A. (2005). Combination of SRTM3 and repeat ASTER data for deriving alpine glacier flow velocities in the Bhutan Himalaya. *Remote Sensing of Environment,* 94, 463–474.

Kellndorfer, J. , Walker, W., Pierce, L., Dobson, C., Fites, J . A., Hunsaker, C., et al. (2004) . Vegetation height estimation from shuttle radar topography mission and national elevation data sets . *Remote Sensing of Environment*, 93,339-358.

Kobrick, M. (2006). On the toes of Giants – How SRTM was born. Photogramm. *Eng. Remote Sens,* 72, 206-210.

Kocak, G., Buyuksalih, G., and Oruc, M. (2005). Accuracy assessment of interferometric digital elevation models derived from the Shuttle Radar Topography Mission X- and C-band data in a test area with rolling topography and moderate forest cover, *Optical Engineering*, 44(3), 1-7.

Miliaresis, G.C., and Paraschou, C.V.E. (2005). Vertical accuracy of the SRTM DTED level 1 of Crete. *International Journal of Applied Earth Observation and Geoinformation* 7: 49–59.

Ojigi, M.L. and Dang, B.A. (2010). 3-Dimensional Data Validation of Shuttle Radar Topographic Mission (SRTM) in Lokoja Area of Nigeria. *Nigerian Journal of Surveying and Geoinformatics,* 3(1), 67-85.

Rabus B, Eineder M, Roth A, Bamler R. (2003). The shuttle radar topography mission – a new class of digital elevation models acquired by spaceborne radar. *ISPRS Journal of Photogrammetry and Remote Sensing* 57: 241–262.

Smith, B. and Sandwell, D. (2003). Accuracy and resolution of shuttle radar topography mission data. *Geophysical Research Letters*, 30(9), 1467.

Van Zyl, J.J. (2001). The Shuttle Radar Topography Mission (SRTM): a breakthrough in remote sensing of topography. *Acta Astonautica* 48(5– 12): 559–565.

APENDIXES A: GPS data and it corresponding SRTM points

	GPS Points				Corresponding SRTM Points		
S/No.	X	Y	H		X	Y	H
1	352366.38848	1233786.07357	673.907		352366.38848	1233786.07357	678
2	352366.38848	1233786.07357	673.493		352366.38848	1233786.07357	676
3	352039.24856	1233898.16270	671.318		352039.24856	1233898.16270	671
4	351929.02018	1233677.48099	671.270		351929.02018	1233677.48099	666
5	351818.28360	1233346.20854	676.383		351818.28360	1233346.20854	675
6	351925.98146	1233013.93546	676.069		351925.98146	1233013.93546	671
7	352472.07156	1233011.43991	675.882		352472.07156	1233011.43991	669
8	352800.73185	1233231.12814	675.875		352800.73185	1233231.12814	673
9	352692.01861	1233342.21611	676.365		352692.01861	1233342.21611	674
10	352912.46465	1233783.58391	676.324		352912.46465	1233783.58391	674
11	352149.98161	1234229.43553	676.744		352149.98161	1234229.43553	675
12	352366.38848	1233786.07357	674.974		352366.38848	1233786.07357	675
13	354220.54987	1233224.69619	670.355		354220.54987	1233224.69619	665
14	353130.39233	1233672.00016	673.790		353130.39233	1233672.00016	670
15	352570.21059	1230577.94940	669.338		352570.21059	1230577.94940	654
16	352351.25451	1230468.35334	669.218		352351.25451	1230468.35334	670
17	352132.80134	1230469.34924	671.149		352132.80134	1230469.34924	675

18	352240.51565	1230137.07930	673.328		352240.51565	1230137.07930	676
19	352348.73610	1229915.40058	675.471		352348.73610	1229915.40058	674
20	353447.51979	1231348.11734	674.982		353447.51979	1231348.11734	676
21	359231.00409	1230105.97290	681.672		359231.00409	1230105.97290	677
22	359228.12383	1229442.44541	684.548		359228.12383	1229442.44541	678
23	359227.16408	1229221.26964	682.999		359227.16408	1229221.26964	676
24	359227.16408	1229221.26964	680.402		359227.16408	1229221.26964	677
25	359226.20451	1229000.09390	683.693		359226.20451	1229000.09390	680
26	359554.36940	1229109.26175	679.094		359554.36940	1229109.26175	678
27	353446.51904	1231126.93695	682.631		353446.51904	1231126.93695	678
28	353662.96874	1230683.58903	683.392		353662.96874	1230683.58903	674
29	352789.16504	1230687.54677	675.059		352789.16504	1230687.54677	666
30	353116.34049	1230575.46957	673.664		353116.34049	1230575.46957	672
31	358196.54355	1230363.31540	667.815		358196.54355	1230363.31540	669
32	356205.93411	1231285.43595	673.102		356205.93411	1231285.43595	671
33	357084.14415	1232002.64082	675.410		357084.14415	1232002.64082	670
34	358474.64339	1233071.12971	676.658		358474.64339	1233071.12971	670
35	356762.13380	1233349.22955	678.028		356762.13380	1233349.22955	674
36	355796.10275	1232353.92484	678.620		355796.10275	1232353.92484	677
37	353746.94598	1232412.47217	681.848		353746.94598	1232412.47217	678
38	356235.20778	1230187.67339	682.812		356235.20778	1230187.67339	679
39	357669.61752	1230992.69927	647.995		357669.61752	1230992.69927	653

40	354639.79286	1231651.35680	649.267		354639.79286	1231651.35680	651
41	355210.62939	1229763.20520	648.491		355210.62939	1229763.20520	653
42	356937.77581	1229865.66304	652.564		356937.77581	1229865.66304	660
43	355327.72406	1231168.34127	662.419		355327.72406	1231168.34127	665
44	352795.55177	1232031.91449	650.503		352795.55177	1232031.91449	659
45	351448.96303	1230919.51510	643.835		351448.96303	1230919.51510	645
46	351068.40534	1229543.65269	644.183		351068.40534	1229543.65269	644
47	353542.03030	1229002.08983	655.757		353542.03030	1229002.08983	654
48	351419.68936	1231973.36715	658.130		351419.68936	1231973.36715	660
49	353234.65679	1232822.30353	684.160		353234.65679	1232822.30353	655
50	355122.80839	1233788.33458	696.705		355122.80839	1233788.33458	655
51	354976.44005	1232617.38785	681.637		354976.44005	1232617.38785	647
52	356688.94963	1232734.48252	655.701		356688.94963	1232734.48252	652
53	358196.54355	1231944.09348	647.247		358196.54355	1231944.09348	642
54	358796.65374	1230934.15193	648.777		358796.65374	1230934.15193	645
55	357010.95998	1230743.87309	650.200		357010.95998	1230743.87309	654
56	357684.25435	1229865.66304	653.151		357684.25435	1229865.66304	656
57	354098.23000	1233729.78724	647.953		354098.23000	1233729.78724	652
58	357523.24918	1232866.21403	643.498		357523.24918	1232866.21403	653

APENDIXES B: RELATIVE ALTITUDINAL DISCREPANCIES

S/No.	SRTM Relative Height Diff (m)	Topo_Map Relative Height Diff (m)	S/No.	SRTM Relative Height Diff (m)	Topo_Map Relative Height Diff (m)
1	28.00	30.48	29	69.00	60.96
2	112.00	121.92	30	128.00	152.40
3	88.00	91.44	31	62.00	91.44
4	45.00	30.48	32	36.00	30.48
5	23.00	30.48	33	89.00	91.44
6	118.00	121.92	34	127.00	121.92
7	139.00	152.40	35	66.00	60.96
8	117.00	121.92	36	26.00	30.48
9	88.00	91.44	37	49.00	60.96
10	115.00	121.92	38	22.00	30.48
11	92.00	91.44	39	117.00	121.92
12	35.00	30.48	40	19.00	14.01
13	54.00	60.96	41	9.00	10.65

14	136.00	152.40	42	27.00	21.45
15	77.00	91.44	43	5.00	6.95
16	34.00	30.48	44	4.00	1.93
17	34.00	30.48	45	3.00	5.58
18	93.00	91.44	46	1.00	5.40
19	56.00	60.96	47	6.00	0.93
20	20.00	30.48	48	2.00	13.47
21	59.00	60.96	49	9.00	14.65
22	38.00	30.48	50	5.00	2.31
23	14.00	30.48	51	3.00	5.32
24	119.00	121.92	52	2.00	3.02
25	58.00	60.96	53	6.00	2.70
26	2.00	4.16	54	2.00	1.85
27	49.00	60.96	55	6.00	6.88
28	88.00	91.44	56	1.00	4.11
			57	22.00	30.48