Evaluating Digital Elevation Models: A Comparison of Terrestrial, UAV, Satellite, and Airborne Sources in District Six, Cape Town

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Keywords: Shuttle Radar Topography Mission, Digital Elevation Model, Unmanned Aerial Vehicle, LiDAR, Absolute, Relative, Accuracy

SUMMARY

This paper evaluates the accuracy and resolution of Digital Elevation Models (DEMs) generated from Unmanned Aerial Vehicles (UAVs) in comparison to traditional terrestrial, satellite, and airborne sources within the context of District Six area in Cape Town, South Africa. Known for its rich historical significance and complex urban landscape, District Six offers a unique and valuable case study for analysing various DEM generation methods. The primary objective of this paper is to assess the applicability of UAV-generated DEMs for urban planning and heritage conservation, in areas that require high-resolution, accurate and cost-effective elevation data. This paper utilized UAV technology to create high-resolution DEMs, capturing detailed elevation data with resolutions ranging from 5 to 20 centimeters. This fine level of detail enables precise analysis of urban features and topography. A DEM generated from a Total Station represents 3D terrain elevation based on precise measurements taken with the instrument. Total Stations typically offers high resolutions because it captures precise point measurements at specific locations, allowing for dense point spacing and more accurate terrain representation. The Total Station captures the horizontal distance and vertical angle to calculate the exact 3D coordinates of each point. These coordinates are then used to create a DEM, which visually represents the elevation changes across a landscape. The DEM generated from a Total Station is useful for applications in many various fields requiring detailed topographic data. Conversely, satellite-based DEMs, such as those derived from the Shuttle Radar Topography Mission (SRTM), typically offer lower resolutions, often between 10 and 30 meters. These satellite models face challenges in urban environments due to building obstructions and vegetation, which can significantly affect elevation accuracy. Airborne LiDAR was also incorporated into the analysis, offering moderate resolution and accuracy at a higher operational cost. While airborne methods provide valuable data, they do not match the spatial resolution achieved by UAVs for localized studies. Ground control points were employed to assess the accuracy of each DEM type, revealing that UAV-generated models significantly outperformed their satellite and airborne counterparts, with a Root Mean Square Error (RMSE) of less than 8 cm. These advantages make UAV's a promising tool for enhancing urban planning and heritage conservation efforts. The ability to capture high-resolution data rapidly and cost-effectively positions UAVs as a vital tool for urban planners and heritage managers. This research suggests that integrating UAV-derived DEMs with existing datasets can enhance decision-making and contribute to preserving culturally significant areas like District Six.

1. INTRODUCTION

Digital Elevation Models (DEMs) serve as vital tools across various fields such as urban planning, environmental oversight, hydrology, and disaster response. The precision and resolution of elevation data are crucial in shaping our comprehension of geographical features, influencing land-use strategies, and aiding in risk evaluations for natural disasters like floods and landslides (Jones et al, 2022). As cities expand and evolve, the need for high-quality, accurate, and dependable DEMs has become increasingly urgent (Elkhrachy, 2021). Recent advancements in remote sensing technologies have revolutionized how elevation data is collected. Unmanned Aerial Vehicles (UAVs), terrestrial, satellite platforms, and airborne LiDAR have emerged as prominent techniques for generating DEMs, each with unique benefits and drawbacks (Polat et al, 2015). UAVs, which are fitted with high-resolution cameras and sensors, allow for capturing detailed images and data at a granular level, making them particularly beneficial for localized research (Zhang et al, 2018). On the other hand, satellite-derived DEMs, such as those generated from the Shuttle Radar Topography Mission (SRTM), provide extensive coverage and a global viewpoint, although they may compromise accuracy in intricate terrains (Wang et al., 2021). Airborne LiDAR is recognized for its accuracy in capturing complex topographical details, rendering it essential for applications where precision is critical (Chen & Zhang, 2020). A DEM generated from a Total Station typically offers high resolution compared to satellite or airborne-based DEMs (Babatunde et al, 2021). This is because the Total Station captures precise point measurements at specific locations, allowing for dense point spacing and a more accurate representation of the terrain, especially for smaller, focused areas.

Despite the wide availability of these varied data sources, there remains a significant gap in the literature concerning thorough comparative studies that assess their accuracy, especially within urban settings (Remondino et al, 2014). District Six, located in Cape Town, serves as an intriguing case study due to its rich historical background and complicated topography. Once a thriving community, District Six suffered extensive socio-political turmoil that resulted in its devastation and ongoing neglect (Davies, 2018). Currently, the area is marked by a mixture of urban renewal projects, presenting a distinctive and challenging environment for elevation modelling. The diversity of land use and the remnants of past structures further complicate the evaluation of elevation data (Smith and Jones, 2021). This research aims to assess and compare the accuracy of DEMs obtained from Total Station, UAV, SRTM, and LiDAR sources specifically in District Six. By utilizing rigorous techniques such as Root Mean Square Error (RMSE) analysis, the study will evaluate how closely these different sources match ground truth data collected from extensive field surveys (Pereira et al, 2020). Concentrating on accuracy not only enhances the understanding of each data source's effectiveness but also provides insights into their relevance for various urban planning contexts (Zhang et al, 2016).

Specifically, this paper intends to answer crucial questions: How do the accuracy rates of UAV-derived DEMs stack up against those produced from Total Station, SRTM, and LiDAR? What consequences do these discrepancies hold for urban planners and decision-makers who depend on precise elevation data for effective land management? Addressing these questions aims to bridge a significant gap in the current body of knowledge and offer meaningful direction for future research and practical applications. Ultimately, the outcomes of this study bear considerable implications for land surveying, urban planning and policymaking, particularly in historically intricate urban settings like District Six. The ability to accurately evaluate elevation data can enhance decision-making processes, ensuring that urban development is both sustainable and attuned to the region's historical context (Roberts, 2022). This study not only enriches the academic discussion surrounding DEMs but also functions as a practical resource for stakeholders engaged in land surveying, urban renewal and planning in comparable environments.

2. STUDY AREA

District Six (Figure 1) is an area of historical importance in Cape Town, South Africa, recognized for its lively community that was forcibly displaced during the Apartheid period. Founded in the 1800s, it had a diverse demographic and a rich cultural scene, but by 1966, it was designated as a "whites-only" area, resulting in the destruction of homes and the uprooting of its residents. Situated against the slopes of Table Mountain, the location poses unique topographical challenges, combining flat terrain with steep inclines. In recent times, efforts for urban renewal have sought to revitalize District Six, making it crucial to employ precise DEMs for effective land-use planning and infrastructure enhancement. The intricacies of its historical background and varied land use render District Six an excellent case study for assessing the accuracy of various DEM sources, including TS, UAV, SRTM, and LiDAR. District Six features a varied topography characterized by its location on the lower slopes of Table Mountain. The area includes a mix of flat terrain and steep inclines, contributing to its unique landscape. The elevation ranges from sea level at the northern edge to higher elevations as one moves southward toward the mountain. The area is situated between Nelson Mandela Boulevard and Christian Street in Cape Town, South Africa. This area covers roughly 0.33 km^2.

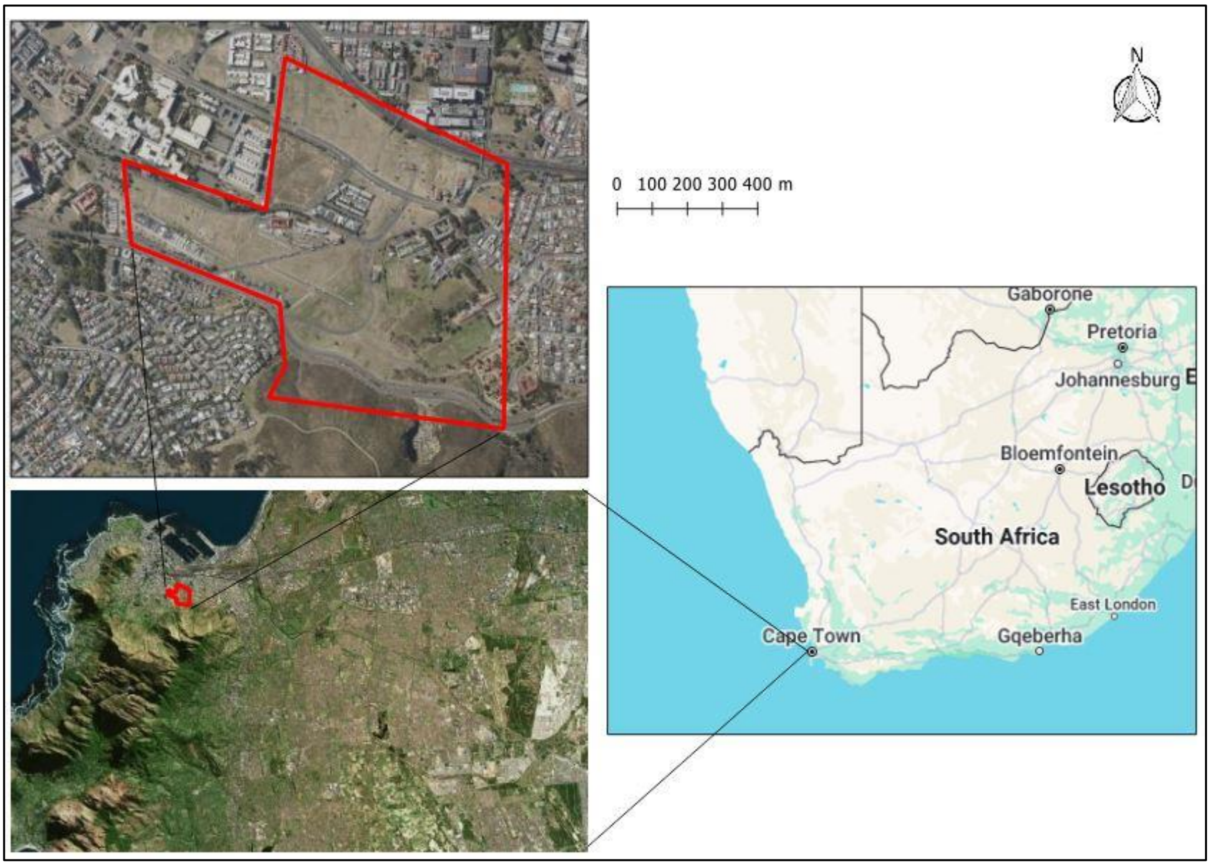

Figure 1: Field site location

3. MATERIALS AND METHODS

3.1 Data Collection

3.1.1 Verification/Checkpoints

A total of 157 evenly spaced pre-marked check (verification) points were surveyed across the 0.33 km² test area. The checkpoints were pre-marked before the drone flight to guarantee their visibility in the UAV photography. The layout of the checkpoints was designed in a "grid" pattern to ensure that there were adequate points located across various slopes and elevation ranges for statistical analysis (refer to Figure 2).

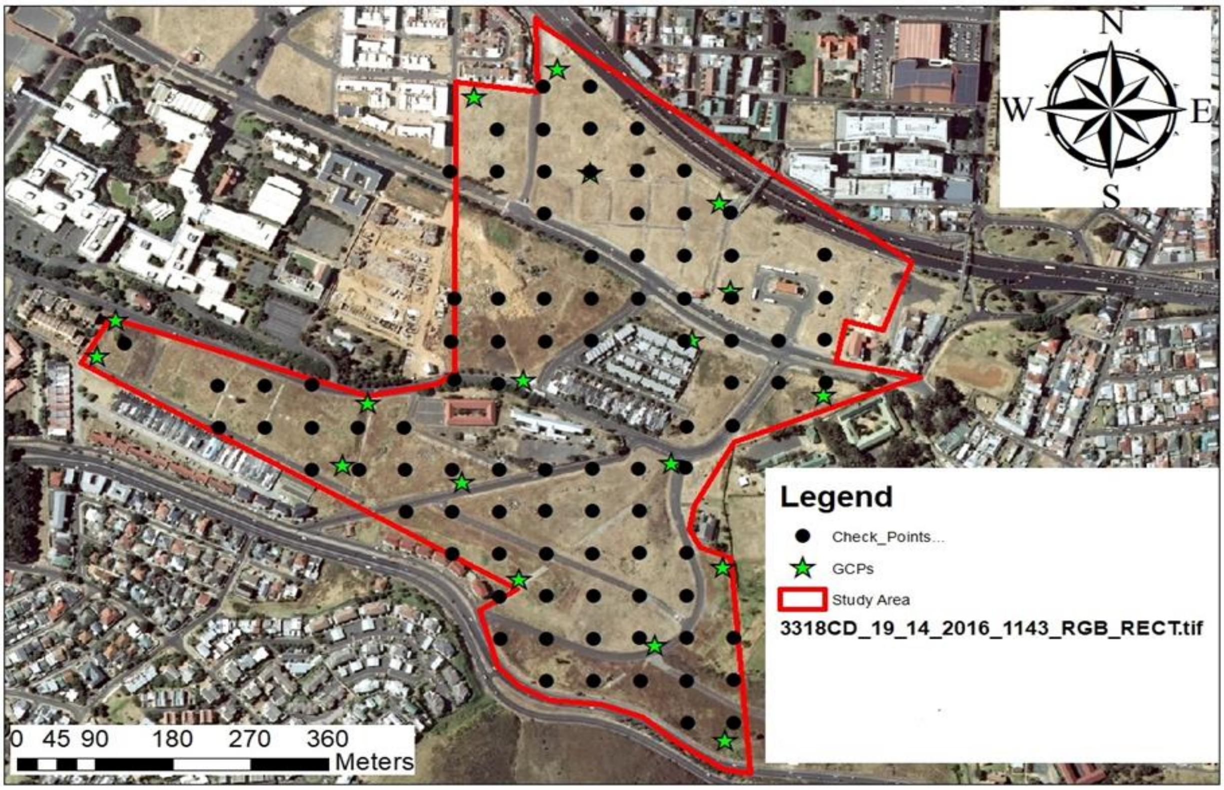

Figure 2. Distribution of checkpoints across the study area

3.1.2 Total Station Data

A Trimble M3 total station was used for the traditional field survey. By selecting points throughout the study area, a topographical survey (spot shots) was used to ascertain the horizontal and vertical positions. The survey's area of interest was covered by spot shots observed using several Town Survey Marks. Trigonometric methods were used for all field observations, which were conducted from a total station to a prism pole that was 2m long and had a prism mounted. After that, each observation's trigonometric location data and comprehensive feature coding information were entered into the internal data recorder of the total station. Because of this accurate feature coding, the survey software was able to create contour and break-line data, place various feature types on separate data levels, and draw lines between data. To create the triangle file required to create a DTM, the contour and break-line information were utilized.

3.1.3 UAV data – sensor and flight parameters

A DJI Phantom 4 Professional drone equipped with a 1/2.3" CMOS camera sensor featuring 12.4 effective pixels was utilized to take aerial photos from an altitude of 120 m above the ground. This camera includes a 94° FOV 20 mm (equivalent to 35 mm format) f/2.8 focus lens and supports a maximum image resolution of 4864 x 3648. In total, 290 images were taken, utilizing 75% and 70% front and side overlaps to enhance stereoscopic imaging and prevent gaps. To create a stereoscopic representation of a scene and eliminate voids for effective photogrammetric outcomes, a minimum of 60% forward and 30% lateral overlaps is necessary (Rau et al., 2011). Considerations such as flight regulations, maximum flight duration, and ground pixel resolution were taken into account to establish the flight elevation. The chosen altitude of 120 m aligned with all these factors. It remained within the maximum permissible flight height in South Africa, and the mission could be accomplished within one battery charge, providing roughly 20 minutes of flying time. This resulted in capturing 290 images within each required strip to comprehensively cover the study area (Refer to Figure 3 for flight details). Additionally, our initial evaluation of flight heights indicated that 120 m was more advantageous than both 100 and 140 m heights. The flight at 120 m achieved an RMSE of 0.079 m, while flights at 100 m and 140 m produced RMSEs of 0.338 and 0.264 m, respectively.

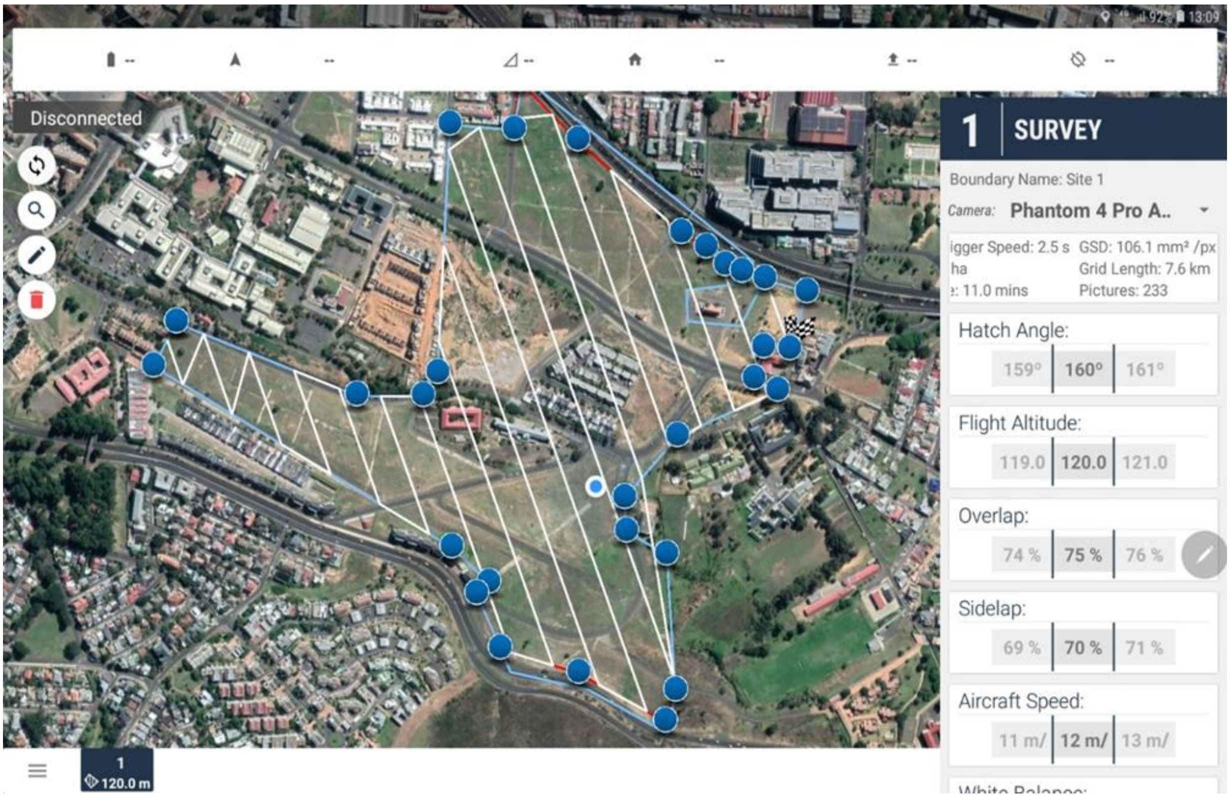

Figure 3. Flight parameters– Altitude, overlap, Ground Sampling Distance, and flight path design.

3.1.4 Satellite Data

The global 1-arcsecond (30-m) SRTM DEM is now accessible to the public via sites such as Earth Explorer on the United States Geological Survey website. The SRTM elevation data for the study area was downloaded from the (http://earthexplorer.usgs.gov) website. The downloaded data were then projected to the Hart 94 coordinate system using ArcMap based on the WGS84 reference system. The original SRTM was available in the United States with a 30 m resolution and a 90 m resolution everywhere else. NASA released the global 30-m resolution (1-arcsecond) DEM in 2014; a report found that the current 1-arcsecond Level-2 product had an absolute (vertical) accuracy of 16 m and a relative (horizontal) accuracy of 6 m at a 90% confidence level (Bamler, 1990).

3.1.5 Air-borne Data

Light Detection and Ranging (LiDAR) data was provided by the City of Cape Town. It was captured in the years 2011 to 2015. The point cloud has a density of 2 to 3 points/m2. The LiDAR data was processed and referenced onto the current South African geodetic datum (Hart94 datum) and land levelling datum, for horizontal and vertical positioning, respectively. Hart94 datum is based on WGS84 reference system (Wonnacott, 1999), hence all datasets (UAV, LiDAR, and SRTM) are based on the same horizontal geodetic datum. The heights obtained from UAV, LiDAR, and SRTM are also compatible because spheroidal orthometric height system used in South Africa is close to normal height system as applied in practice. Assessment of the vertical accuracy of DEMs is achieved by comparing SRTM, and LiDAR DEMs heights with the UAV data. The LiDAR DEM used for this research has a resolution of 1m. This enabled the research to compare with the UAV and SRTM DEMs.

3.2 Data Processing

3.2.1 Total Station data

The M3 Trimble Total Station digital data were exported as a.csv file to an SD card. QGIS and other survey software programs use this file format as a standard. After being copied to the PC from the SD card, the .csv file was imported into QGIS. The import process entails transforming the raw bearings and distances from the observation data into points in coordinate format. A unique point identity that can be understood by the QGIS software is then encoded using an alphabetic coding system into the field observation data. Lastly, to build lines between frequent points, point coding is combined with additional string information. QGIS can also automatically name contour-able points and other features thanks to this coding and string system. Additionally, QGIS can automatically label contour-able points and break-lines to create a 3-dimensional triangle file, which is utilized to generate contour data, DSM, and DTM (see Figure 4) within the program, thanks to this coding and string system. After the reduction process was finished, the data and reduction report were manually reviewed for errors.

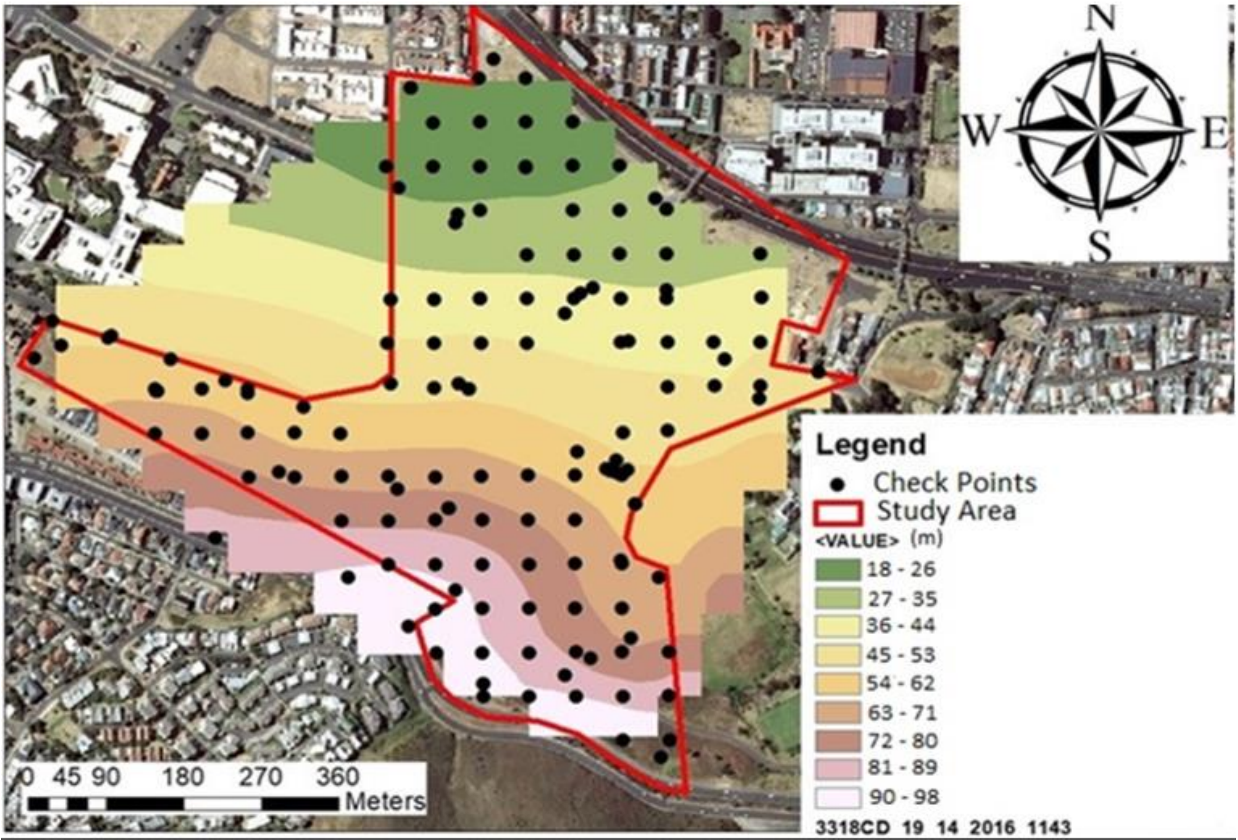

Figure 4 Digital Terrain Model of the Total Station Data

3.2.2 UAV drone data

The image processing was carried out using Pix4D software. For geo-referencing the ortho-rectified images captured by the UAV during the field survey, a total of 18 ground control points (GCPs) were utilized. The GCPs were integrated into the project to accurately geo-reference the point cloud. The Pix4D software features a three-stage automatic image processing system, which completes each stage upon user command. The resulting Digital Surface Model and Ortho-mosaic are illustrated in Figure 5.

The image processing took less than five hours to complete with Pix4D software. A total of 290 images were collected, resulting in a ground sampling resolution (GSR) of 34.30 mm/pixel over a flight altitude of 120 m. The Pix4D software calculated the total area covered by the ortho-rectified georeferenced image to be 0.583 km². During the field test, 18 GCPs were employed to geo-reference the ortho-rectified or 'tiled' images taken by the UAV. The Pix4D software determined a root mean square error (RMSE) of 0.006 m in the geo-rectification step. Additionally, the report indicated a 100% image calibration with a median of 34678 matches per calibrated image. The low RMSE for the GCPs demonstrates that the georeferenced UAV survey model possesses a high level of three-dimensional accuracy.

The flight surface model exported from Pix4D was imported into the ArcGIS project. The project workspace was configured to the Hartebeeshoek 94 coordinate system. The generation of the DEM was completed using a medium-resolution setting (refer to Figure 6). A crucial evaluation of these processes involved an independent assessment of the vertical accuracy of the DEM utilizing checkpoints. An orthophoto, which is an image of the area, was generated through the aerial triangulation method, which was based on the measurement of tie points. After successfully registering all overlapping image pairs of the study location captured by the UAV and confirming that height and tilt distortions were corrected (through orthorectification) to ensure geometric accuracy, spatial information could be accurately extracted from the captured area (using the orthophoto). marking points on the ground before the flight was essential to guarantee their visibility in the images post-flight. These points were then digitized, and the height (H) was acquired from the georeferenced image (ortho-mosaic) and the DEM. Following the digitization of the checkpoints, values were retrieved from the UAV DEM to support the validation process.

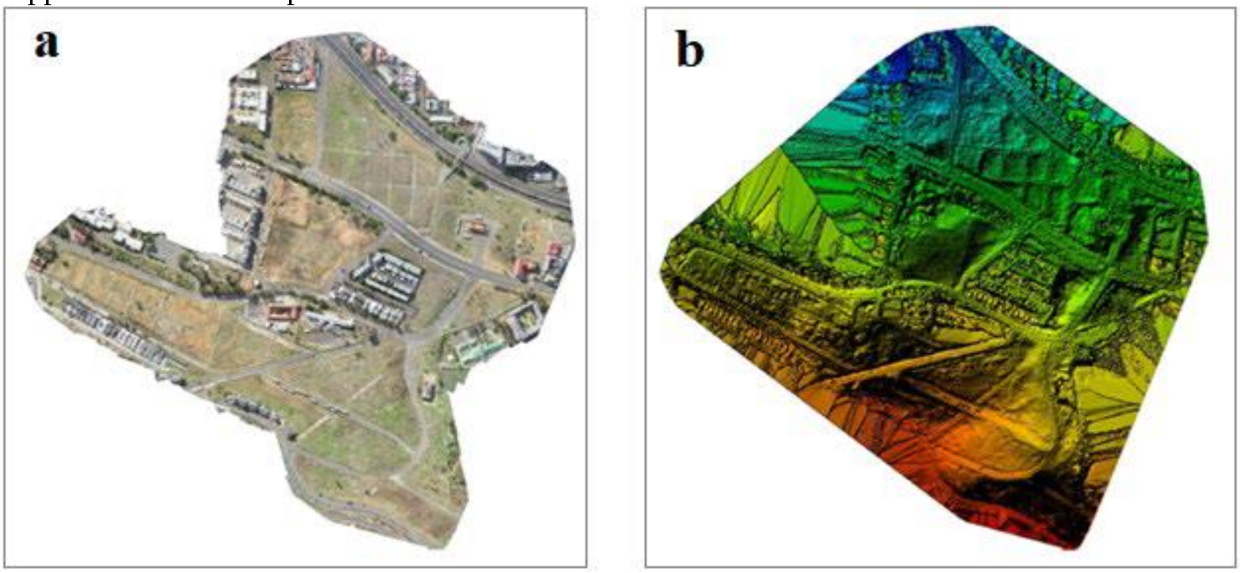

Figure 5. Screenshot of the Ortho-mosaic from UAV data (a) and Digital Surface Model from UAV data (b)

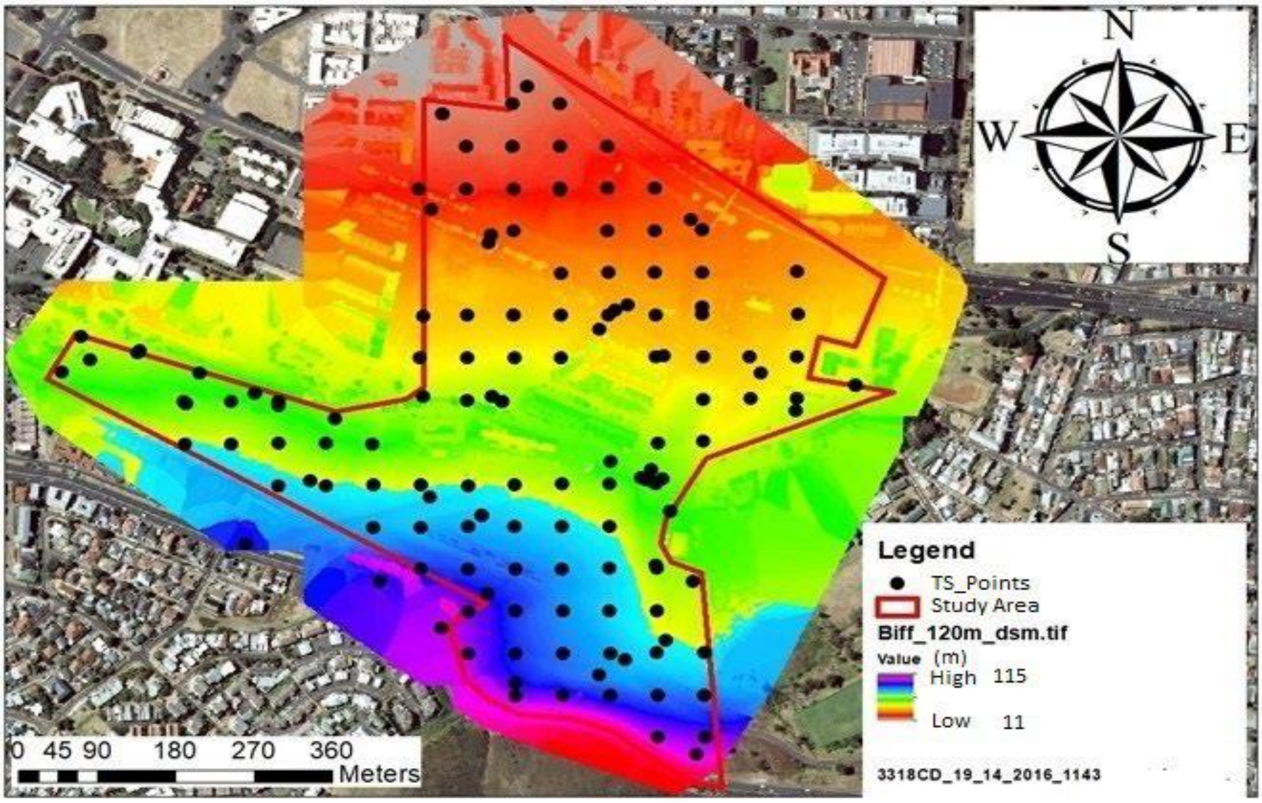

Figure 6. Digital Elevation Model from UAV data

3.2.2 Other satellite and airborne data

The Shuttle Radar Topographic Mission (SRTM) conducted by the National Aeronautics and Space Administration (NASA) has generated digital elevation models (DEMs) for more than 80% of the Earth's surface (Rodriguez et al., 2005). This information is currently available from the USGS and can be downloaded through the National Map Seamless Data Distribution System or the USGS ftp site (https://earthexplorer.usgs.gov/). The SRTM 1 Arc-Second Global elevation data provide comprehensive coverage of filled void data at a resolution of 1 arc-second (30 meters) and allows for open access to this high-resolution global dataset. To derive elevation information from SRTM imagery for the area of interest, the downloaded GeoTiff file was displayed in ArcGIS using the WGS84 Hartebeeshoek 94 coordinate system, (see Figure 7). The resulting elevation data were compared with those obtained from on-the-ground surveys. The horizontal reference system used is the World Geodetic System of 1984 (WGS84), while the vertical reference is based on the Earth Gravitational Model of 1996 (EGM96).

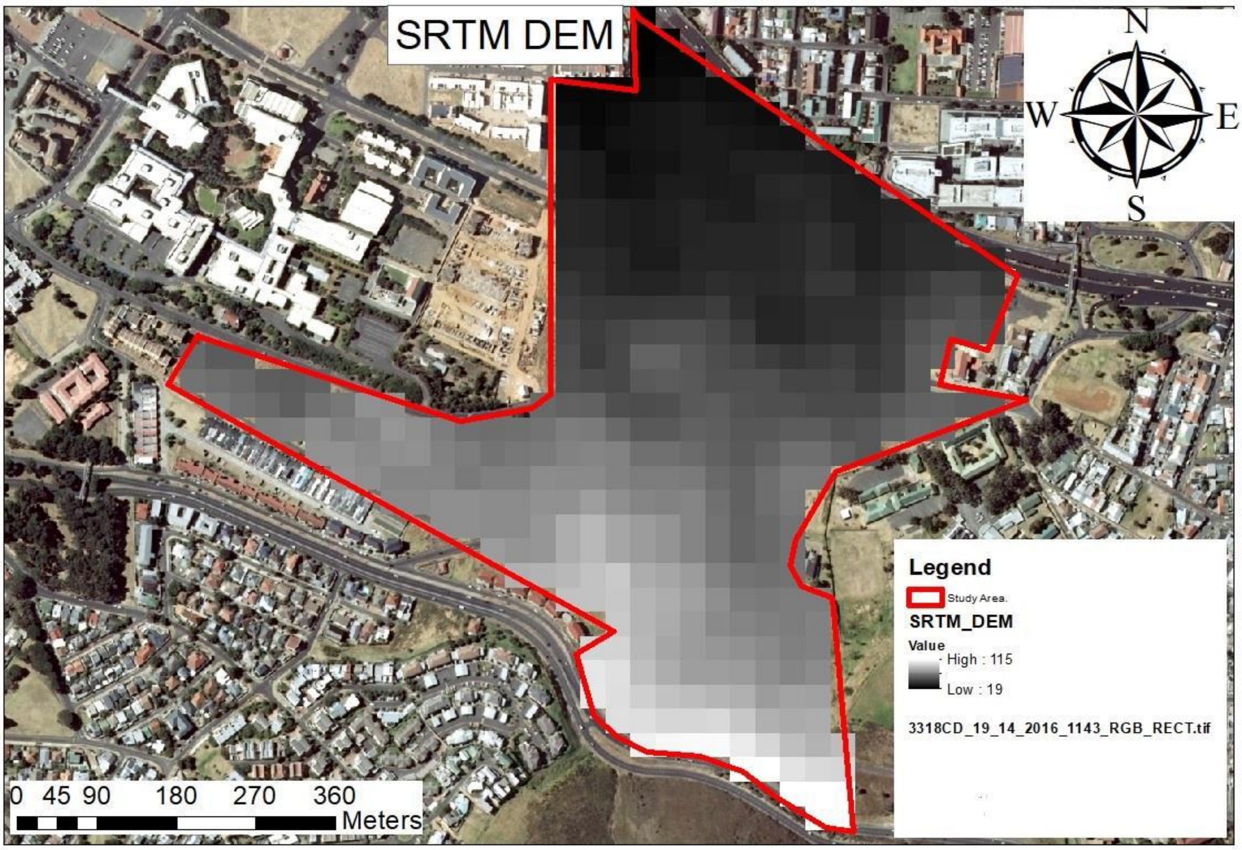

Figure 7 Digital Elevation Model from SRTM data

Light Detection and Ranging (LiDAR) data was sourced from the City of Cape Town and was collected between 2011 and 2015. The point cloud exhibits a density of 2 to 3 points per square meter. The LiDAR data underwent processing and was aligned to the current South African geodetic datum (Hart94 datum) and the land levelling datum for both horizontal and vertical positioning (see Figure 8). The Hart94 datum is founded on the WGS84 reference system (Wonnacott, 1999), which means that all datasets (LiDAR, TS, UAV, and SRTM) are aligned to the same vertical geodetic datum. The heights derived from total station surveys, LiDAR, UAV, and SRTM are consistent because the spheroidal orthometric height system utilized in South Africa closely approximates the normal height system used in practice. The vertical accuracy of the DEMs is evaluated by comparing heights from the SRTM, UAV, and LiDAR DEMs against ground total station data in the western region of South Africa as well as in the City of Cape Town (District 6 area). The LiDAR DEM utilized for this study has a resolution of 1 meter, allowing for comparison with data from total station surveys, UAV, and SRTM DEMs.

Figure 8 Digital Elevation Model from LiDAR data

3.2.3 DEM Accuracy

We employed root mean square error (RMSE) to evaluate the precision of the vertical coordinates obtained from UAV data across the study region. RMSE represents the average square root of the squared discrepancies between the reconstructed model and the surveyed coordinates (Congalton, 2005) at 157 checkpoints (CPs). In this context, the errors are the variations between the ground-surveyed coordinates and those generated from the UAV, SRTM, and LiDAR data models. RMSE is sensitive to estimated outlier values, as significant errors greatly influence this measure. Nevertheless, it remains one of the most utilized statistics in many validation studies. Equations [1] provide the formulas for calculating RMSE values for the H component.

$$RMSEH = \sqrt{\frac{\sum_{i=1}^{n}(HDEM1{,}2{,}3{,}4 - HDEM1{,}2{,}3{,}4\,)^2}{n}} \qquad [1]$$

where:

n is the number of points observed,

HDEM1-4, DEM1 (TS), DEM2 (UAV), DEM 3 (SRTM), and DEM4 (LiDAR) are *H* coordinates estimated by the Total Station, UAV, SRTM, and LiDAR models

4. COMPARISON AND EVALUATION

4.1 Accuracy Assessment

The assessment of accuracy for DEMs derived from UAVs in relation to other DEMs, including those generated from Total Station, SRTM, and LiDAR, emphasizes the evaluation of the precision and dependability of elevation data produced by these methods. UAV-derived DEMs are recognized for their exceptional spatial resolution and accuracy, frequently achieving precision at the centimeter level, particularly when utilized in conjunction with Real-Time Kinematic (RTK) or Post-Processed Kinematic (PPK) systems. Conversely, LiDAR DEMs also exhibit high accuracy, providing precise vertical measurements and detailed representations of intricate terrains, notably in forested or urban settings. LiDAR is often regarded as the benchmark for DEM accuracy due to its capability to capture intricate surface characteristics. In contrast, satellite-based DEMs, such as those from SRTM, typically offer coarser resolutions (for instance, 30 meters) and are less reliable in representing terrain, especially in areas characterized by rugged landscapes, dense vegetation, or urban development. A DEM generated from a Total Station typically offers high resolution compared to satellite or airborne-based DEMs. This is because the Total Station captures precise point measurements at specific locations, allowing for dense point spacing and a more accurate representation of the terrain, especially for smaller, focused areas. To evaluate the accuracy of UAV against other terrestrial, satellite, and airborne DEMs, prevalent methods included comparing the datasets using ground checkpoints utilizing metrics such as RMSE and overall accuracy. This analysis aids in identifying the suitability of Total Station, UAV, and LiDAR-derived DEMs for applications that demand high precision, while also uncovering the shortcomings of satellite-based DEMs, especially in regions where detailed topographic features are essential.

In two ways, comparisons were made: Absolute and Relative accuracy

Absolute differences in height:

- Extracting height values from SRTM using the coordinates of checkpoints, then comparing extracted height with UAV (SRTM and UAV).

- Extraction of height values from LiDAR using coordinates of the checkpoints followed by a comparison of extracted height with UAV (LiDAR and UAV). Comparing the heights of the LiDAR and SRTM grids.

Table 1 absolute differences in height between, TS, UAV DEM, LiDAR DEM, and SRTM DEM data - 120m flight height at 157 checkpoints

Differences in DEMS	Minimum (m)	Maximum (m)	Mean (m)	Standard Deviation (m)	RMSE (m)
TS and UAV	-0.270	0.369	-0.042	0.067	0.079
TS and LiDAR	-2.867	0.751	-0.198	0.400	0.445
TS and SRTM	-14.170	11.676	-1.053	4.054	4.176
UAV and LiDAR	-2.868	0.718	-0.156	0.401	0.429
UAV and SRTM	-14.074	11.725	-1.011	4.054	4.166
LiDAR and SRTM	--14.040	11.785	-0.855	4.003	4.081

This study examined terrestrial, UAV, satellite and airborne (TS, UAV, SRTM, and LiDAR) DEM for elevation reference data at 157 CPs. The absolute differences between TS and UAV, TS and LiDAR, and TS and SRTM were presented in three ways, see Table 1. First, the map depicts the locations of the 157 CPs (Figure 2). Using total station elevations as reference data, the statistical computation (RMSE) for the absolute vertical accuracy of SRTM elevation data for the study site yielded a value of 4,176m. When comparing TS and UAV for the study site, the RMSE for absolute vertical (H) 0.079m. When comparing TS and LiDAR for absolute vertical accuracy at the study site, the RMSE value was 0.445m. This finding demonstrates that the practical accuracy of (H) data derived from UAV photogrammetry is comparable to that of Total Station, which is commonly used for cadastral, topographic and engineering surveying. This indicates that UAV photogrammetry can be utilised as a surveying technique to collect data for topographical surveying and the generation of DEMs. LiDAR provides high resolution but at a broader scale. Airborne LiDAR offered point spacing from 0.5 to 2 meters. Ground-based LiDAR captures the surface features more continuously and automatically, making it suitable for large-area surveys. The absolute vertical accuracy of the UAV and SRTM elevation data is significantly lower than the value of 16m specified in the SRTM data specification. The analyses presented in this paper indicate that the absolute vertical accuracy of less than 5m for all the flight is less than the original SRTM requirement specification value of 16m.

Relative differences in height:

A total of 369 points were generated in the study area using the fishnet function of the ArcGIS software at a 30m x 30m Grid (see figure 9). Table 2 displays the relative height differences between UAV DEM, LiDAR DEM and SRTM DEM at each of the three heights.

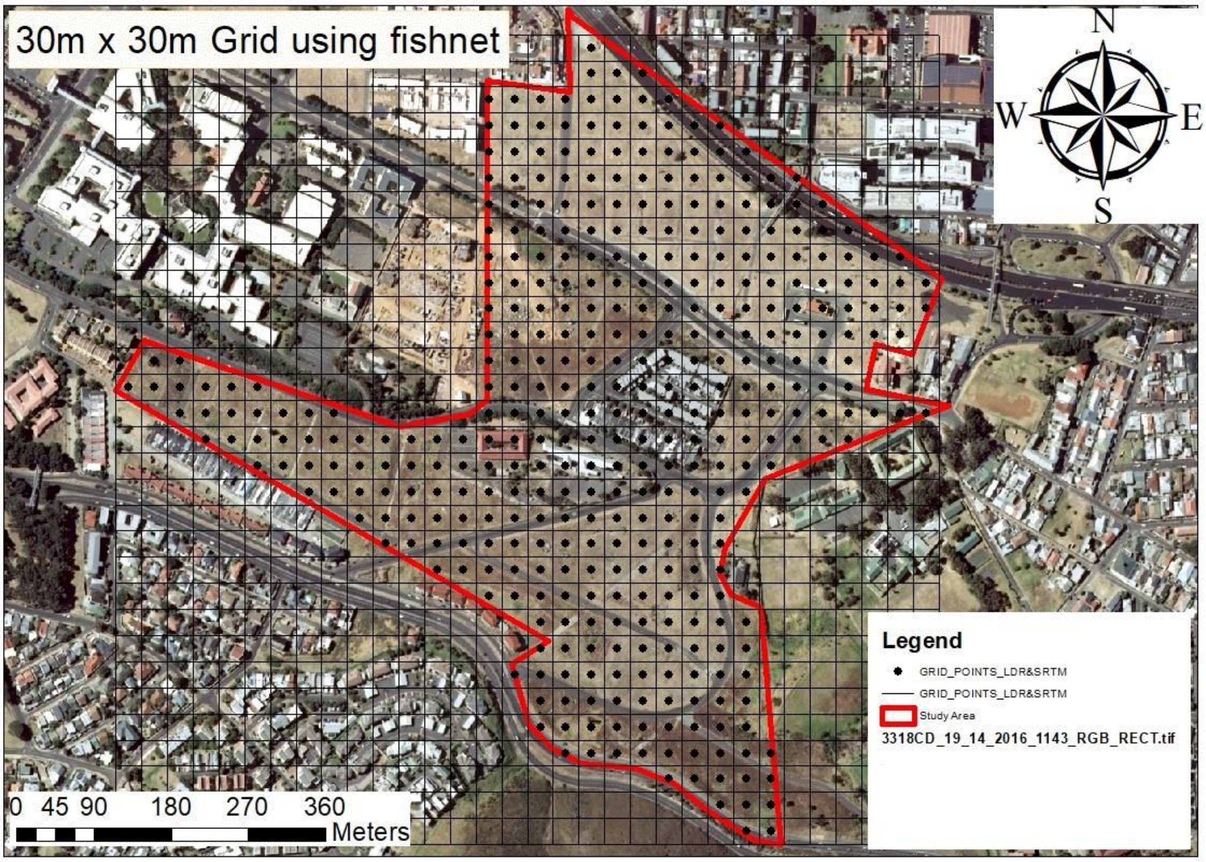

Figure 9: 30mx 30m grid points (fishnet)

Table 2 Relative differences in height between, UAV DEM, LiDAR DEM, and SRTM DEM data - 120m flight height at 369 grid points

Differences in DEMS	Minimum (m)	Maximum (m)	Mean (m)	Standard Deviation (m)	RMSE (m)
UAV and LiDAR	-3.712	1.957	-0.170	0.500	0.528
UAV and SRTM	-12.079	14.124	-0.635	0.440	4.479
LiDAR and SRTM	-11.583	14.120	-0.465	4.363	4.382

As depicted in Figure 9, 369 grid points (30x30m) were generated using the fishnet function in the ArcGIS software Table 2 displays the relative height differences between UAV DEM, LiDAR DEM and SRTM DEM at the 120m flight height. Three methods were used to determine the relative differences: UAV and SRTM, UAV and LiDAR and LiDAR and SRTM. The relative vertical accuracy (RMSE) between UAV and SRTM elevation data for the study site was calculated to be 4.479m. The RMSE for relative vertical accuracy between UAV and LiDAR at the study site was 0.528m. The RMSE for relative vertical accuracy between SRTM and LiDAR at the study site was 4,382m. The relative vertical accuracy of the UAV and SRTM elevation data is less than 5m which is acceptable given the SRTM data relative accuracy specification of 6m. According to the analyses presented in this paper, the relative vertical accuracy of UAV data for our datasets has proven to be comparable to that of SRTM. The UAV elevation data exhibits acceptable relative vertical accuracy compared to LiDAR elevation data. Compared to LiDAR data, the relative vertical accuracy of UAV data for our datasets has proven to be acceptable, according to the analyses presented in this paper.

5. Conclusions

The results of this paper indicate that UAV Photogrammetry data are sufficiently precise. Therefore, it is possible to use UAV Photogrammetry data for map-making, surveying, and topographical surveying applications with low-cost, time-saving, and minimal fieldwork benefits. SRTM data are frequently incorporated into global elevation models. Nonetheless, this data, with a resolution of 30m, is not favoured for sensitive geographical research. The error margin is significantly larger, even though the data is widely accepted and widely used, as demonstrated by the results of this study. The method's applicability is confirmed by the accuracy of the UAV DEM generated from SRTM DEM and LiDAR comparisons. It was observed that LiDAR and UAV-based data and products were in good agreement. UAV data provides more geometrical details than LiDAR, resulting in enhanced feature detection. The UAV-based data have a larger RMSE in heights than the LiDAR-based data. This observation can be explained by the higher point density in the UAV data, as discussed in the results. According to these results, UAV image data can be used as a substitute for LiDAR data in areas where it is unavailable or where frequent acquisitions are required. The results indicate that photogrammetry data products are a viable alternative to LiDAR in areas with limited vegetation and surface disturbances and may be preferred due to their lower cost and immediate access to data products, as observed by (Vilbig et al, 2020). The findings demonstrate that UAV-generated DEMs significantly outperform satellite-based and airborne methods in terms of resolution and accuracy. This supports the conclusion that UAV technology provides superior data for urban planning and heritage conservation, particularly in densely built environments like District Six. The high-resolution data captured by UAVs allow for detailed analysis of topographical features. Furthermore, the UAV elevation data exhibits acceptable relative vertical accuracy compared to LiDAR elevation data. Compared to LiDAR, Total Station, and SRTM data, the relative vertical accuracy of UAV data for our datasets has proven to be acceptable, according to the analyses presented in this paper. Our findings corroborate those of comparable studies (Agüera-Vega et al, 2016) and further validate the use of UAVs for DEM generation and other general applications such as topographical mapping, which offer cost and time savings.

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BIOGRAPHICAL NOTES

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