Positional accuracy assessment of historical Google Earth imagery in Lagos State, Nigeria

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Abstract
The horizontal accuracy of historical Google Earth (GE) images at four epochs between the years 2000 and 2018, and the vertical accuracy of its elevation data within Lagos State, in Nigeria, are respectively evaluated by comparison with a very high–resolution digital orthomosaic and comparison with 558 ground control points. Two readily available 30-m digital elevation models (DEMs) — the Shuttle Radar Topography Mission (SRTM) v3.0 and the Advanced Land Observing Satellite World 3D (AW3D) DEM v2.1. — were also compared with GE elevations. A novel approach for assessing the space–time variations in the magnitude and direction of errors in GE imagery is presented. For horizontal accuracy, the root mean square errors (RMSEs) are as follows — year 2000 (16.9 m), year 2008 (16.4 m), year 2012 (6.1 m) and year 2018 (6.1 m). The most recent GE imagery (year 2018) had the least horizontal error while year 2000 had the largest horizontal error. The horizontal shift was skewed towards the western and north-western directions, indicative of systematic error. In terms of the vertical accuracy, GE elevation data had the lowest accuracy and highest RMSE of 6.21 m followed by AW3D with an RMSE of 4.39 m and SRTM with an RMSE of 3.68 m.

Keywords Google Earth Imagery · Positional accuracy · Global Positioning System · Digital elevation models · Root mean square error

Introduction
The integration of spatial technologies with the World Wide Web has led to the evolution of virtual globes which provide worldwide access to geospatial data (Elvidge and Tuttle 2008). Allen (2008) defines a virtual globe as “a 3D software model of the Earth (or other planets) that provides a user interactivity and freedom to view the globe from different viewing angles, positions, and overlays of actual or abstract geographic data.” The ease of use of digital virtual globes and their capacity for display and visualisation of spatial information make them a powerful communication tool for researchers, decision-makers and the general public (Aurambout et al. 2008). Virtual globes present a simpler alternative to technocratic and costly Geographic Information System (GIS) software, and this facilitates sharing of spatial data on a global scale (Yu and Gong 2012). Virtual globes can be viewed as technological realisations of the Digital Earth (DE) concept introduced by former US Vice President Al Gore (Gore 1998; Liang et al. 2018) and have led to new paradigms in the concept of Digital Earth (Goodchild et al. 2012; Pulighe et al. 2016). Digital Earth is described as “a multiresolution and three-dimensional visual representation of Earth that would help humankind take advantage of georeferenced information on physical and social environments, linked to an interconnected web of digital libraries” (Gore 1999 in Liu et al. 2020).
Examples of free and publicly available virtual globes/image services include Google Earth, Google Maps, NASA World Wind, Microsoft Bing Maps and Apple Maps (Pulighe et al. 2016; Goudarzi and Landry 2017). Among these examples, Google Earth (GE) is the most popular and versatile. It renders a three-dimensional (3D) representation of Earth by the superimposition of images obtained from satellite imagery with worldwide coverage, aerial photography from local or national mapping agencies, near-orthophoto collections in GeoPortals and GIS 3D globe. Google Earth can show various kinds of images overlaid on the surface of the earth and is also a Web Map Service client. The core technology behind Google Earth was originally developed at Intrinsic Graphics in the late 1990s. In version 5.0, Google introduced “Historical Imagery” allowing users to view images of a region at different epochs and to observe an area’s changes over time (see Fig. 1). 3D coverage of cities by Google Earth began in 2012 (Ubukawa 2013). By early 2016, it had been expanded from 21 cities in 4 countries to hundreds of cities in over 40 countries, including every US state and encompassing every continent except Antarctica. The very high-resolution (VHR) satellite images on Google Earth have a spatial resolution finer than 5 m (Lesiv et al. 2018). However, the spatial resolution of the images depends on the characteristics of the satellite such as the altitude and type of instruments (Buka et al. 2015). In reality, GE images are not spatiotemporally continuous or homogenous but are mosaicked using multiple images from different periods, different spatial resolutions ranging from 15 to 10 cm, and from different imagery providers (Lesiv et al. 2018). The images are compiled from a wide variety of sources such as SPOT 5, Rapid Eye, Earth Resource Observation Satellites (EROS), Meteosat 2, Geoeye 1 and Digital Globe World View 2 satellite (Buka et al. 2015). Since Google Earth images are sourced from multiple sources, they do not have identical positional accuracy or spatial resolution (Goudarzi and Landry 2017). The satellite images are sometimes supplemented with aerial photographs which have a higher resolution. In places where high-resolution imagery is unavailable, GE defaults to Landsat imagery (Potere 2008).

On the frequency of updates, Google aims to update satellite imagery of places that undergo frequent changes, once a year for big cities, every 2 years for medium-sized cities and up to every 3 years for smaller cities (Schottenfels 2020).

There is some ambiguity in the source of Google Earth elevation data (Goudarzi and Landry 2017). It is possibly derived from the Shuttle Radar Topography Mission (SRTM) DEM, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global DEM and Light Detection and Ranging (LiDAR) (Goudarzi and Landry 2017; Chigbu et al. 2019; MES Innovation Sdn Bhd 2018). The recent introduction of elevation data sourced from LiDAR interestingly makes it possible for height accuracy of about 5–25 cm. Ironically, the location of such places where LiDAR data covers is not known or revealed by GE (MES Innovation Sdn Bhd 2018). It is expected that errors inherent in the elevation data sources would naturally propagate into GE elevation data.

Since the launch of Google Earth in 2005, it has enjoyed ever-increasing popularity from map makers, pathfinders, navigators, planners, application developers, etc. as a free data source providing a pseudo-realistic view of the world through satellite images, maps, digital terrain, 3D buildings, land use information, identification of monuments

Fig. 1 Historical Google Earth imagery over a part of Beijing city in China at three periods — (a) 8 November, 2002, (b) 29 March, 2012, (c) 28 August, 2020. The Historical Imagery slider is visible at the top left corner of the images
and locational data. Google Earth imagery has found wide applications in health geography research (Curtis et al. 2006), land use/land cover mapping (Hu et al. 2013; Malarvizhi et al. 2016), land conversion studies (Jacobson et al. 2015), mapping of lakes (Shen et al. 2006), internet GIS (Henry 2009), real estate (Hwang 2008) and relief/humanitarian efforts (Nourbaksh et al. 2006). GE Historical Imagery provides images taken at different periods, and this has wide applications in land use change detection studies (Malarvizhi et al. 2016). Generally, the use of GE in research projects has been summarised into the following categories: visualisation, data collection, validation, data integration, communication/dissemination of research results, modelling, data exploration and decision support (Yu and Gong 2012). In the scientific community, its use pertains to earth surface processes, habitat availability, health and surveillance systems, biology, land use/land cover (LULC), agriculture, landscape etc. (Pulighe et al. 2016). Comprehensive reviews of earth science applications of Google Earth are provided in Yu and Gong (2012) and Liang et al. (2018).

Google Earth presents a new paradigm in Digital Earth and in the quest by man to understand the environment and effectively manage its resources. It also presents a clear advantage to achieving the United Nations 2030 Agenda for sustainable development. As a virtual globe, Google Earth connects all parts of the world in a virtual environment with free access to geospatial data to support global partnerships in attaining the sustainable development goals (SDGs). More so, policy and decision-making at every level (local, national, regional or global) are dependent on up-to-date geospatial data. Globally, there is a continuous drive by policymakers to deliver sustainable development within, and in accordance with the templates provided by the SDGs. The SDGs are earth-centred and driven by geospatial data. For example, without geospatial data in place, the idea of location-based services would, to a large extent, remain a mirage. Google Earth is therefore relevant for achieving SDG 2 (zero hunger), SDG 6 (clean water and sanitation), SDG 9 (industry, innovation and infrastructure), SDG 11 (sustainable cities and communities), SDG 13 (climate action), SDG 14 (life below water), SDG 15 (life on land) and SDG 7 (affordable and clean energy). As a virtual globe, Google Earth is also a crucial tool for bridging the global North–South divide in terms of access to geospatial data for international partnerships and collaborations.

Given the popularity of Google Earth, users tend to assume that it is a highly accurate source of information with no doubt about its positional accuracy (Flanagan and Metzger 2008). However, there are questions surrounding the reliability of GE imagery, since very little is known about its metadata including the sensors, imagery resolutions and overlay/mosaicking techniques (Pulighe et al. 2016). According to Paredes-Hernández et al. (2013), Google geographic data products are only approximations without officially documented accuracies. Wang et al. (2017) note that Google has been unwilling to release comprehensive information on the accuracy of the GE archive. It is also mentioned that GE images are also not orthorectified and lack photogrammetric accuracy (Goudarzi and Landry 2017). The uncertainty surrounding the horizontal accuracy of the imagery could lead to feature misrepresentations and incorrect inferences (McRoberts 2010 in Pulighe et al. 2016).

There are also errors in image alignment manifesting at the transition zones between mosaicked images on Google Earth (Potere 2008) (e.g., disjoint shorelines and roads shown in Fig. 2). This presents some uncertainty on the usability of GE imagery for sensitive applications requiring very high accuracy such as high-precision engineering surveys and autonomous navigation. The practice of reporting coordinates with a precision that does not match its accuracy misleads users to believe that it is an accurate source of information (Goodchild et al. 2012). Moreover, Benker et al. (2011) noted that Google’s representatives stated that the coordinates provided by Google and the data available in their geographic products are only approximations and that Google makes no claim to the accuracy of their geographic information products. A quick check of the GE historical images at some locations (Fig. 3) shows that the magnitude of these horizontal shifts varies with time. In some cases, the positional errors are not consistent when viewed at different periods with the Historical Imagery slider (see Fig. 3). Another limitation is that little is known about the volume of historical imagery in Google Earth’s archive and where it can be found (Lesiv et al. 2018).

Positional accuracy is traditionally divided into two classes: horizontal accuracy and vertical accuracy (Goudarzi and Landry 2017). Becek et al. (2011) identified the flaws associated with the positional identities of some known points from the Global Elevation Data Testing Facility (GEDTF) and their corresponding points on GE imagery. A remarkable error of more than 1.5 km was noticed in some cases after measuring the discrepancies using some tools and basic statistics. In Paredes-Hernández et al. (2013), geo-registration and large horizontal errors were shown to occur in GE imagery. However, the authors suggested the possibility of GE imagery satisfying the horizontal accuracy requirements of the American Society for Photogrammetry and Remote Sensing (ASPRS), assessed in terms of root mean square error (RMSE) for $x$, $y$ and $z$ coordinates, for the production of “Class 1” 1: 20,000 maps, if a large number of well-defined points are extracted from areas of high-resolution imagery over rural areas. Mulu and Derib (2019) evaluated the accuracy of GE imagery in Khartoum, Sudan, and showed that the horizontal RMSE was suitable for

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producing a Class 1 map of 1:20,000 scale (as recommended by ASPRS 1990). However, they pointed out that the resolution of the acquired Google Earth imagery was a major factor affecting the accuracy of the GE dataset, as coarser resolutions appeared to have higher RMSE values probably due to the less accurate location of control points on such coarse resolutions. Goudarzi and Landry (2017) assessed the horizontal accuracy of GE in the city of Montreal, Canada using ten Global Positioning System (GPS) reference points. In their results, the positional accuracy varied between ~ 0.1 m in the south and ~ 2.7 m in the north of the city.

According to El-Ashmawy (2016), the accuracies of DEMs prepared from GE data are only suitable for certain engineering applications but inadequate for very precise engineering studies. It might satisfy the vertical accuracy requirements of the ASPRS (1993) standards for the production of “Class III” contour maps. Other applications of GE elevation data include the preparation of large-area cadastral, city planning, or land classification maps. In Aba metropolis of south-eastern Nigeria, Chigbu et al. (2019) assessed GE elevation data using a 10.16-km elevation profile data obtained by means of ground survey as reference. They reported a mean error of 1.65 m, RMSE of 2.79 m, a standard deviation of 2.27 m and median absolute deviation of 1.72 m for the GE elevations. However, on the strength of further incisive statistical tests (Mann–Whitney U Test of group and the t-test), they concluded that GE elevation data was unfit for any form of levelling operation that would eventually lead to engineering construction.

The issue of GE’s positional accuracy has received little interest from researchers around the world. Most of the studies discovered in the literature survey focused only on the horizontal accuracy, and there was little interest in the vertical accuracy of its elevation data.

**Fig. 2** Region of image misalignment (within the red circles) on Google Earth imagery in Lagos, Nigeria — a disjoint shoreline, imagery date — December 2018; b disjoint roads along Carter Bridge, imagery date — March 2005
Moreover, a literature search did not reveal any study dealing with the issue of horizontal error in historical GE imagery. Errors in the geo-registration of GE images could limit the scientific value of the archive (Potere 2008). Hence, the present study investigated (locally) the horizontal accuracy of historical GE imagery at four periods between 2000 and 2018 and the vertical accuracy of its elevation data within Lagos State in Nigeria, West Africa. The horizontal accuracies of the images were assessed by comparison with a highly accurate digital orthomosaic, while the vertical accuracy was assessed by comparison with a network of ground control points. The novelty of this study is shown in the assessing of the direction and orientation of the horizontal error, unlike most of the previous studies, which only focused on the magnitude. The GE elevations were also compared to elevation data from two publicly available 30-m DEMs — the Shuttle Radar Topography Mission (SRTM) v3.0 DEM and the Advanced Land Observing Satellite World 3D (AW3D) DEM v2.1. To our knowledge, this is the first study to assess the horizontal accuracy of Google Earth “historical imagery”. The findings are important to inform users of the reliability and potential limitations of GE imagery for use in change detection studies and other analyses that involve spatiotemporal variability. It also provides a critical knowledge base to inform end-users on the quality and reliability of the data for a myriad of applications.

**Materials and methods**

This study involved the acquisition of various datasets relevant to the evaluation of the positional accuracy. The steps involved in achieving this are as outlined in the subsections below.

**Study area**

The study area is Lagos State in Nigeria, West Africa. Lagos State is located in the southwestern part of Nigeria (Fig. 4) and is bounded in the south by the Atlantic Ocean, in the west by the Republic of Benin, and in north
and east by Ogun State. The state was once the administrative capital of Nigeria between 1976 and 1991. It is currently the commercial capital, a beehive of commercial and industrial activities, and has an estimated population of over 24 million (Lagos Digest of Statistics 2017). It has a total area of about 3577.28 km², of which 2792.72 km² is covered by land and 779.56 km² is water (BudgIT 2018). The state is geographically located between longitudes 2°41'55"E–4°22'00"E and latitudes 6°22'22"N–6°43'20"N. It has a generally low-lying terrain with the Lagos and Lekki lagoons as its major water bodies. There are two major climatic seasons: the rainy and dry season. The mangrove swamp forest and freshwater swamp constitute some of its most dominant vegetation types. Temperature ranges from 20 to 32 °C and the mean annual rainfall exceeds 1700 mm (Nwilo et al. 2020). For the horizontal accuracy assessment in this study, a digital orthomosaic of the University of Lagos was acquired. The University of Lagos is one of the federal universities in Nigeria, situated within metropolitan Lagos. It is located between longitudes 3°23'00"E–3°24'30"E and latitudes 6°30'00"N–6°31'30"N. As an institution for learning and research, it is surrounded by research infrastructure, buildings and commercial activities, and is also bounded eastwards by the Lagos Lagoon.

**Description of datasets**

The datasets used are discussed below.

**GCPs for horizontal accuracy assessment**

The rectification of the orthomosaic was done using highly accurate ground control points (GCPs) within the University of Lagos.
of Lagos. The GCPs were surveyed with the Trimble R8 dual-frequency Global Navigation Satellite System (GNSS). The details of the GNSS field procedure and data processing can be found in Gbopa et al. (2021). Fourteen GCPs (shown in Fig. 5) were signalised on the ground. Ground control signalisation is the selection of ground control identification style or pattern. The signalisation was done with cross markings using white emulsion paint to ensure their visibility from a high altitude during the unmanned aerial vehicle (UAV) survey. The cross markings were approximately 80–100 cm in length and 15–20 cm in breadth. Figure 6 shows two signalised GCPs within the university, YTT 28/186 and XST 347. The GNSS observation was then carried out on the GCPs in static mode with about 30–40-min occupation time on each point. After completion of the survey, the data was downloaded from the GNSS receivers and post-processed to derive the final coordinates in the WGS84 system, UTM Zone 31 N. The accuracies of the GCPs were at the sub-centimetre level, and the horizontal and vertical precisions ranged from 0.2 to 1.0 cm.

GCPs for vertical accuracy assessment

For the vertical accuracy assessment, 558 geodetic GCPs in Lagos State were acquired from the Lagos State Surveyor General’s Office. These points were established by Differential Global Positioning System (DGPS) survey in static mode and are accurate to the sub-centimetre level. The GCPs were delivered with heights in both orthometric and ellipsoidal systems. We adopted the orthometric heights for this study. The height systems of all three elevation data sources (SRTM, AW3D-30, and Google Earth) are also based on the orthometric system.

Digital orthomosaic

The reference dataset for the horizontal accuracy assessment was a digital orthomosaic which was derived from overlapping images of the University of Lagos main campus captured during a UAV survey conducted in July 2019. A more detailed discussion of the UAV flight and orthomosaic processing is presented in Gbopa et al. (2021). The DJI Phantom 4 Professional UAV with a camera lens of 84° field of view (FOV) and a focal length of 8.8 mm/24 mm (35 mm format equivalent) was used for the survey. The gimbal has a controllable range of −90° to +30° and a maximum controllable angular speed of 90°/s (Iheaturu et al. 2020; Gbopa et al. 2021). The flight was conducted at an altitude of 90 m, a UAV speed limit of 15 m/s, flight direction of 126°, and generous overlaps of 75% fore and 65% side. Figure 7 shows the UAV flight in progress at two locations within the University of Lagos while Fig. 8 shows some
images captured from the UAV survey. After the flight, the raw photos were downloaded and imported into the Pix4D Mapper software environment. The processing with Pix4D Mapper addressed the image alignment, geo-rectification with GCPs, point cloud, and mesh processing, and orthomosaic generation. The orthomosaic was produced at a ground sampling distance (GSD) of 4.36 cm. Gbopa et al. (2021) evaluated the accuracy (RMSE) of the orthomosaic using 7 checkpoints and obtained horizontal and vertical accuracies of 0.183 m and 0.157 m, respectively. This shows a high level of accuracy adequate for use as a reference dataset to evaluate the horizontal accuracy of the GE images. Figure 9 shows the final orthomosaic with 45 points initially selected as reference points for the horizontal accuracy assessment.

Google earth historical imagery

The Historical Imagery tool in Google Earth Pro v.7.3 enables viewing of images at different epochs, and allows for observation of an area’s changes over time. Historical Google Earth images between the years 2000 and 2018 were considered. The criteria for selecting a particular year included the image clarity and degree of cloud cover. After a meticulous inspection, the following periods were selected: 13 December 2000, 7 October 2008, 4 June 2012 and 28 December 2018. The spatial resolutions of the Google Earth images are estimated to be in the range of 0.5–2.0 m based on our visual inspection. Google Earth images are referenced to the WGS84 datum. For practical purposes, the WGS84 ellipsoid is considered equivalent to the GRS80 ellipsoid (Buka et al. 2015). Figure 10 shows the points selected on the historical images to coincide with the reference points from the orthomosaic.

Google earth elevation data, SRTM v3.0 and AW3D30 v2.1

Elevation data were extracted from Google Earth at points coincident with the 558 GCPs in Lagos State. The SRTM v3.0 DEM covering Lagos State was downloaded from the US Geological Survey (USGS) Earth Explorer website (https://earthexplorer.usgs.gov/). The SRTM project was jointly executed by the National Aeronautics and Space Administration (NASA) and the National Imagery and Mapping Agency (NIMA) of the US Department of Defense. The mission was designed to use a single-pass radar interferometer to produce a digital elevation model (DEM) of the Earth’s land surface between 60° N and 56° S latitude (Farr and Kobrick 2000). The SRTM DEM of 1 arc-second, resolution which corresponds to 30 m spatial resolution at the equator is distributed in 1° × 1° tiles and has higher accuracy than the earlier 90-m SRTM DEM product (Mukul et al. 2017). The SRTM mission goal of LE90 error of 16 m (RMSE ≈ 10 m) was assessed worldwide and validated using dual-frequency, Real-Time Kinematic (RTK) GPS data (Üstün et al. 2016). In the published global assessment report of SRTM DEM, it is stated that the vertical accuracy meets and exceeds the performance requirements of the mission.
by a factor of nearly two in comparison to ground-truth data such as kinematic GPS trajectories on road networks (Mukul et al. 2015). The EGM96 geoid provides the vertical datum for SRTM.

In 2015, the Advanced Land Observing Satellite (ALOS) World 3D-30 m (AW3D30) DEM was made available as an Earth topography elevation data product (https://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm). AW3D30 was photogrammetrically developed using optical imagery collected during the ALOS mission (Tadono et al. 2016). The ALOS elevation maps were produced at a spatial resolution of 5 m with an accuracy of 5 m (standard deviation). In 2016, JAXA released a 30-m product, the AW3D30 dataset which was generated from the earlier 5 m product (JAXA 2017). From the accuracy assessments by Caglar et al. (2018), the AW3D30 surpassed the accuracies of SRTM and ASTER GDEM Version 2. Figure 11 presents the spatial distribution of the 558 GCPs used for vertical accuracy assessment with SRTM v3.0 and AW3D30 v2.1 shown as the backdrop.

**Data exploration and extraction**

Forty-five points (no. 0 to no. 44) were initially marked as reference points on the orthomosaic for use in the horizontal accuracy assessment. The points were carefully placed in easily identifiable locations such as road intersections,
Fig. 10 Coincident points on Google Earth imagery for comparison with the reference points on the orthomosaic a 13 December, 2000, b 7 October, 2008, c 4 June 2012, d 28 December, 2018.

Fig. 11 Overlay of 558 geodetic GCPs for vertical accuracy assessment on the elevation map of a SRTMv3.0 and b AW3D30 v2.1.
roundabouts, and corner points of buildings. The dates were set on Google Earth using the historical imagery time slider, and the easting and northing coordinates of corresponding points on Google Earth were extracted. After inspecting the positions of all the points on the orthomosaic and Google Earth images, it was observed that some points on the Google Earth images were located in problematic places such as cloud-covered areas etc. The problematic points were eliminated thus reducing the final selection to 27 points. To extract the Google Earth elevations for vertical accuracy assessment, the 558 GCPs were first converted to keyhole markup language (kmal/kmz) format and imported into Google Earth. Next, each point was zoomed to and the corresponding elevation on Google Earth was copied from the status bar and pasted directly into a Microsoft Excel sheet. The corresponding elevations from SRTM and AW3D were extracted in the ArcGIS 10.1 environment using the ‘extract values to points’ tool in Spatial Analyst.

**Quantitative analysis**

**Horizontal accuracy**

The coordinate differences between the orthomosaic reference points and the coincident points on the Google Earth images were used as a basic metric in assessing the horizontal accuracy. Coordinates of points on the orthomosaic were subtracted from those of the various epochs for the GE historical imagery. The differences in eastings and northings are given as follows:

\[
\Delta E = E_{GE} - E_{OP}
\]

\[
\Delta N = N_{GE} - N_{OP}
\]

where \(\Delta E\) and \(\Delta N\) are the differences in eastings and northings, respectively, for the selected points. \(E_{GE}\) and \(E_{OP}\) are Eastings of selected points on the GE historical imagery and orthomosaic, respectively. \(N_{GE}\) and \(N_{OP}\) are Northings of selected points on the GE historical imagery and orthomosaic, respectively. The linear separation between the position of a point on the orthomosaic and on Google Earth is the horizontal error/shift (S) (Fig. 12).

The assessment of the horizontal accuracy is based on the ASPRS Positional Accuracy Standards for Digital Geospatial Data version 1.0 (ASPRS 2014). Horizontal accuracy was assessed using root mean square error (RMSE) statistics in the horizontal plane (i.e., \(RMSE_x\), \(RMSE_y\) and \(RMSE_r\)), while the vertical accuracy was assessed in the z-dimension. In addition, the standard deviation (SD) and standard error of the mean (SEM) of the coordinate differences were also calculated. Figure 13 shows an overlay of orthomosaic reference points and GE points in two areas within the University of Lagos. ASPRS (2014) defines positional accuracy as “the accuracy of the position of features, including horizontal and vertical positions, with respect to horizontal and vertical datums.” Based on the ASPRS recommendations for imagery at an estimated pixel size of 60 cm, the Google Earth images used in this study are expected to meet the ASPRS Accuracy Standards of 120 cm \(RMSE_x\) and \(RMSE_y\) Horizontal Accuracy Class for Standard Mapping and GIS work. The corresponding estimates of horizontal accuracy at the 95% confidence level were computed using methodologies documented in the National Standard for Spatial Data Accuracy (NSSDA).

The horizontal \(RMSE_r\) (\(RMSE_{hr}\)) is given as:

\[
RMSE_r = \sqrt{(RMSE_x)^2 + (RMSE_y)^2}
\]

\[
= \sqrt{\frac{\sum (\Delta E^2 + \Delta N^2)}{n}}
\]

The horizontal linear RMSE in the X direction (Easting) is given below:
The horizontal linear RMSE in the Y direction (Northing) is given below:

\[
RMSE_Y = \sqrt{\frac{\sum (N_{GE} - N_{OP})^2}{n}}
\]

(5)

where

- \( n \) — the number of check points

**NSSDA Horizontal Accuracy at 95% confidence level**

\[
= RMSEr \times 1.7308
\]

(6)

Vertical accuracy

The most widely adopted approach for the accuracy assessment of DEMs is to use reference height sources such as GCPs or DEMs of higher accuracy (Okolie and Smit 2022). Following the approach of Olusina and Okolie (2018); Nwilo et al. (2021); Okolie and Arungwa (2022) and Altunel et al. (2022), the vertical accuracies of the elevation data (Google Earth, SRTM and AW3D) were quantified by comparison at sample points with the GCPs described in “GCPs for vertical accuracy assessment”. Besides the regular error indices of mean error (ME), standard deviation (SD) and root mean square error (RMSE) that are sufficient for data with normal distribution, other calculated metrics include the median, median absolute deviation (MAD) and the normalised median absolute deviation (NMAD). Linear errors were also computed at 68% (LE68) and 90% (LE90). The latter indices are very robust for understanding data that do not follow a normal distribution. The median, MAD, and NMAD are less sensitive to the preponderant nature of outliers. The normal assumption is that errors in the DEMs are normally
distributed (Höhle and Höhle 2009; Carrera-Hernandez 2021). Unfortunately, these assumptions do not always hold. Consequently, in addition to the regular parametric accuracy indices (ME, SD and RMSE), the aforementioned non-parametric indices were employed for a more robust analysis. These accuracy parameters have been used extensively by researchers (e.g., Höhle and Höhle 2009; Carrera-Hernandez 2021; Grohmann 2018; Wessel et al. 2018; Okolie and Arungwa 2022; Altunel et al. 2022) to evaluate DEM accuracies.

The ME was calculated as follows (Patel et al. 2016):

$$ ME = \frac{1}{n} \sum_{i=1}^{n} (H_{DEM} - H_{GCP}) = \frac{\sum_{i=1}^{n} \Delta H_i}{n} $$

(7)

The SD is given as

$$ SD = \sqrt{\frac{\sum_{i=1}^{n} (\Delta H_i - ME)^2}{n - 1}} $$

(8)

The ASPRS standards for vertical accuracy specify absolute vertical accuracy measures for various classes of elevation data based on their spatial resolution (ranging from 1 to 333.3 cm). However, due to the uncertainty surrounding the source of GE elevations including its resolution characteristics, the vertical accuracy assessment is based solely on the reference GCPs. It was computed using the RMSE statistics for non-vegetated terrain (most of the 558 GCPs are located in non-vegetated terrain):

$$ NSSDAVerticalAccuracy = RMSE_z $$

(9)

$$ RMSE_z = \sqrt{\frac{\sum (H_{DEM} - H_{GCP})^2}{n}} $$

(10)

The MAD and NMAD were calculated for the data as follows (Wessel et al. 2018):

$$ MAD = MD(\lvert \Delta H_i - MD_{\Delta H_i} \rvert) $$

(11)

$$ NMAD = 1.4826 \times MAD $$

(12)

$$ NMAD $$ is a nonparametric estimate for SD that is resilient to the influence of outliers and is equivalent to SD if the data conforms to a normal distribution (Zhang, et al 2019).

At confidence levels of 68%, and 90%, the LE was calculated as follows (Grohmann 2018):

$$ LE_{68} = SD \times 1.00 $$

(13)

$$ LE_{90} = SD \times 1.65 $$

(14)

In the above equations, $ n $ is the number of points under consideration, $ H_{DEM} $ represents the heights from Google Earth, SRTM and AW3D30, respectively, and $ H_{GCP} $ represents, heights of the GCPs which are the reference dataset. $ MD $ represents the median of a set of data, while $ MD_{\Delta H_i} $ represents the median of the height differences or the 50% quartile (Grohmann 2018). Equations 7–10, 13 and 14 were deployed under assumptions of normal distribution of height differences.

**Results and discussion**

The results are analysed and discussed for both horizontal and vertical accuracies.

**Analysis of horizontal accuracy**

Table 1 shows the coordinates of the orthomosaic reference points and the Google Earth (GE) coincident points. The coordinates are presented in the Universal Transverse Mercator (UTM) system — Eastings and Northings. Table 2 presents the coordinate differences between the reference points and the GE points. The difference in the eastings of the orthomosaic reference points and the corresponding GE easting values ranged from −11.9 to 11.0 m in the year 2000, −19.0 to 3.0 m in the year 2008, −4.0 to 16.0 m in the year 2012 and −8.0 to (−1.1) m in the year 2018. In the northings, the differences ranged from 0 to 24.9 m, −4.8 to 10.3 m, −5.4 to 10.3 m, and −5.4 to 11.9 m in the year 2000, 2008, 2012 and 2018 respectively. The SDs and RMSEs of the differences in eastings were derived as follows: year 2000 (SD: 4.8 m; $ RMSE_x $: 9.5 m), year 2008 (SD: 4.3 m; $ RMSE_x $: 16 m), year 2012 (SD: 4.4 m; $ RMSE_x $: 4.9 m) and year 2018 (SD: 1.5 m; $ RMSE_x $: 4.4 m). The SDs and RMSEs of the differences in northings were derived as follows: year 2000 (SD: 4.8 m; $ RMSE_y $: 14.0 m), year 2008 (SD: 3.7 m; $ RMSE_y $: 3.7 m), year 2012 (SD: 3.5 m; $ RMSE_y $: 3.7 m) and year 2018 (SD: 3.7 m; $ RMSE_y $: 4.3 m).

The differences in eastings and northings of the orthomosaic reference points and GE coincident points are represented by stacked columns in Fig. 14a and b respectively. Consistent ΔE negative values in the years 2000, 2008, and 2018 are suggestive of a systematic error that displaces the Google Earth imagery westwards from the true positions. The largest easting differences are observed in the 2008 imagery with some exceeding 15 m while the least differences are observed in the 2012 imagery. The highest horizontal linear RMSE in the easting ($ X $) direction ($ RMSE_x $) is observed in the 2008 imagery (16.0 m), whereas the least horizontal linear RMSE is observed in the 2018 imagery (4.4 m). Surprisingly, the year 2000 imagery seems to perform better than 2008 in terms of the magnitude of its differences relative to the source of ground truth (orthomosaic). In 2012, the easting coordinates are generally
Table 1  Coordinates of the orthomosaic reference points and GE points

| ID | Orthomosaic | GE — 2000 | GE — 2008 | GE — 2012 | GE — 2018 |
|----|-------------|-----------|-----------|-----------|-----------|
|    | Easting (m) | Northing (m) | Easting (m) | Northing (m) | Easting (m) | Northing (m) | Easting (m) | Northing (m) | Easting (m) | Northing (m) |
| 1  | 543,316.50  | 720,678.04 | 543,309.00 | 720,690.00 | 543,301.00 | 720,676.00 | 543,317.00 | 720,676.00 | 543,313.00 | 720,678.00 |
| 3  | 544,045.31  | 720,527.11 | 543,527.00 | 720,608.96 | 543,520.00 | 720,606.00 | 543,530.00 | 720,606.00 | 543,522.00 | 720,610.00 |
| 5  | 544,153.99  | 720,521.52 | 543,859.00 | 720,597.77 | 543,858.00 | 720,596.00 | 543,859.00 | 720,596.00 | 543,855.00 | 720,598.00 |
| 7  | 544,045.31  | 720,527.11 | 543,527.00 | 720,608.96 | 543,520.00 | 720,606.00 | 543,530.00 | 720,606.00 | 543,522.00 | 720,610.00 |
| 9  | 544,153.99  | 720,521.52 | 543,859.00 | 720,597.77 | 543,858.00 | 720,596.00 | 543,859.00 | 720,596.00 | 543,855.00 | 720,598.00 |
| 11 | 544,045.31  | 720,527.11 | 543,527.00 | 720,608.96 | 543,520.00 | 720,606.00 | 543,530.00 | 720,606.00 | 543,522.00 | 720,610.00 |
| 13 | 544,153.99  | 720,521.52 | 543,859.00 | 720,597.77 | 543,858.00 | 720,596.00 | 543,859.00 | 720,596.00 | 543,855.00 | 720,598.00 |
| 15 | 544,045.31  | 720,527.11 | 543,527.00 | 720,608.96 | 543,520.00 | 720,606.00 | 543,530.00 | 720,606.00 | 543,522.00 | 720,610.00 |
| 17 | 544,153.99  | 720,521.52 | 543,859.00 | 720,597.77 | 543,858.00 | 720,596.00 | 543,859.00 | 720,596.00 | 543,855.00 | 720,598.00 |
| 19 | 544,045.31  | 720,527.11 | 543,527.00 | 720,608.96 | 543,520.00 | 720,606.00 | 543,530.00 | 720,606.00 | 543,522.00 | 720,610.00 |
| 21 | 544,153.99  | 720,521.52 | 543,859.00 | 720,597.77 | 543,858.00 | 720,596.00 | 543,859.00 | 720,596.00 | 543,855.00 | 720,598.00 |
| 23 | 544,045.31  | 720,527.11 | 543,527.00 | 720,608.96 | 543,520.00 | 720,606.00 | 543,530.00 | 720,606.00 | 543,522.00 | 720,610.00 |
| 25 | 544,153.99  | 720,521.52 | 543,859.00 | 720,597.77 | 543,858.00 | 720,596.00 | 543,859.00 | 720,596.00 | 543,855.00 | 720,598.00 |
| 27 | 544,045.31  | 720,527.11 | 543,527.00 | 720,608.96 | 543,520.00 | 720,606.00 | 543,530.00 | 720,606.00 | 543,522.00 | 720,610.00 |
| 29 | 544,153.99  | 720,521.52 | 543,859.00 | 720,597.77 | 543,858.00 | 720,596.00 | 543,859.00 | 720,596.00 | 543,855.00 | 720,598.00 |
| 31 | 544,045.31  | 720,527.11 | 543,527.00 | 720,608.96 | 543,520.00 | 720,606.00 | 543,530.00 | 720,606.00 | 543,522.00 | 720,610.00 |
| 33 | 544,153.99  | 720,521.52 | 543,859.00 | 720,597.77 | 543,858.00 | 720,596.00 | 543,859.00 | 720,596.00 | 543,855.00 | 720,598.00 |
| 35 | 544,045.31  | 720,527.11 | 543,527.00 | 720,608.96 | 543,520.00 | 720,606.00 | 543,530.00 | 720,606.00 | 543,522.00 | 720,610.00 |
| 37 | 544,153.99  | 720,521.52 | 543,859.00 | 720,597.77 | 543,858.00 | 720,596.00 | 543,859.00 | 720,596.00 | 543,855.00 | 720,598.00 |
| 39 | 544,045.31  | 720,527.11 | 543,527.00 | 720,608.96 | 543,520.00 | 720,606.00 | 543,530.00 | 720,606.00 | 543,522.00 | 720,610.00 |
| 41 | 544,153.99  | 720,521.52 | 543,859.00 | 720,597.77 | 543,858.00 | 720,596.00 | 543,859.00 | 720,596.00 | 543,855.00 | 720,598.00 |
better fitted with absolute differences closer to zero than in prior years. However, it is interesting to note the spikes at some points such as no. 25 which indicate anomalies in the image planimetry. In 2018, there is a generally better fit for all easting coordinates, with differences very close to zero and the elimination of the spike, which had probably been rectified in this recent version of the imagery.

The differences in northings ($\Delta N$) are shown in Fig. 14b. For the years 2000 and 2018, the differences are mostly positive and reasonably consistent. In contrast, the differences between 2008 and 2012 are mostly negative. The trend suggests a systematic or consistent shift in the positions of the GE images generally occurring in the north–south axis; towards the north for years 2000 and 2018 and southwards for years 2008 and 2012. However, the magnitude of the shift is relatively large northwards but minimal southwards.

It is again evident that the GE imagery is skewed northward within the study area. In terms of the horizontal linear error in the northing ($Y$) direction RMSE ($RMSE_y$), the year 2000 imagery has the highest RMSE of 14.0 m while the years 2008 and 2012 imagery have the least RMSEs of 3.7 m. The northing differences from the year 2000 are generally worst off by a significant measure than all other periods. Its absolute differences generally range from 6.6 to 25 m, with the exception of point 30 whose absolute difference is exactly zero. Spikes at point nos. 19 and 20 are seen in the images for 2008 to 2018. Years 2008 and 2012 images generally yield northing differences that are closest to zero.

Figure 14c shows the horizontal errors/shifts in Google Earth images. Table 3 shows the horizontal errors in the GE points including the horizontal linear RMSE in the radial direction that includes both easting ($x$)- and northing

### Table 2 Coordinate differences between the orthomosaic reference points and the GE points

| ID | $\Delta E$ (m) | Year 2000 | Year 2008 | Year 2012 | Year 2018 | $\Delta N$ (m) | Year 2000 | Year 2008 | Year 2012 | Year 2018 |
|----|---------------|------------|------------|------------|------------|---------------|------------|------------|------------|------------|
| 1  | -7.5          | -15.5      | 0.5        | -3.5       | 1          | 12.0          | -2.0      | -2.0      | -2.0      | 0.0        |
| 3  | -10.1         | -17.1      | 2.9        | -5.1       | 3          | 12.0          | -3.0      | -3.0      | -3.0      | 1.0        |
| 6  | -8.2          | -16.2      | -0.2       | -4.2       | 6          | 11.2          | -1.8      | -1.8      | -1.8      | 0.2        |
| 7  | -8.3          | -15.3      | 0.7        | -4.3       | 7          | 10.0          | -2.0      | -2.0      | -2.0      | 1.0        |
| 8  | -11.0         | -18.0      | 3.0        | -3.0       | 8          | 14.8          | 3.8       | -1.2      | -1.2      | 2.8        |
| 9  | -11.9         | -13.9      | 5.1        | -2.9       | 9          | 16.4          | -2.6      | -2.6      | -2.6      | 4.4        |
| 10 | -9.0          | -18.0      | 0.0        | -4.0       | 10         | 13.9          | -0.1      | -1.1      | -1.1      | -0.1       |
| 11 | -9.1          | -18.1      | 0.9        | -4.1       | 11         | 12.3          | -0.7      | -0.7      | -0.7      | 0.3        |
| 12 | -9.7          | -16.7      | 1.3        | -4.7       | 12         | 12.6          | -2.4      | -1.4      | -1.4      | 1.6        |
| 13 | -8.8          | -15.8      | 0.2        | -4.8       | 13         | 12.8          | -1.2      | -1.2      | -1.2      | 0.8        |
| 14 | -9.6          | -18.6      | -0.6       | -4.6       | 14         | 12.1          | -1.9      | 0.1       | 0.1       | -0.1       |
| 16 | -9.7          | -17.7      | -0.7       | -5.7       | 16         | 12.0          | -1.0      | -1.0      | -1.0      | 2.0        |
| 19 | -11.7         | -18.7      | -2.7       | -6.7       | 19         | 21.3          | 10.3      | 10.3      | 10.3      | 11.3       |
| 20 | -11.9         | -16.9      | -0.9       | -5.9       | 20         | 24.9          | 9.9       | 8.9       | 9.9       | 11.9       |
| 22 | -11.9         | -16.9      | 4.1        | -3.9       | 22         | 15.4          | -0.6      | -1.6      | -1.6      | 4.4        |
| 25 | 11.0          | 3.0        | 16.0       | -3.0       | 25         | 8.4           | -3.6      | -5.6      | -5.6      | 2.4        |
| 26 | 1.9           | 8.1        | 6.9        | -3.1       | 26         | 10.5          | 3.5       | 2.5       | 2.5       | 1.5        |
| 27 | -7.0          | -18.0      | -2.0       | -5.0       | 27         | 11.3          | -1.7      | -1.7      | -1.7      | -1.7       |
| 29 | -8.7          | -15.7      | 2.3        | -3.7       | 29         | 12.5          | 0.5       | 0.5       | 0.5       | 3.5        |
| 30 | 0.0           | -15.9      | 3.1        | -4.9       | 30         | 0.0           | -2.0      | -3.0      | -3.0      | 1.0        |
| 32 | -8.8          | -16.8      | 1.2        | -3.8       | 32         | 12.9          | -2.1      | -3.1      | -3.1      | 0.9        |
| 35 | -12.0         | -19.0      | -4.0       | -8.0       | 35         | 6.6           | -2.4      | -2.4      | -2.4      | -5.4       |
| 37 | -8.6          | -16.6      | -0.6       | -4.6       | 37         | 10.3          | -1.7      | -0.7      | -0.7      | -0.7       |
| 41 | -9.4          | -15.4      | 3.6        | -3.4       | 41         | 13.6          | -2.4      | -2.4      | -2.4      | 1.6        |
| 42 | -9.7          | -12.7      | 9.3        | -1.7       | 42         | 18.2          | -4.8      | -4.8      | -4.8      | 5.2        |
| 43 | -10.9         | -13.9      | 9.1        | -1.9       | 43         | 19.5          | -4.5      | -4.5      | -4.5      | 6.5        |
| 44 | -10.1         | -13.1      | 7.9        | -1.1       | 44         | 19.5          | -4.5      | -4.5      | -4.5      | 6.5        |
| Mean| -8.2          | -15.4      | 2.5        | -4.1       | Mean       | 13.2          | -0.8      | -1.1      | -1.1      | 2.3        |
| SD  | 5.0           | 4.3        | 4.4        | 1.5        | SD         | 4.8           | 3.7       | 3.5       | 3.7        | 3.7        |

$$RMSE_x = 9.5 \quad 16.0 \quad 4.9 \quad 4.4$$  
$$RMSE_y = 14.0 \quad 3.7 \quad 3.7 \quad 4.3$$
Fig. 14 Stacked columns showing a differences in eastings of the orthomosaic reference points and GE coincident points, b differences in northings of the orthomosaic reference points and GE coincident points, and c horizontal errors/shifts in Google Earth images.
The errors ranged from 0 to 27.6 m in year 2000, 4.7 to 21.4 m in year 2008, 0.7 to 16.9 m in year 2012 and 3.4 to 13.3 m in year 2018. The SDs generally reduce for later epochs for both easting and northing coordinates, with very slight deviations as shown in the increase in SD of easting coordinate differences from 2008 to 2012 and northing coordinate differences from 2012 to 2018. The trend is slightly different for the RMSEs, where there is a significant increase in \( RMSE_x \) from 2000 to 2008, before generally dropping off. While for \( RMSE_y \), it decreases from 2000 till 2012 before picking up again in 2018.

Following Eq. 6, the NSSDA horizontal accuracies at 95% confidence level were calculated as follows — year 2000 (29.37 m), year 2008 (28.39 m), year 2012 (10.62 m) and year 2018 (10.60 m). The most recent imagery (year 2018) emerged the most accurate followed by the year 2012 imagery. However, the difference in accuracy between 2012 and 2018 is negligible. The images for 2000 and 2008 are the worst in terms of horizontal accuracy.

**Magnitude and direction of horizontal error**

Table 4 shows the directions and whole circle bearings (WCBs) of the horizontal errors/shifts. In general, the maximum shifts in the four periods of study are in the NW direction: 2000 (Mag: 27.6 m; Dir: 334.55°), 2008 (Mag: 21.4 m; Dir: 300.47°), 2012 (Mag: 16.9 m; Dir: 354.49°) and 2018 (Mag: 13.3 m; Dir: 350.02°). The mean quadrants of the shifts are shown in Table 4. With the exception of year 2012, the mean shifts are generally skewed towards the western direction: 2000 (Mag: 16.3 m; Dir: 300.70°), 2008 (Mag: 16.1 m; Dir: 262.59°), 2018 (Mag: 5.6 m; Dir: 294.88°). In the 2000 imagery, the general shift is in the northern direction, more notably NW with mean and maximum displacement of 16.3 m and 27.6 m respectively in that direction (see Table 4). The mean shifts for the 2000 imagery (16.3 m) and 2008 imagery (16.1 m) are within similar range, but there is a sharp drop to 4.7 m in year 2012, and in 2018, it rises to 5.6 m. Although considerable similarity exists between the maximum shifts in 2000 and 2008, however, their mean shifts are in opposite directions. For year 2012, the mean shift is 4.7 m in the SE direction. A remarkable feature of the 2018 imagery is a general shift that is skewed to the western axis.

### Table 3: Horizontal errors/shifts (S) in the Google Earth images

| ID | Horizontal error/shift |
|----|------------------------|
|    | Year 2000 (m) | Year 2008 (m) | Year 2012 (m) | Year 2018 (m) |
| 1  | 14.1         | 15.6         | 2.1           | 3.5           |
| 3  | 15.7         | 17.4         | 4.1           | 5.2           |
| 6  | 13.9         | 16.3         | 1.8           | 4.2           |
| 7  | 13.0         | 15.4         | 2.1           | 4.4           |
| 8  | 18.5         | 18.4         | 3.2           | 4.1           |
| 9  | 20.3         | 14.2         | 5.7           | 5.3           |
| 10 | 16.6         | 18.0         | 1.1           | 4.0           |
| 11 | 15.4         | 18.2         | 1.1           | 4.2           |
| 12 | 15.9         | 16.8         | 1.9           | 4.9           |
| 13 | 15.5         | 15.8         | 1.2           | 4.8           |
| 14 | 15.5         | 18.7         | 0.7           | 4.6           |
| 16 | 15.4         | 17.7         | 1.2           | 6.0           |
| 19 | 24.3         | 21.4         | 10.7          | 13.2          |
| 20 | 27.6         | 19.6         | 9.0           | 13.3          |
| 22 | 19.4         | 16.9         | 4.5           | 5.8           |
| 25 | 13.8         | 4.7          | 16.9          | 3.8           |
| 26 | 10.7         | 8.8          | 7.4           | 3.4           |
| 27 | 13.3         | 18.1         | 2.6           | 5.3           |
| 29 | 15.2         | 15.7         | 2.4           | 5.1           |
| 30 | 0.0          | 16.1         | 4.3           | 5.0           |
| 32 | 15.6         | 16.9         | 3.4           | 3.9           |
| 35 | 13.7         | 19.2         | 4.7           | 9.7           |
| 37 | 13.5         | 16.7         | 0.9           | 4.7           |
| 41 | 16.5         | 15.6         | 4.3           | 3.8           |
| 42 | 20.7         | 13.6         | 10.5          | 5.5           |
| 43 | 22.3         | 14.7         | 10.1          | 6.7           |
| 44 | 22.0         | 13.9         | 9.1           | 6.6           |

**RMSE:** 16.9 16.4 6.1 6.1
of systematic error that skews position westward away from their true value. The case is slightly different when one considers displacement along the NS axis. Displacement/shift along this axis generally occurs within ±5 m from the origin. In the year 2012, the shifts are generally skewed towards the SE quadrant. Along the NS axis, displacement generally occurs within ±5 m. A similar feature is also noticeable in the shift along the EW axis. In the year 2018, the shifts generally occurred towards the NW quadrant. Interestingly, no displacement occurred as one moves eastward. Only at three locations were displacement within −2 to −1 m observed. A significant number occurred within −6 m and −1 m along the EW axis. Along the NS axis, displacement majorly occurs within −2 to +6 m (Fig. 15).

| Year | Shift | ΔE (m) | ΔN (m) | Magnitude (m) | Direction (°) | Quadrant |
|------|-------|--------|--------|---------------|---------------|----------|
| 2000 | Max   | 11     | 24.9   | 27.6          | 334.55        | NW       |
|      | Mean  | −8.2   | 13.2   | 16.3          | 300.70        | NW       |
|      | Min   | −12.0  | 0.0    | 0.9           | 10.49         | NE       |
| 2008 | Max   | 3.0    | 10.3   | 21.4          | 300.47        | NW       |
|      | Mean  | −15.4  | −0.8   | 16.1          | 262.59        | SW       |
|      | Min   | −19.0  | −4.8   | 4.7           | 140.69        | SE       |
| 2012 | Max   | 16.0   | 10.3   | 16.9          | 354.49        | NW       |
|      | Mean  | 2.5    | −1.1   | 4.7           | 167.31        | SE       |
|      | Min   | −4.0   | −5.6   | 0.7           | 70.34         | NE       |
| 2018 | Max   | −1.1   | 11.9   | 13.3          | 350.02        | NW       |
|      | Mean  | −4.1   | 2.3    | 5.6           | 294.88        | NW       |
|      | Min   | −8.0   | −5.4   | 3.4           | 235.70        | SW       |

**Analysis of vertical accuracy**

This section presents the analysis of the vertical accuracy of GE heights \(H_{GE}\), including the comparison with the AW3D-30 v2.1 \(H_{AW3D}\) and SRTM v3.0 \(H_{SRTM}\) DEMs. The basis of the assessment was the heights (elevations) of 558 GCPs spread around Lagos State. The heights from all three datasets fell within the general range of 0–73 m. The mean heights are as follows: GCP (16.41 m), Google Earth (16.59 m) AW3D (18.48 m) and SRTM (18.19 m). Table 6 presents the medians, MADs, NMADs, SEMs, SDs, LEs and RMSEs of the height differences. The lowest RMSE (3.68 m) and highest vertical accuracy were observed in SRTM followed
by AW3D with an RMSE of 4.39 m. Google Earth had the highest RMSE (6.21 m) and lowest vertical accuracy. The mean height differences in GE are the least at 0.18 m. However, the range of GE height differences is the highest (64.15 m), which shows that the errors have a wider spread relative to the GCPs, and is consistent with the findings of Chigbu et al (2019). These results show a lower reliability of estimated elevations from GE relative to AW3D and SRTM DEM. This conclusion is also supported by its high values for RMSE and SD, indicating a much larger spread of elevations about the mean, relative to other DEMs in comparison.

Statistics suggest the SRTM DEM is the most reliable of all three height estimation products. It has the least range of height differences, a relatively modest mean elevation error, and the least standard deviation, which implies a low spread of elevations about its mean value. Hence, we can safely conclude it is a more reliable product for estimating the heights of objects or points than AW3D and GE historical imagery. Finally, AW3D has a slightly lower range of errors than GE, the highest mean error and an SD slightly higher than that of SRTM. GE elevations are the least reliable while SRTM is the most reliable.

The linear errors for Google Earth, AW3D and SRTM were derived as 6.22 m, 3.87 m and 3.23 m (LE68%), and

| ID | 2000 | 2008 | 2012 | 2018 |
|----|------|------|------|------|
|    | Dir (°) | WCB (°) | Dir (°) | WCB (°) | Dir (°) | WCB (°) | Dir (°) | WCB (°) |
| 1  | −32.09 | 327.91 | 82.50 | 262.50 | −13.77 | 166.23 | 89.35 | 269.35 |
| 3  | −40.02 | 319.98 | 80.19 | 260.19 | −44.31 | 135.69 | −78.50 | 281.50 |
| 6  | −36.17 | 323.83 | 83.77 | 263.77 | 6.77 | 186.77 | −86.87 | 273.13 |
| 7  | −39.61 | 320.39 | 82.70 | 262.70 | −19.39 | 160.61 | −76.43 | 283.57 |
| 8  | −36.54 | 323.46 | −77.98 | 282.02 | −68.76 | 111.24 | −46.57 | 313.43 |
| 9  | −36.13 | 323.87 | 79.32 | 259.32 | −62.49 | 117.51 | −34.02 | 329.23 |
| 10 | −33.06 | 326.94 | 89.65 | 269.65 | 2.06 | 182.06 | 86.44 | 268.44 |
| 11 | −36.53 | 323.47 | 87.92 | 267.92 | −52.50 | 127.50 | −85.31 | 274.69 |
| 12 | −37.53 | 322.47 | 81.77 | 261.77 | −43.33 | 136.67 | −71.20 | 288.80 |
| 13 | −34.38 | 325.62 | 85.61 | 265.61 | −11.67 | 168.33 | −80.56 | 279.44 |
| 14 | −38.60 | 321.40 | 84.15 | 264.15 | −82.12 | 277.88 | −88.89 | 271.11 |
| 16 | −38.95 | 321.05 | 86.77 | 266.77 | 34.99 | 214.99 | −70.67 | 289.33 |
| 19 | −28.84 | 331.16 | −61.16 | 298.84 | −14.87 | 345.13 | −30.77 | 329.23 |
| 20 | −25.45 | 334.55 | −59.53 | 300.47 | −5.46 | 354.49 | −26.18 | 333.82 |
| 22 | −37.65 | 323.25 | 87.83 | 267.83 | −68.44 | 111.56 | −41.45 | 318.55 |
| 25 | 52.72  | 52.72 | −39.31 | 140.69 | −70.56 | 109.44 | −51.99 | 308.01 |
| 26 | 10.49  | 10.49 | −66.65 | 293.35 | 70.34 | 70.34 | −64.19 | 295.81 |
| 27 | −31.79 | 328.21 | 84.64 | 264.64 | 49.94 | 229.94 | 71.36 | 251.36 |
| 29 | −34.79 | 325.21 | −88.25 | 271.75 | 78.36 | 78.36 | −46.52 | 313.48 |
| 30 | 88.77  | 268.77 | 82.77 | 262.77 | −45.47 | 134.53 | −78.76 | 281.24 |
| 32 | −34.31 | 325.69 | 82.69 | 262.69 | −21.33 | 158.67 | −77.29 | 282.71 |
| 35 | −61.35 | 298.65 | 82.65 | 262.65 | 58.45 | 238.45 | 55.70 | 235.70 |
| 37 | −39.94 | 320.06 | 84.27 | 264.27 | 44.13 | 224.13 | 81.80 | 261.80 |
| 41 | −34.54 | 325.46 | 81.24 | 261.24 | −56.79 | 123.21 | −64.25 | 295.75 |
| 42 | −28.00 | 332.00 | 69.45 | 249.45 | −62.90 | 117.10 | −17.97 | 342.03 |
| 43 | −29.32 | 330.68 | 71.95 | 251.95 | −63.41 | 116.59 | −16.63 | 343.37 |
| 44 | −27.50 | 332.50 | 71.02 | 251.02 | −60.10 | 119.90 | −9.98 | 350.02 |

| Parameter | ΔH_{GE-GCP}(m) | ΔH_{AW3D-GCP}(m) | ΔH_{SRTM-GCP}(m) |
|-----------|-----------------|-------------------|------------------|
| Range     | 64.15           | 58.85             | 35.57            |
| Mean      | 0.18            | 2.07              | 1.78             |
| Median    | 0.84            | 1.83              | 1.69             |
| LE68      | 6.22            | 3.87              | 3.23             |
| LE90      | 10.26           | 6.39              | 5.33             |
| SEM       | 0.26            | 0.16              | 0.14             |
| MAD       | 2.61            | 1.58              | 1.60             |
| NMAD      | 3.88            | 2.34              | 2.37             |
| SD        | 6.22            | 3.87              | 3.23             |
| RMSEz     | 6.21            | 4.39              | 3.68             |
10.26 m, 6.39 m and 5.33 m (LE90%) respectively. Initially, the mean error of the height differences of Google earth is suggestive of minimal bias. However, the difference of 66 cm between its mean and median error is indicative of the influence of outliers. The mean and median error differences are lower in the other datasets (SRTM — 9 cm and AW3D — 24 cm). Expectedly, the values of MAD and NMAD are smaller when compared to the SD and $RMSE_z$. The median, MAD and NMAD of SRTM and AW3D differ slightly by 14 cm, 2 cm and 3 cm respectively. However, the differences are higher in the mean error (29 cm), SD (64 cm) and RMSE (71 cm). The accuracies achieved by SRTM and AW3D are corroborated by previous studies in similar environments within Lagos, Nigeria (e.g., Nwilo et al. 2017; Arungwa et al. 2018; Olusina and Okolie 2018; Okolie and Arungwa 2022). Both products are regarded among the best global DEMs in distribution today. Olusina and Okolie (2018) showed that the vertical accuracy of SRTM v3.0 in parts of Lagos was 4.23 m, much higher than the value of 16 m presented in the original SRTM requirement specification. Arungwa et al. (2018) tested an earlier version, SRTM v4.1 in Lagos, and obtained an RMSE of 3.75 m which surpassed several global DEMs including the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and GTOPO30. Similarly, Okolie and Arungwa (2022) evaluated the accuracy of three versions of AW3D30 — the average (v1.1AVE) and median (v1.1MED) products of version 1.1 and version 2.1. They showed that v1.1MED had the highest accuracy over Lagos with an RMSE of 4.38 m. However, the accuracies of DEMs are influenced by the nature of the terrain (Okolie and Smit 2022). Hence, in other environments, AW3D could surpass SRTM and vice versa. For example, in the coastal island of Hispaniola, AW3D surpassed SRTM in accuracy (Zhang et al. 2019). Florinsky et al. (2018) tested AW3D30 in the Zaoksky testing ground, Central European Russia. With a mean absolute error of 7.69 m, and root mean square error (RMSE) of 7.87 m, AW3D30 was adjudged the best elevation model within that locality when compared with the SRTM1 DEM and ASTER DEM. In Nigeria, Apeh et al. (2019) evaluated the accuracy of the AW3D30 version 2.1, SRTM30 and the ASTER version 2.0 DEMs using highly accurate GCPs. RMSEs of ~ 5.40 m, ~ 7.47 m and ~ 20.03 m were obtained for AW3D30, SRTM30 and ASTER GDEM v2 respectively. The differences in accuracy of DEMs could also be related to their production technologies, i.e. AW3D30 — image matching, and SRTM — interferometric synthetic aperture radar). However, both DEMs have been subjected to numerous improvements since the release of their initial versions.

Figure 16 shows histograms of height differences in the three datasets. SRTM DEMs have the least spread of height differences, with significant height differences ranging from just less than − 10 m to over 10 m. Also, the relative
frequency of various height differences has a near-normal distribution, suggesting reliability and predictability. The most common height differences are near the zero mark, suggesting a mean close to zero. The GE histogram has a similar bell shape for its height differences. The most commonly occurring differences and mean also hover about the zero point, with nearly evenly distributed differences, although slightly skewed to the left. Height differences for AW3D are significantly skewed to the right, with its most commonly occurring elevation differences close to zero. However, its obvious range for differences is much lower than that of GE which is by far the greatest and probably the least reliable.

**Discussion**

The difference between the 2018 and 2012 images is quite negligible; hence, they can be said to be of similar accuracy. The images for 2000 and 2008 are the worst in terms of horizontal accuracy. The accuracy is lowest in the year 2000 and gradually improves over time till 2018. This suggests that Google has made efforts at improving the quality of its satellite imagery over the years. Also, it shows there is a continuous enhancement in the accuracy and reliability of satellite imagery data sources which form the source of Google Earth data. In terms of the vertical accuracy, Google Earth elevation data had the highest RMSE of 6.21 m followed by AW3D with an RMSE of 4.39 m and SRTM with an RMSE of 3.68 m. A crucial observation is the tendency of significant variability in the accuracy of GE images within a relatively small area of study. The noticeable spikes at certain points within the area of study supports this fact. It would therefore be safe to note that accuracy may vary greatly between points within the same study area. Another fact that becomes clear from this study is that horizontal shifts in GE images are significantly skewed westward within the study area. With the exception of the 2008 and 2012 imagery which may be regarded as having a respective mean SW and SE skewness, all other images tend to be skewed towards the NW direction. This skewness towards certain directions which strongly indicates the presence of systematic error must be taken into account when using the imagery. More research is needed in other locations to determine if this skewness is a general trend with GE imagery.

The inquiry into the exact source(s) of the elevation data in Google Earth is still unresolved. However, within the study area, our analysis has shown that the vertical accuracies of SRTM v3.0 and AW3D v2.1 surpass that of Google Earth. Google Earth still presents clear advantages in terms of its ease-of-use and contextual awareness. For example, a wide variety of end-users and software developers including those not allied to spatial sciences can easily interact with GE data and utilise it for their applications. Google Earth APIs (application programming interfaces) enable developers to embed Google Earth imagery into web applications. Moreover, Google Earth is ubiquitous, and it has a very user-friendly interface that appeals to users from all spheres of life.

**Conclusion and recommendations**

This study assessed Google Earth historical imagery’s positional (horizontal and vertical) accuracy in Lagos, Nigeria. The horizontal accuracy was assessed in terms of the RMSE using historical images of the University of Lagos acquired at four epochs — 2000, 2008, 2012, and 2018.

In accordance with the ASPRS recommendations for images at an estimated pixel size of 60 cm, the Google Earth images assessed in this study are expected to meet the ASPRS Accuracy Standards of 120 cm RMSEx and RMSEy Horizontal Accuracy Class for Standard Mapping and GIS work. While we were unable to confirm the exact spatial resolution of GE images within the study area (estimated range is 0.5 - 2m), the absolute horizontal accuracies in the 4 years considered do not satisfy the ASPRS standard. In terms of vertical accuracy, Google Earth elevation data had the highest RMSE of 6.21 m and thus the lowest accuracy. The SRTM DEM had the highest vertical accuracy with an RMSE of 3.68 m followed by AW3D with an RMSE of 4.39 m. These findings strengthen the chain of evidence on the positional accuracies of Google Earth imagery in previous studies (e.g. Ubukawa 2013 and Paredes-Hernández et al. 2013).

The main contribution of this study lies in the relevance of the findings to end-users of Google Earth images and the broad Digital Earth community, particularly for local end-users. It again highlights the need for local assessments of GE imagery before use in any locality. Although the data for this study was limited to Lagos State in Nigeria, further assessments by researchers for other regions will enable a holistic perspective of the estimated magnitude and direction of positional errors in Google Earth’s global imagery archive. It presents an informed perspective through (vectorial) quantitative analysis, on the limitations of the historical archive of Google Earth’s imagery in terms of the horizontal accuracy and also the vertical accuracy of the elevation data. It is clear from the literature that variations exist in map and satellite information, thereby making the services error-prone. Users of these services are advised to use GE map and satellite information with caution as stated in GE’s terms of service. Beyond the caveats from Google, this research provides crucial insights on the extent of caution that should be exercised by users. It accomplishes this, by laying bare the empirical evidence in space, time and
direction. It is also important to point out that the positional accuracy of GE can be enhanced by carrying out geometric correction on the imagery using established geodetic control points. By carrying out this improvement, the application of GE imagery becomes extensive. The trends for GE imagery in this study have shown improvement in positional accuracy in more recent years. It might be advisable for users to go for the most recent imagery as the trend suggests higher accuracy in recent times. Furthermore, users should not rely on just GE imagery but instead acquire supporting data for their analysis. It is reasonable to augment GE acquired data with other relevant and more accurate sources.

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Data availability The data that supports the findings of this study are available in Figshare at https://doi.org/10.6084/m9.figshare.14562678 for download. The raw data was provided by JAXA, USGS/NASA and the Lagos State Surveyor General’s Office. Direct requests for these materials may be made to the providers as indicated in the Acknowledgements.

Declarations

Conflict of interest The authors declare no competing interests.

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