Vertical Accuracy of Google Earth Data

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ABSTRACT

Digital Elevation Models (DEMs) are an important data source used in many engineering and Geographic Information System (GIS) applications. This paper illustrates a strategy for creating a DEM by utilizing elevation data from Google Earth and evaluating the vertical positional accuracy of the generated DEM adopting a well-defined methodology. To ensure the accuracy of the elevation data obtained from Google Earth, a thorough evaluation was done in three diverse small districts of the northern shoreline in Egypt. The evaluation process involved determining the ground coordinates of reference points utilizing two surveying techniques: total station and Real-Time Kinematic (RTK) Global Positioning System (GPS) surveys. These coordinates were compared with the ones predicated by the DEM generated by putting into service Google Earth's elevation data. Furthermore, the vertical accuracy was assessed using Shuttle Radar Topographic Mission (SRTM) data of Google Earth collected at two different periods in 2015 and 2023. The vertical accuracy of the Google Earth data is detailed utilizing Mean Error (ME), Maximum Absolute Error (MAE), and Root Mean Square Error (RMSE). According to the results, Google Earth's elevation data accuracy remains consistent from 2015 to 2023, and refining SRTM data does not improve the vertical accuracy. The vertical accuracy of the total station survey surpasses the one of the RTK GPS survey, and the elevation accuracy of the RTK GPS survey decreases with increasing height difference. In addition, the vertical accuracy of DEMs was found to be sufficient for some engineering applications but not accurate enough for precise engineering studies. The accuracy achieved in small height difference terrain can be utilized to produce large-scale cadastral maps, city plans, or land use maps. Finally, the elevation data offered by Google Earth can be utilized for preliminary studies at a low cost. However, to ensure the accuracy of these data, it is recommended that users compare them with reference data before implementation.

Keywords-Google Earth; vertical accuracy; digital elevation model; RTK GPS; total station; surfer; SRTM data; terrain zonum

I. INTRODUCTION

Topographic information is crucial for various engineering applications like canal construction, dam building, bridge construction, drainage, and highway development. The determination of elevation is considered critical in topographic information. Sometimes, a project's success hinges on having elevation data that are very accurate and highly detailed. Currently, there are numerous techniques to acquire terrain elevation data from a specific topography. The most frequently employed practices include traditional or modern land surveying techniques, satellite imagery, aerial photogrammetry, radar, Lidar scanning, and Global Positioning System (GPS). Height data acquired through these techniques are freely accessible globally. The global accessibility of height datasets has completely transformed how engineering research and applications acquire topographical data.

GoogleEarth has been a popular application for map enthusiasts, navigators, and explorers since its launch in June 2005 [1-3]. Google Earth can provide both the plane and elevation information of a target. Additionally, many global DEMs are available to provide elevation information, and researchers have evaluated their accuracy in various locations [4]. In 2011, authors in [5] conducted a study in the Big Bend area of Texas, USA to assess the accuracy of Google Earth. Their findings revealed that the horizontal accuracy was 2.64 m and the RMSE of the vertical accuracy was 1.63 m. Despite these results, the authors advised users to be careful when utilizing the Google Earth DEMs for remote sensing research purposes. Authors in [6] evaluated the accuracy of Google Earth's horizontal and vertical measurements in the Khartoum area. They found that the RMSE for horizontal coordinates was 1.59 m and 1.7 m for elevation measurements. Authors in [7] performed a study in the King Saud University area of Riyadh to examine the accuracy of horizontal and vertical measurements. They compared the estimated coordinates from Google Earth imagery to the measured coordinates obtained using Differential GPS at nine different stations. The RMSE for horizontal and vertical positions were 1.51 m and 2.18 m respectively. Authors in [8] proceeded with a study of specific areas in the Ain Shams University campus in Cairo. The study involved evaluation of the positional accuracy of Google Earth by comparing coordinates extracted from georeferenced Google Earth images with the ground coordinates of points obtained using GPS. The study found that the deviation of the horizontal coordinate ranged from 5.89 m to 15.68 m, while the RMSE was calculated to be 10.58 m.

In 2016, author in [9] conducted an investigation into the vertical accuracy of Google Earth for creating DEMs in three regions of the northern coast of Egypt. He compared the estimated elevations of Google Earth with the elevations of 200 reference points that were measured implementing a total station. The RMSE of the vertical data were computed for the case study regions and were 1.85, 3.57, and 5.69 m. The results showed that the accuracy of the DEM created deploying Google Earth decreased as the elevation difference increased. Authors in [10] found that when comparing Google Earth data with roadway elevation data, the MAE, RMSE, and Standard Deviation (SD) were 1.32 m, 2.27 m, and 2.7 m, respectively. However, when comparing Google Earth data with the GPS benchmark in the conterminous USA, the RMSE, ME, MAE, and SD were 22.31 m, 0.13 m, 10.72 m, and 22.31 m, accordingly. The study concludes that the accuracy of Google Earth data varies across different locations, but it is generally satisfactory along roadways. Authors in [11] conducted a review to compare DEMs created from Google Earth information with those created from DGPS information. The examination found that the Google Earth determined DEM performed inadequately in addressing steep slopes. Even though the focus of the study was on the Google Earth-derived DEM's ability to characterize surfaces, the data were not rigorously analyzed with robust statistical methods.

In 2019, authors in [12] evaluated the vertical accuracy of Google Earth using the elevation data of a 10.16 km profile acquired using the total station as a reference. The results display that the average Google Earth height error is 1.65 m, the RMSE is 2.79 m, the SD is 2.27 m, and the median absolute deviation is 1.72 m. They concluded that Google Earth's elevation data were not suitable for any grading work, which could ultimately lead to construction work. In 2020, authors in [13] found that the accuracy of DEMs decreased as terrain elevation and slope increased. However, the error of DEMs remained unaffected by changes in terrain slope. In 2023, authors in [14] evaluated the horizontal and vertical accuracies of Google Earth and the elevation accuracy of two open-source DEMs deploying 325 high-precision GPS survey points across 16 regions in China. The results disclosed that Google Earth had RMSE values of 2.495 m and 2.610 m for horizontal and vertical accuracies, respectively.

To improve the accuracy of Google Earth positional data, Google Earth continues to enhance SRTM data by supplementing them with available high-resolution and accurate data from different sources [1].

After reviewing the relevant literature, it can be concluded that Google Earth is a powerful tool with a vast amount of data and great potential for development. However, it is notable that the horizontal accuracy its imagery is much better than its vertical. Moreover, the Google Earth positional accuracy is not suitable for engineering applications and construction. Despite its potential, the accuracy of Google Earth's elevation data is still relatively shallow. Therefore, it is crucial to assess the accuracy of the available elevation data on Google Earth.

The current paper has two main objectives. First, it aims to develop a methodology for obtaining Google Earth elevation data. Second, it intends to study the impact of total station and GPS surveys, as well as the refinement of SRTM data, on the accuracy of the acquired Google Earth elevation data.

II. CASE STUDY

Elevation data were gathered from three separate areas along the northern coast of Egypt [9]. These areas, namely Area 1, Area 2, and Area 3, are located in uninhabited desert areas of the cities of Dhaba, Elalamein, and Marsa Matroh. The height differences in these areas are 5 m (Figure 1), 15 m (Figure 2) and 25 m (Figure 3), respectively.

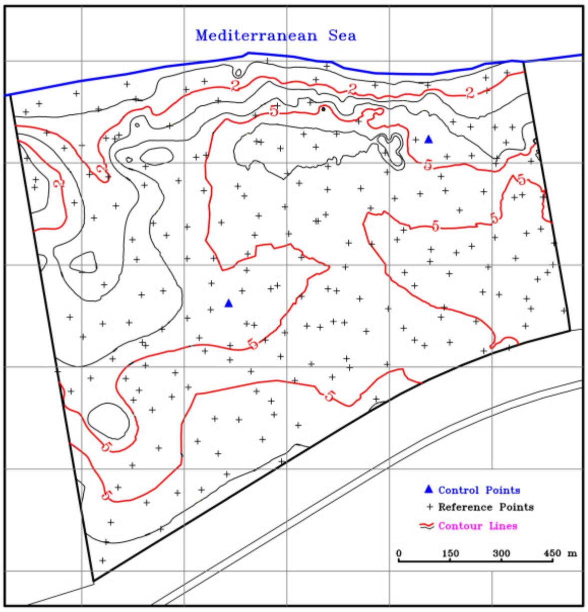

Fig. 1. Reference and control points in Area 1.

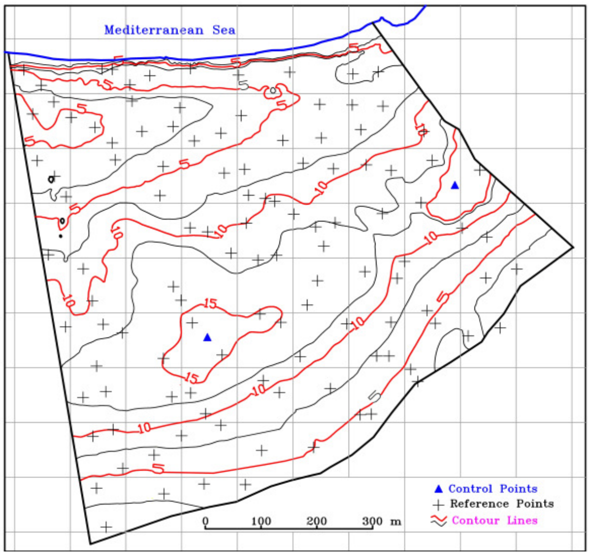

Fig. 2. Reference and control points in Area 2.

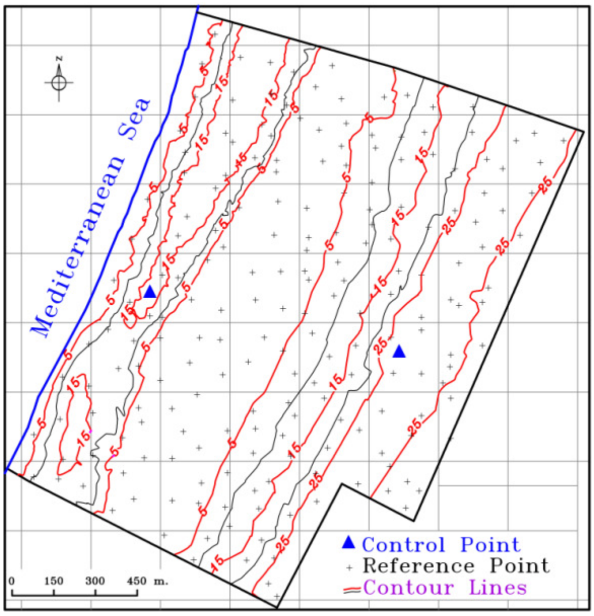

Fig. 3. Reference and control points in Area 3.

Each area includes two GPS control points, and relevant information, such as control point numbers, ground coordinates, and SDs are clear at a glance. In addition, 200 reference points were assigned to each area to evaluate the vertical accuracy of Google Earth data. The methods for getting the reference points' ground coordinates will be described below.

III. THE PROPOSED METHODOLOGY

The proposed methodology utilized to accomplish the study's aims is presented in Figure 4.

A. Surveys for Obtaining the Ground Coordinates of Reference Points

Data acquisition of each area in the case study was involved applying two surveying techniques, total station and Real-Time Kinematic (RTK) GPS surveys, to obtain the ground coordinates of 200 reference points as follows:

1) Total Station Survey

This survey was conducted in November 2015 [9] and October 2023 employing the GTS710 Topcon Total Station [15]. The Total Station can take measurements up to 2400 m on hard rock surfaces and has sufficient memory to store all the collected data. Additionally, it is equipped with software that can be used to transfer the recorded data to a computer. The survey process was carried out in two steps. To relate the instrument's location to a known ground coordinate system, the first step required the instrument to be precisely positioned on a leveled ground control point and its height was measured. After that, the back sight target was set up over the second ground control point, its height was measured and was monitored by the total station to arrange the coordinate system. In the subsequent step, points on the ground were recorded by putting the prism with its pole on each reference point, called side shots. From these side shots, the x,y, and z ground coordinates could be determined for the reference points. These two steps were repeated until all reference points were surveyed and their ground coordinates were recorded in the memory of the total station. Finally, the ground coordinates of the reference points of each case study area were downloaded into the computer and exported to an ASCII file for later processing.

2) RTK GPS Survey

Two Sokkia dual-frequency GSR2600 receivers with RTK GPS observation capabilities were deployed for the research [16]. RTK positioning makes use of two GPS receivers: one is a fixed reference station situated at a known point and the other is a portable rover that can move and survey any required point. The two receivers simultaneously observe the GPS signals, and a radio information connection between them permits information to be sent from the reference to the rover. These data are then employed to calculate the coordinates of the rover's position. In October 2023, a survey was conducted using RTK GPS technology. The survey involved placing the reference receiver on the control points with known ground coordinates. The surveyor then walked over the ground surface with an antenna, collecting data at various ground reference points while ensuring that the antenna remained vertical. The GPS receiver was utilized to obtain and store the coordinates of the reference points. The next step involved downloading and exporting the ground coordinates of the reference points for each area of the case study to an ASCII file, which would be processed later.

B. Exporting Google Earth Positional Data

Employing the free online tool Terrain Zonum [17], Google Earth positional data for each area of the case study were extracted from Google Earth. Terrain Zonum generates the positional data as WGS84 latitude, longitude, and elevation coordinates [17]. The extracted or sampled data were saved in an ASCII file for later processing.

C. Converting Google Earth Positional Data from WGS84 Longitude and Latitude to UTM North and East Coordinates

The Coordinates Transformation module of SurveyingMap software [18] was engaged to convert the coordinates of the Google Earth extracted or sampled data from WGS84 longitude and latitude to UTM North and East coordinates.

D. Generating DEMs for Case Study Areas using Google Earth Positional Data

A DEM is a way of digitally representing natural surface shapes and appropriate for stockpiling in a PC. Since natural surfaces have random shapes, the resulting network of surveyed points typically forms an irregular pattern containing horizontal coordinates and associated elevations. There are two main techniques deployed to create a DEM: the Square Grid and Triangular Grid techniques. The Square Grid technique involves obtaining data points at the nodes of a square grid. The computer then interpolates the elevations of the grid nodes using the provided data from the field. The Triangular Grid technique includes inserting data of interest at the points of connected triangles. These triangles are situated to give the most dependable portrayal of the ground surface.

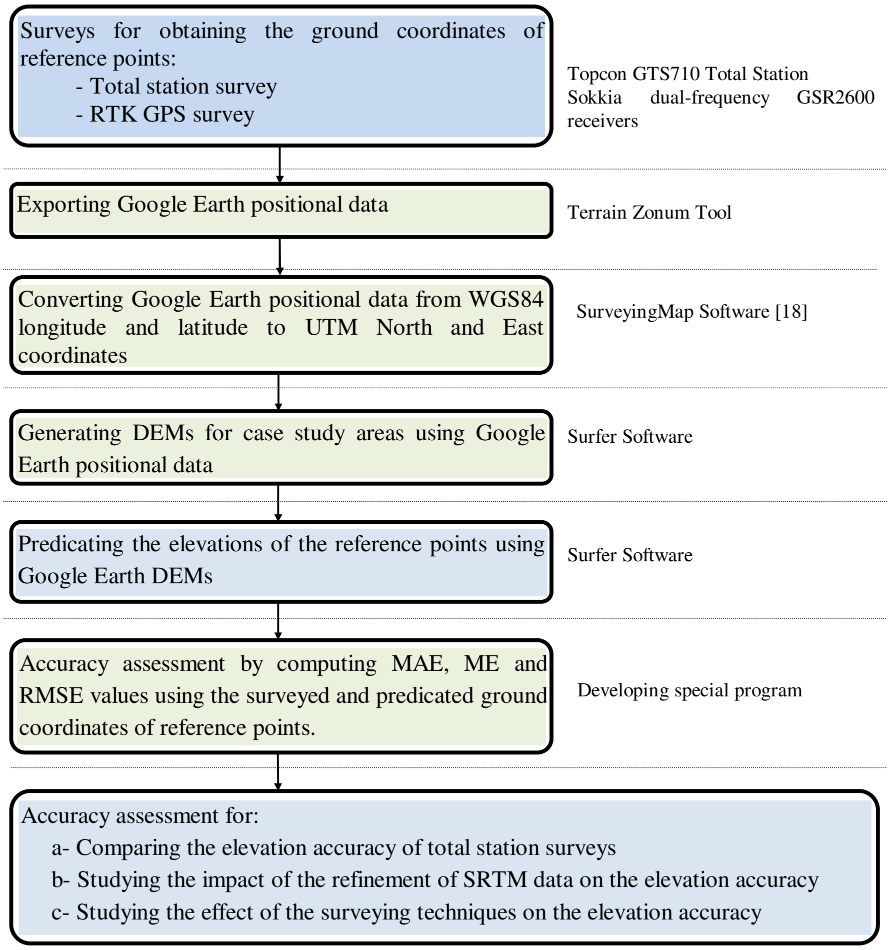

Fig. 4. The process of the proposed methodology.

Square-gridded representations of DEMs are widely utilized due to their compatibility with computerized calculations. This research focuses solely on gridded DEMs, which refer to elevation data represented in a regular matrix format. It is important to note that the nature of the DEM can fluctuate fundamentally contingent upon factors, such as the source of data and the interpolation method used. To ensure comparison consistency, Google Earth DEMs for each area of the case study were generated with the Surfer software, which is a widely used software package for generating contours and DEMs [19, 20]. Surfer is designed to read ground coordinates (X, Y, Z) from regularly and irregularly spaced points. It generates a regularly gridded DEM for each area, from which nearly continuous surfaces can be created. Grid size can be specified by the user either by the number of grid lines in X or Y directions or the distance between the grid lines. Additionally, Surfer permits users to select the interpolation technique (gridding method) to be applied. Surfer has twelve interpolation techniques. Of the different grid interpolation techniques, the Kriging technique is recommended [21] and utilized for the current research. The generation of grid files enables the creation and viewing of the DEM. Additionally, the grid files can be employed to predict any point elevation within the specified area.

E. Predicating the Elevations of the Reference Points using Google Earth DEMs

Surfer has a feature called "Grid | Residuals" that can be exploited to predict the elevation value of any point on a gridded surface [19]. This feature is widely employed for determining the predicated elevations of reference points for each area of a case study using Google Earth DEMs.

F. Accuracy Assessment

After conducting total station and GPS surveys and collecting data from Google Earth, the elevation accuracy of the reference points can be evaluated with the deployment of MAE, ME, and RMSE. These can be calculated by determining the predicated elevations of the reference points and then analyzing the data implementing the following formulas [22]:

$$\text{Absolute Error} = |k - p| \quad (1)$$

$$\text{Mean Error} = \left(\sum_{i=1}^{n} (k-p)_i\right) / n \quad (2)$$

$$RMSE = \sqrt{\sum_{i=1}^{n} (k-p)_i^2 / n} \quad (3)$$

where n is the number of reference data points, k is the known elevation, and p is the predicated elevation.

IV. RESULTS AND DISCUSSION

Accuracy is a critical exhibition pointer for surveying techniques. It is essentially reliant upon the study application, data, procedure, and anticipated results. The accuracies obtained during this study are shown in Tables I-III.

A. Comparing the Elevation Accuracy of Total Station Surveys

Two Total Station surveys were conducted, one in November 2015 [9] and the other in October 2023. To compare the data, the reference points' ground coordinates were obtained for the two surveying dates. The positional data of Google Earth in 2015 were exported and utilized to create a Google Earth DEM. This DEM was then employed to predicate the elevations of the reference points for each surveying date. The MAE, ME, and RMSE values were computed based on the known and predicated elevation of reference points for each surveying date and are tabulated in Table I. Based on the results presented in Table I, it should be noted that:

- DEM accuracy is significantly affected by the difference in elevation. For instance, the RMSE changes from 1.85 to 3.57 m for an elevation difference of 5 m and 15 m, respectively. In general, the accuracy of the DEM decreases as the height variation increases.
- There is no significant difference in accuracy between the two total station surveys. This suggests that the case study areas remained unchanged during the period between the two surveys. This finding is expected since the case study areas are uninhabited, desert and rocky terrain.

TABLE I. ACCURACY COMPARISON OF TOTAL STATION SURVEYS

Total Station Survey	Conducted in 2015 [9]			Conducted on 2023		
Case study area	Area 1	Area 2	Area 3	Area 1	Area 2	Area 3
Maximum elevation difference (m)	5	15	25	5	15	25
MAE (m)	3.72	6.39	8.78	3.74	6.40	8.76
ME (m)	0.51	1.13	1.52	0.53	1.12	1.50
RMSE (m)	1.85	3.57	5.69	1.83	3.56	5.72

B. Studying the Impact of the Refinement of SRTM Data on Elevation Accuracy

This study was conducted in several steps. In November 2015, the reference points ground coordinates were determined through Total Station surveys [9]. Google Earth positional data were acquired in two dates: 2015 and 2023. These data sets were used to generate a Google Earth DEM for each exporting date. The generated Google Earth DEMs were then implemented to predicate the elevations of the reference points for each exporting date. Finally, the values of MAE, ME, and RMSE were determined for each exporting date based on the Google Earth predicted elevations and the known elevations of the reference points. According to the obtained results observed in Table II, it can be concluded that:

- The vertical accuracy of Google Earth Data obtained in 2015 and 2023 is not significantly different.
- The refinement of SRTM data, if any, does not appear to have any effect on the vertical accuracy obtained.

C. Studying the Effect of the Surveying Techniques on Elevation Accuracy

As mentioned above, field data acquisition for determining the ground coordinates of the reference points was conducted using total station survey, either in 2015 or 2023 and RTK GPS in 2023.

TABLE II. ELEVATION ACCURACY COMPARISON OF GOOGLE EARTH DATA IN 2015 AND 2023

Google Earth elevation data	Google Earth Data of 2015 [9]			Google Earth Data of 2023		
Case study area	Area 1	Area 2	Area 3	Area 1	Area 2	Area 3
Maximum elevation difference (m)	5	15	25	5	15	25
MAE (m)	3.72	6.39	8.78	3.74	6.40	8.76
ME (m)	0.51	1.13	1.52	0.53	1.12	1.50
RMSE (m)	1.85	3.57	5.69	1.83	3.56	5.72

The study was performed impeccably, ensuring accurate results. The Google Earth positional data from 2023 were carefully exported and used to generate the Google Earth DEM. With the help of Google Earth DEM, the elevations of the reference points for total station and RTK GPS surveys in 2023 were accurately predicted. The MAE, ME, and RMSE results of each surveying method were calculated and are exhibited in Table III.

TABLE III. ACCURACY COMPARISON OF TOTAL STATION AND RTK GPS TECHNIQUES

Surveying Technique	Total Station Survey (in 2015 or 2023)			RTK GPS Survey		
Case study area	Area 1	Area 2	Area 3	Area 1	Area 2	Area 3
Maximum elevation difference (m)	5	15	25	5	15	25
MAE (m)	3.75	6.33	8.83	3.95	6.60	9.11
ME (m)	0.53	1.12	1.55	0.90	1.42	1.95
RMSE (m)	1.88	3.52	5.73	2.09	3.82	6.22

The findings presented in Table III lead to the following conclusions:

- There is a notable variation between the elevation accuracy of the total station survey and the RTK GPS survey.
- The elevation accuracy of the total station survey is considerably higher than that of the RTK GPS survey.
- Additionally, it is observed that when the height difference increases, the elevation accuracy decreases significantly, particularly in the case of the RTK GPS survey. For

instance, RMSE values increase from 1.88 to 5.73 m for the total station survey and from 2.09 to 6.22 m for the RTK GPS survey according to the height difference increment from 5 to 25 m.

D. Discussion

After analyzing the data presented in Tables I, II, and III, it is evident that:

- The refinement of Google Earth SRTM data does not affect the obtained vertical accuracy.
- The total station survey is much more accurate than the RTK GPS survey for elevation determination.
- The vertical accuracy of the Google Earth is approximately 1.85 m, as measured by the RMSE for elevation determination.
- The elevation data provided by Google Earth are more accurate in areas of small height differences or flat terrain, with an RMSE value of 1.85 m and an error range of less than 3.72 m, with some results even less than 1 m.
- However, the vertical accuracy decreases due to the increment of the height difference. For instance, RMSE values increase from 1.85 to 5.69 m for the height difference increment from 5 to 25 m, respectively.

Furthermore, by comparing the RMSE values in Tables I-III against the ASPRS [23] limits in Table IV, the following findings can be obtained:

- The results obtained for terrain with a height difference of 5 m are adequate for the generation of contour maps of Class III with a contour interval of 4.0 m or higher.
- The accuracy of the data collected for terrains with a height difference greater than 5 m is insufficient for generating contour maps with any value of contour interval in the table.

TABLE IV. ASPRS TOPOGRAPHIC ELEVATION ACCURACY REQUIREMENT FOR WELL-DEFINED POINTS [23]

Contour interval (m)	ASPRS limiting RMSE (m) spot or digital terrain model elevation points		
	Class I*	Class II*	Class III*
0.5	0.08	0.16	0.25
1	0.17	0.33	0.5
2	0.33	0.67	1
4	0.67	1.33	2
5	0.83	1.67	2.5

* Class I: holds the highest accuracies. Site plans for construction fit this category. Class II: has half the overall accuracy of Class I. Typical projects may include excavation, road grading, or disposal operations. Class III: has one third the accuracy or three times the allowable error of Class I maps. Large area cadastral, city planning, or land classification maps are typically in this category.

From the above results and discussion, Google Earth data are not suitable for precise applications, such as engineering applications or engineering studies. Engineering applications include canal construction, dam building, bridge construction, drainage, and highway development. Engineering studies may be monitoring the deformation of structures, studying Earth's crust movement, and soil stabilization. Google Earth can be employed to create large-scale cadastral maps, city plans, or land use maps for a terrain with a height difference of 5 m or less. Moreover, using Google Earth vertical data for contour map generation is not applicable for terrain with a height difference of more than 5 m.

V. CONCLUSIONS

Google Earth is a user-friendly tool that provides aerial imagery and elevation data for creating DEMs. This study presents a technique for creating a DEM using elevation data from Google Earth and evaluates its vertical positional accuracy with a clearly defined methodology. To ensure the accuracy of Google Earth's elevation data, a thorough evaluation was conducted in three different case study areas. The evaluation involved determining the ground coordinates of reference points adopting two surveying techniques, i.e. total station and RTK GPS surveys. These coordinates were then compared with the coordinates predicated by Google Earth's DEMs. In addition, the vertical accuracy was assessed using the SRTM data of Google Earth acquired at two different periods, i.e. 2015 and 2023.

The study finds that the refinement of SRTM data, if any, does not affect the elevation accuracy. Moreover, the elevation accuracy of the total station survey is considerably higher than that of the RTK GPS survey. Besides, it has been observed that as the elevation height difference increases, the elevation accuracy decreases significantly, especially in the case of the RTK GPS survey. So, Google Earth data are suitable only for small height difference terrain to create large-scale cadastral maps, city plans, or land use maps.

Finally, the elevation data offered by Google Earth can be utilized for preliminary studies at a low cost. However, to ensure the accuracy of these data, it is recommended that users compare it with reference data prior to its implementation.

REFERENCES

[1] "How images are collected - Google Earth Help," *Google*. https://support.google.com/earth/answer/6327779.

[2] V. Kumar *et al.*, "GIS-Based Analysis of a Rainwater Harvesting System in the Multipurpose Hall of Quaid-e-Awam University of Engineering, Science, and Technology," *Engineering, Technology & Applied Science Research*, vol. 12, no. 4, pp. 8837–8842, Aug. 2022, https://doi.org/10.48084/etasr.4995.

[3] N. Kumar and R. Jha, "GIS-based Flood Risk Mapping: The Case Study of Kosi River Basin, Bihar, India," *Engineering, Technology & Applied Science Research*, vol. 13, no. 1, pp. 9830–9836, Feb. 2023, https://doi.org/10.48084/etasr.5377.

[4] R. Kattan, F. Abdulrahman, and H. Hassan, "Evaluating the accuracy of Google Earth DEM using GPS coordinates Case study: Duhok Governorate," *Journal of University of Duhok*, vol. 19, pp. 1–16, Aug. 2016.

[5] S. C. Benker, R. P. Langford, and T. L. Pavlis, "Positional accuracy of the Google Earth terrain model derived from stratigraphic unconformities in the Big Bend region, Texas, USA," *Geocarto International*, vol. 26, no. 4, pp. 291–303, Jul. 2011, https://doi.org/10.1080/10106049.2011.568125.

[6] N. Z. Mohammed, A. Ghazi, and H. E. Mustafa, "Positional Accuracy Testing of Google Earth," *International Journal of Multidisciplinary Sciences and Engineering*, vol. 4, no. 6, pp. 6–9, 2013.

[7] A. Farah and D. Algarni, "Positional Accuracy Assessment of Googleearth in Riyadh," *Artificial Satellites*, vol. 49, no. 2, pp. 101–106, Jun. 2014, https://doi.org/10.2478/arsa-2014-0008.

[8] A. Ragheb and A. Ragab, "Enhancement of Google Earth Positional Accuracy," *International Journal of Engineering Research & Technology*, vol. 4, no. 1, pp. 627–630, Jan. 2015.

[9] K. L. A. El-Ashmawy, "Investigation of the Accuracy of Google Earth Elevation Data," *Artificial Satellites*, vol. 51, no. 3, pp. 89–97, Sep. 2016, https://doi.org/10.1515/arsa-2016-0008.

[10] Y. Wang, Y. Zou, K. Henrickson, Y. Wang, J. Tang, and B.-J. Park, "Google Earth elevation data extraction and accuracy assessment for transportation applications," *PLOS ONE*, vol. 12, no. 4, 2017, Art. no. e0175756, https://doi.org/10.1371/journal.pone.0175756.

[11] J. Richard and C. Ogba, "Analysis of Accuracy of Differential Global Positioning System (DGPS) and Google Earth Digital Terrain Model (DTM) Data using Geographic Information System Techniques," presented at the FIG Working Week 2017, Helsinki, Finland, 2017.

[12] M. Okezie, I. Arungwa, and C. Ogba, "Comparative Analysis of Google Earth Derived Elevation with In-Situ Total Station Method for Engineering Constructions," presented at the FIG Working Week 2019, May 2019.

[13] Z. Liu, J. Zhu, H. Fu, C. Zhou, and T. Zuo, "Evaluation of the Vertical Accuracy of Open Global DEMs over Steep Terrain Regions Using ICESat Data: A Case Study over Hunan Province, China," *Sensors*, vol. 20, no. 17, Jan. 2020, Art. no. 4865, https://doi.org/10.3390/s20174865.

[14] X. Zhang, L. You, M. Deng, Y. Kou, and Y. Yang, "Accuracy Assessment of Google Earth and Open-source Digital Elevation Models in China Using GPS on Field Control Points," *Sensors and Materials*, vol. 35, no. 9, Sep. 2023, Art. no. 3325, https://doi.org/10.18494/SAM4379.

[15] "TOPCON," *TOPCON*. https://www.topcon.co.jp/.

[16] "SOKKIA Global Portal," *SOKKIA*. https://sokkia.com/.

[17] "Terrain," *Zonums*. http://www.zonums.com/gmaps/terrain.php.

[18] K. L. A. El-Ashmawy, "A Cost-Effective Land Surveying System for Engineering Applications," *International Journal of Computer Science and Network Security*, vol. 22, no. 11, pp. 373–380, Nov. 2022, https://doi.org/10.22937/IJCSNS.2022.22.11.54.

[19] *surfer 12 - Full User's Guide*. Golden, CO, USA: Golden Software, Inc., 2014.

[20] A. M. Ali, "Making Different Topographic Maps with the Surfer Software Package," *Engineering, Technology & Applied Science Research*, vol. 14, no. 1, pp. 12556–12560, Feb. 2024, https://doi.org/10.48084/etasr.6525.

[21] D. K. L. A. El-Ashmawy, "Mathematical Digital Terrain Model (DTM) Data for Testing DTM Generation Methodologies and Software," *American Scientific Research Journal for Engineering, Technology, and Sciences*, vol. 76, no. 1, pp. 239–252, Feb. 2021.

[22] C. D. Ghilani, *Adjustment Computations: Spatial Data Analysis*, 6th ed. Hoboken, NJ, USA: Wiley, 2017.

[23] "ASPRS Accuracy Standards for Large-Scale Maps," *PE&RS*, pp. 1068–1070, Jul. 1990.