ASSESSMENT OF CLASSICAL, ASTER AND SRTM DEMs IN NAIROBI REGION, KENYA

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Abstract
A digital elevation model (DEM) is a 3-D representation of the earth's topography. Vertical accuracy of a global digital elevation model (GDEM) is necessary for optimal application of satellite-based terrain elevation datasets. This study carries out an assessment of the vertical accuracy of Classical, ASTER (30 m) and SRTM (90 m) digital elevation models (DEMs) which are normally used for reconnaissance surveys, hydrological analysis, biomass estimation and geoid modelling among others. Classical DEMs are drawn from regional topographical maps while ASTER and SRTM DEMs are obtained from satellite-based remote sensing missions. The assessment is carried out by comparing orthometric heights from precise levelling at 18 points and heights derived from the DEMs over Nairobi County and its environs. The study found that the mean and standard deviation of the direct differences between precisely levelled heights and DEM heights are: 3.97 m and ±7.76 m respectively for classical DEM; 16.36 m and ±7.79 m respectively for ASTER DEM and -0.25 m and ±4.00 m respectively for SRTM DEM. The results indicate that SRTM DEM is the most accurate followed by the classical and ASTER DEMs in that order. We then modelled the differences between the DEM heights and the orthometric heights using a second order surface polynomial at 12 points; the polynomial was then applied to 6 test points in a cross-validation manner. The results from the polynomial improved accuracy of height determination in SRTM DEM but degraded accuracies in the classical and ASTER DEMs.

Key words: ASTER DEM, SRTM DEM, Classical DEM, GPS, orthometric height, second order surface polynomial

1.0 Introduction

Digital elevation models (DEMs) are numerical representations of topography. Some of their major applications include: digital surface modeling, 3-D visualization of terrain, hydrology, run-off analysis and project feasibility studies among many others. Vertical accuracy assessments of Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) and Shuttle Radar Topographic Mission (SRTM) digital elevation models (DEMs) have been done in various countries over the world (Nikolakopoulos et al., 2006; Gorokhovich and Voustianiouk, 2006; ASTER GDEM Validation Team, 2009; Sertel, 2010; Zhao et al., 2011; Ioannidis et al., 2014; Kolecka and Kozak, 2014). The vertical accuracies of ASTER and SRTM DEMs in Kenya are not known, hence the need for this study. The choice for their application is normally based on the spatial resolution, which may not necessarily indicate vertical accuracy in a rigorous sense. ASTER and SRTM DEMs data require regional studies involving ground truthing data as control to evaluate their accuracies (e.g., Gorokhovic and Voustianiouk, 2006). Classical DEMs are derived from digitized contours of regional topographical maps while ASTER and SRTM DEMs are generated from data collected from ASTER and SRTM space missions respectively. The spatial resolutions for these satellite-based DEMs are 30 m × 30 m and 90 m × 90 m for ASTER and SRTM respectively.

Some of the countries where accuracy assessment of global DEMs has been done include: Japan, China, Poland and Turkey. In the case study of Japan, ASTER DEM's vertical accuracy was compared to over 13,000 benchmarks scattered throughout the country; there was a consistent negative bias on ASTER DEM's heights; the result was a RMSE of ±10.87 m (ASTER GDEM Validation Team, 2009). In the case study of China, the study area was Loess plateau which has a varying terrain and North China plains which are flat; in both cases the GCPs (ground control points) were compared to corresponding heights from both ASTER and SRTM DEMs. The conclusion was that SRTM DEM was better than ASTER DEM; however, for both DEMs the approximation of height on rugged terrain had a larger error margin; the RMSE for SRTM DEM was ±2.22 m while for ASTER it was ±7.95 m (Zhao et al., 2011). In the case study of Turkey, the study area was Istanbul, which has a wide range of topographic variations covering coastal, mountainous and heavily built up areas; the comparison was done between a highly accurate locally available DEM constructed from aerial photos with that of ASTER DEM; a RMSE value of ±20 m was obtained (Sertel, 2010). In the case study of Poland, the study area was the Tatra Polish Mountains which has extremely rugged terrain; a highly accurate DEM was compared to SRTM DEM; a RMSE value of ±14.74 m was obtained (Kolecka and Kozak, 2014).

This study seeks to compare precisely levelled orthometric height data with that estimated from Classical, ASTER and SRTM DEMs over Nairobi region. The differences between precise levelled orthometric heights and DEMs derived orthometric heights are modeled using a second order surface polynomial to provide corrections for the DEMs heights. It concludes by describing relevant applications for the DEMs considered in the current study.

2.0 Materials and Methods

2.1 Ground Control Points

Eighteen (18) Ground Control Points (GCPs) have been used for the assessment of the three DEMs; their positions are described by ellipsoidal curvilinear coordinates (ϕ, λ) determined using Global Positioning System (GPS) and orthometric heights (H) determined by spirit levelling over Nairobi region. Theoretically, DEMs should accurately approximate orthometric heights; however, this is normally not the case, which means DEMs have errors. Orthometric heights are displacements along curved trajectories called plumb lines that are orthogonal to the geoid, they accurately represent potential (Torge, 2001; Hofmann-Wellenhof and Moritz, 2005). The flow of fluids is mostly governed by potential; hence orthometric heights are the most useful heights for engineering works. Details on orthometric height systems can be found in Odera et al., 2014 and Odera and Fukuda, 2015.

The study area is Nairobi region which covers Nairobi County and parts of Kiambu, Kajiado and Machakos Counties. Geographically it lies between latitudes 1˚ 25′ 30″ S and 1˚ 7′ 30″ S, and longitudes 36˚ 37′ 30″ E and 37˚ 1′ 30″ E, with an elevation difference of over 600 m; the choice of the study area was based on the availability of data (especially GPS/leveling data). Figure 1 shows the study area and the distribution of the GCPs on the World Geodetic System of 1984 (WGS84).

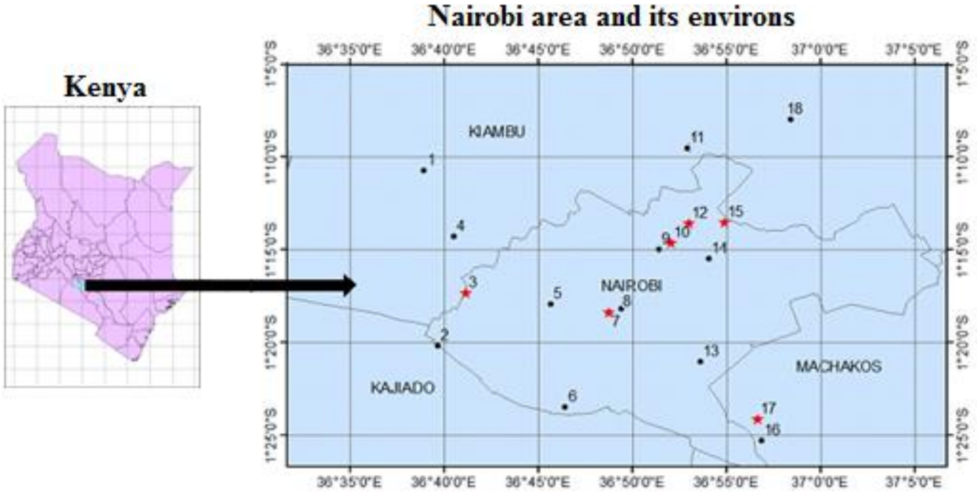

Fig. 1: Study area; black dots show the data points while the red stars show the test points

2.2 Digital Elevation Models

2.2.1 Classical DEMs

Classical DEMs are generated from digitizing contours from topographical maps. These contours constitute a huge bulk of readily available elevation data in Kenya. Topographical maps are plotted from countrywide aerial photogrammetric data obtained by aerial surveys. Such maps are published by the Survey of Kenya at varying scales.

2.2.2 Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER)

ASTER is a joint space mission between United States National Aeronautics and Space Administration (NASA) and the Japanese Ministry of Economy, Trade and Industry (METI) as part of the global earth observing system which includes digital elevation models (Yamaguchi et al., 1998). ASTER consists of multispectral sensors onboard the Terra Satellite which was designed as one of the most accurate satellites in terms of orbital geometry. Terra Satellite is near polar, sun synchronous; has an orbital altitude of 705 km, an inclination of 98.2˚ and a repeat cycle of 16 days; it uses a long track scan method to acquire data. ASTER acquires geospatial data by Thermal Remote Sensing; its multispectral sensors consists of visible near infrared (VNIR), shortwave infrared (SWIR) and thermal infrared (TIR) spectral bands; it's spatial resolution is 1″ or 30 m by 30 m, coverage between 83˚ N and 83˚ S and is available (Tighe, 2012).

2.2.3 Shuttle Radar Topographic Mission (SRTM)

SRTM is an international space mission by NASA, National Imagery and Mapping Agency (NIMA) and German space agency for global earth observation; it includes generation of digital elevation models. SRTM uses Interferometric Synthetic Aperture Radar (InSAR) technique to acquire geospatial data; the space shuttle carried two radar antennae combinations located in the shuttle's cargo bay and tip of a 60-meter-long mast; both for the C and X bands. SRTM initially covered a region of 60˚ N and 56˚ S which is about 80% of the earth's land mass. More information about SRTM can be found in Farr and Kobrick, 2001; Jordan et al., 1996 and Hensley et al., 2000 among others. We used a freely available SRTM 3″ which has a spatial resolution of 90 m by 90 m based on WGS84. We note the recently released SRTM (30 m) for our future studies.

2.3 Numerical Tests

Direct comparison between DEM and orthometric heights was done using equation (1).

$$\Delta H = H - H_{DEM}\,, \qquad (1)$$

where ΔH is the difference between orthometric height (H) and DEM height (H_{DEM}). The DEM heights are obtained from the DEMs (Classical, ASTER and SRTM) through interpolation, while the orthometric heights are obtained from spirit levelling at 18 ground control points (Figure 1).

The orthometric height differences in equation (1) are modelled using 2nd order surface polynomial (quadratic surface) to determine corrections to the estimated othometric heights (from DEMs) to obtain improved orthometric heights. To achieve this, the data points (18 GPS/levelling points) are divided into two: 12 points are used for the determination of the polynomial coefficients while 6 points are used for cross-validation (test points). The second order surface polynomial adopted in this study is given as,

$$\Delta H = k_O + k_1\phi + k_2\lambda + k_3\phi^2 + k_4\lambda^2 + k_5\phi\lambda + bias = Corr., \tag{2}$$

where k_O, k_1, k_2, k_3, k_4 and k_5 are coefficients of the second order surface polynomial, ϕ and λ are the geodetic latitude and longitude of the point respectively, $bias$ is the mean of the differences between the actual orthometric heights and estimated orthometric heights from DEMs. The correction ($Corr.$) is then added to orthometric height estimated from DEM to obtained an improved orthometric height ($H_{improved}$) as,

$$H_{improved} = H_{DEM} + Corr., \tag{3}$$

We then compare improved orthometric height and actual levelled orthometric height (H) as,

$$\delta H = H - H_{improved}. \tag{4}$$

3.0 Results and Discussion

3.1 Direct Comparison

The statistics of the direct differences between levelled orthometric heights and orthometric heights estimated from DEMs at eighteen points in the study area are given in Table 1. A graph of the differences is given in Figure 2. The mean, standard deviation (SD) and range are: 3.97 m, ±7.76 m and 32.25 m respectively for the classical DEM; -0.25 m, ±4.00 m and 14.35 m respectively for SRTM DEM; 16.36 m, ±7.79 m and 25.29 m respectively for ASTER DEM (Table 1). These results indicate that SRTM DEM (90 m spatial resolution) performs better than ASTER (30 m spatial resolution) in the area of study. The DEM developed from topographical map(s) performs practically the same as ASTER DEM in the area of study, although the range of the height differences is smaller in the ASTER DEM. It is worth mentioning that ASTER DEM has always been chosen for hydrologic work based on its small (30 m) spatial resolution but this study reveals that SRTM DEM (90 m) has a better vertical accuracy than ASTER DEM. The choice of a DEM should therefore be based on both spatial resolution and vertical accuracy.

Table 1: Statistics of the differences between levelled and DEM orthometric heights (units are in m)

Point	*Levelled Orthometric Height (H)*	H_{DEMC} *(Classical)*	H_{DEMS} *(SRTM)*	H_{DEMA} *(ASTER)*	ΔH_C *Classical*	ΔH_S *SRTM*	ΔH_A *ASTER*
1	2144.19	2139	2153	2130	5.19	-8.81	14.19
2	1934.59	1911	1935	1912	23.59	-0.41	22.59
3	1894.69	1892	1896	1871	2.69	-1.31	23.69
4	1996.13	1989	2000	1970	7.13	-3.87	26.13
5	1794.63	1785	1795	1779	9.63	-0.37	15.63
6	1716.20	1705	1717	1697	11.2	-0.8	19.2
7	1680.10	1684	1685	1663	-3.9	-4.9	17.1
8	1661.84	1668	1666	1644	-6.16	-4.16	17.84
9	1645.27	1633	1640	1617	12.27	5.27	28.27
10	1620.72	1621	1622	1611	-0.28	-1.28	9.72
11	1590.49	1587	1592	1581	3.49	-1.51	9.49
12	1611.34	1620	1615	1607	-8.66	-3.66	4.34
13	1636.67	1630	1636	1609	6.67	0.67	27.67
14	1596.98	1597	1594	1594	-0.02	2.98	2.98
15	1588.51	1593	1585	1576	-4.49	3.51	12.51
16	1549.54	1545	1544	1527	4.54	5.54	22.54
17	1590.20	1590	1585	1577	0.2	5.2	13.2
18	1534.39	1526	1531	1527	8.39	3.39	7.39
Minimum					*-8.66*	*-8.81*	*2.98*
Maximum					*23.59*	*5.54*	*28.27*
Mean					*3.97*	*-0.25*	*16.36*
SD					*±7.76*	*±4.00*	*±7.79*
Range					*32.25*	*14.35*	*25.29*

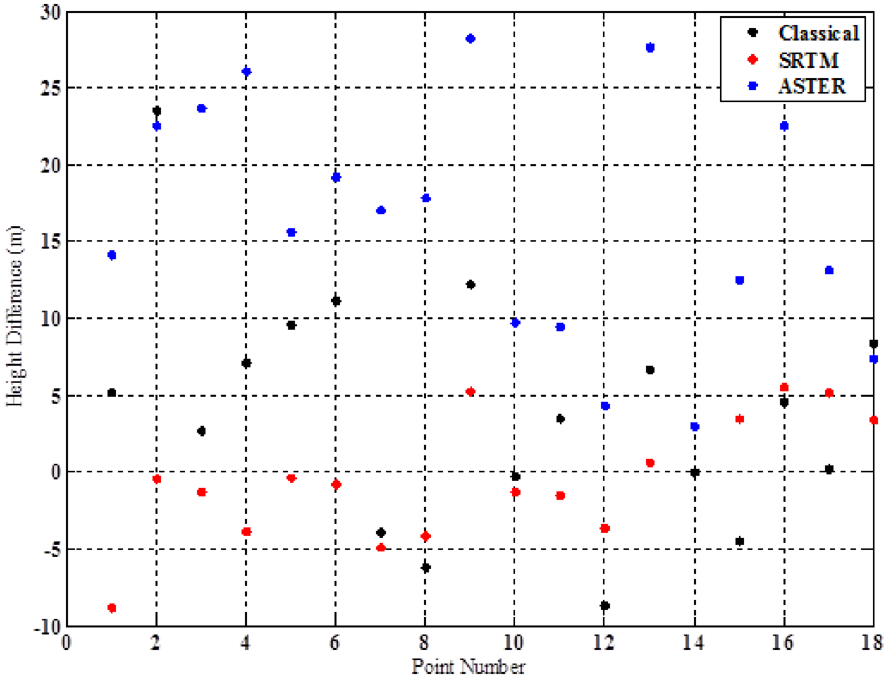

Fig. 1: differences between levelled and DEM orthometric heights

Figure 2 shows well-balanced results (both positive and negative) from SRTM and Classical DEMs. This is illustrated by the relatively small mean in height differences, i.e. -0.25 m and 3.97 m for SRTM and Classical DEMs respectively. A large mean of 16.36 m is observed in the height differences between levelled orthometric heights and ASTER DEM orthometric heights (Table 1) as illustrated in Figure 2. ASTER DEM consistently underestimates orthometric heights in the area of study. In other words, levelled orthometric heights are consistently more than ASTER derived orthometric heights in the area of study.

3.2 Improvement by application of polynomial

The coefficients of the second order surface polynomial are obtained from equation (2) using 12 data points (Figure 1). The coefficients are given in Table 2. These coefficients or parameters are used in the computation of corrections to the estimated orthometric heights from DEMs to obtain improved orthometric heights at 6 test points using equation (3). It should be noted that different sets of coefficients are used for each DEM (Table 2). The 6 test points are excluded in the determination of the second order surface polynomial coefficients to facilitate a cross-validation test. The statistics of the differences between levelled (actual) orthometric heights and improved DEM orthometric heights at the 6 test points are given in Table 3.

The mean and standard deviation (SD) of the direct differences between levelled and DEM orthometric heights at the 6 test points are: -3.32 m and ±7.32 m respectively for the classical DEM; 0.69 m and ±4.55 m respectively for SRTM DEM; 16.52 m and ±8.55 m respectively for ASTER DEM (Table 3). On the other hand, the mean and standard deviation (SD) of the differences between levelled and improved DEM orthometric heights at the 6 test points are: -3.48 m and ±8.30 m respectively for the classical DEM; 0.60 m and ±3.69 m respectively for SRTM DEM; 1.17 m and ±8.87 m respectively for ASTER DEM. These results indicate that the use of second order surface polynomial would improve accuracy of height determination in SRTM DEM from ±4.55 m to ±3.69 m (representing an improvement of 18.9%). However, accuracies of heights from classical and ASTER DEMs are degraded by the application of the second order polynomial.

Table 2: Computed Coefficients (units are in m)

Coefficients	*Classical DEM*	*SRTM DEM*	*ASTER DEM*
k_O	-444480.3084	-219779.6785	-182870.5488
k_1	1412401.1100	694963.5814	562766.3914
k_2	886300.7748	262236.2311	-151834.5926
k_3	-1122065.446	-548846.9402	-432967.0939
k_4	-560514.3904	265427.4083	-191292.3836
k_5	-1413799.7770	-387384.1267	227833.9267

Table 3: Statistics of the differences between levelled and improved DEM orthometric heights (units are in m)

	Direct comparison of heights			*Comparison after improvement on DEM heights*		
Point	ΔH_C *Classical*	ΔH_S *SRTM*	ΔH_A *ASTER*	δH_C *Classical*	δH_S *SRTM*	δH_A *ASTER*
3	2.69	-1.31	23.69	-9.66	1.39	3.60
7	-3.9	-4.9	17.1	-6.54	-3.42	0.99
9	12.27	5.27	28.27	12.95	6.47	16.04
12	-8.66	-3.66	4.34	-8.22	-3.27	-6.34
15	-4.49	3.51	12.51	-5.48	1.89	2.00
17	0.2	5.2	13.2	-3.93	0.54	-9.28
Minimum	*-8.66*	*-4.90*	*4.34*	*-9.66*	*-3.42*	*-9.28*
Maximum	*12.27*	*5.27*	*28.27*	*12.95*	*6.47*	*16.04*

Mean	*-0.32*	*0.69*	*16.52*	*-3.48*	*0.60*	*1.17*
SD	*±7.32*	*±4.55*	*±8.55*	*±8.30*	*±3.69*	*±8.87*
Range	*20.93*	*10.17*	*23.93*	*22.61*	*9.89*	*25.32*

We note that the current study is limited to a small area, hence more research covering a larger area e.g. a country is recommended to reveal exact accuracies of the recent DEMs. However, the current study has given some insights on some of the accuracy parameters that should be considered when selecting a DEM for use in any engineering and related projects.

4.0 Conclusions

In both height approximation and error distribution, SRTM DEM performs better than the classical and ASTER DEMs. The standard deviations of the differences between levelled orthometric heights and DEM estimated orthometric heights are: ±4.00 m, ±7.76 m and ±7.79 m for SRTM, Classical and ASTER DEMs respectively.The results indicate that although SRTM DEM has a spatial resolution of 90 m, it performs better than ASTER DEM which has a spatial resolution of 30 m. It is worth noting that in general practice ASTER DEM has always been chosen due to its high spatial resolution, but this study shows that SRTM DEM has a better vertical resolution in the area of study. This is consistent with the predefined vertical accuracy specifications of SRTM and ASTER DEMs. ASTER DEM had a consistent positive bias where it underestimated orthometric heights, this means the error was poorly distributed. The results of improved DEM heights indicate that the use of second order surface polynomial improves accuracy of height determination in SRTM DEM but degrades accuracies in the classical and ASTER DEMs. SRTM DEM can therefore be used for reconnaissance, 3D visualization, hydrology, mass flow analysis and feasibility studies of proposed sites for large engineering projects while Classical and ASTER DEMs can be used for general reconnaissance surveying.

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References

ASTER GDEM Validation Team. (2009). ASTER Global DEM validation summary report. Available at https://lpdaac.usgs.gov/sites/default/files/public/aster/docs/ASTER_GDEM_Validation_Summary_Report.pdf

Farr T. and Kobrick M. (2001). The Shuttle Radar Topography Mission, Eos Trans. *American Geophysical Union*, 82 (47), 2001.

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 characteristic. *Remote Sensing of Environment*, 104, pp. 409–415.

Hensley S. Rosen P. and Gurrola E. (2000). Topographic map generation from the Shuttle Radar Topography Mission C-band SCANSAR interferometry. Proc. SPIE, 4152, pp. 179–189.

Hofmann-Wellenhof B. and Moritz H. (2005). *Physical geodesy.* Springer, Vienna/New York.

Ioannidis C. Xinogalas E. and Soile S. (2014). Assessment of the global digital elevation models ASTER and SRTM in Greece. *Survey Review*, 46, pp. 342–354.

Jordan R.L. Caro E.R. Kim Y. Kobrick M. Shen Y. Stuhr F.V. and Werner M.U. (1996). Shuttle Radar Topography Mapper (SRTM). Proceedings of SPIE, 2958, pp. 412–422.

Kolecka N. and Kozak J. (2014). Assessment of the accuracy of SRTM C- and X-band high mountain elevation data: a case study of the Polish Tatra Mountains. *Pure and Applied Geophysics*, 171 (6), pp. 897–912.

Nikolakopoulos K.G. Kamaratakis E.K. and Chrysoulakis N. (2006). SRTM vs ASTER elevation products. Comparison for two regions in Crete, Greece. *International Journal of Remote Sensing*, 27 (21), pp. 4819–4838.

Odera P.A. and Fukuda Y. (2015). Comparison of Helmert and rigorous orthometric heights over Japan. *Earth, Planets and Space,* 67(1), pp. 1–9.

Odera P.A. Musyoka S.M. and Gachari M.K. (2014). Practical application of the geometric geoid for heighting over Nairobi County and its environs. *Journal of Agriculture, Science and Technology,* 16 (2), pp. 175–185.

Sertel E. (2010). Accuracy Assessment of ASTER Global DEM over Turkey. *A special joint symposium of ISPRS Technical Commission IV & Auto-Carto in conjunction with ASPRS/CaGIS 2010 Fall Specialty Conference,* November 15–19, 2010, Orlando, Florida.

Tighe, M. L. (2012). Validation of a new 30-meter Ground Sampled Global DEM using ICESAT LiDAR elevation reference data. *Geospatial World Forum 2012*, April 23–27 2012, Amsterdam, Netherlands.

Torge W. (2001). *Geodesy 3rd edition*. Walter de Gruyter, Berlin.

Yamaguchi Y. Kahle A.B. Tsu H. Kawakami T. and Pniel M. (1998). Overview of Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER). *IEEE Transactions on Geoscience and Remote Sensing*, 36 (4), pp. 1062–1071.

Zhao S. Cheng W. Zhou C. Chen Xi. Zhang S. Zhou Z. Liu H. and Chai H. (2011). Accuracy assessment of the ASTER GDEM and SRTM3 DEM: an example in the Loess Plateau and North China Plain of China. *International Journal of Remote Sensing*, 32 (23), pp. 8081–8093.