CHALLENGES IN DETERMINING THE MOST APPROPRIATE DIGITAL ELEVATION MODEL (DEM) RESOLUTION FOR ORTHORECTIFYING 0.25M AERIAL IMAGERY

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Key words: Digital Elevation Model, photogrammetry, LiDAR, orthorectification, high-resolution imagery

SUMMARY

The South African National Geospatial Information (NGI) agency continues to face challenges in achieving high geometric accuracy when orthorectifying high-resolution aerial imagery, largely due to its ongoing reliance on a legacy 25 m Digital Elevation Model (DEM). This study assesses whether a photogrammetric DEM can serve as a viable operational alternative by comparing it with a LiDAR-derived reference DEM across three representative terrain grids (W56, W57, and W58) in the Western Cape, South Africa. These grids encompass rugged mountainous, moderately dissected, and low-relief coastal environments, enabling evaluation across diverse terrain complexities.

DEM comparisons were performed at 5 m and 10 m spatial resolutions, utilizing raster-based elevation differences and statistical accuracy metrics such as mean error and Root Mean Square Error (RMSE). The results showed very small mean elevation differences across all grids, indicating minimal systematic vertical bias between the photogrammetric and LiDAR DEMs. Nonetheless, variability and extreme differences are strongly linked to terrain morphology and image resolution. Rugged terrains displayed larger, localized discrepancies, whereas moderate and low-relief areas generally showed strong agreement, especially at 5 m resolution. The use of coarser resolution tended to increase discrepancies due to surface generalisation.

These findings demonstrate that a 5m photogrammetric DEM can be a reliable and operationally efficient solution for national-scale mapping and orthorectification of 0.25m GSD imagery in suitable terrains. However, they also highlight the ongoing importance of expert-driven DEM production and the need for expanded LiDAR integration in complex landscapes.

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1. INTRODUCTION

Digital Elevation Models (DEMs) are a fundamental component of modern geospatial workflows, underpinning applications such as orthorectification, terrain analysis, hydrological modelling, and infrastructure planning. The accuracy and spatial resolution of a DEM directly influence the geometric fidelity of derived products, particularly in high-resolution remote sensing applications where even small vertical errors can translate into significant horizontal distortions. As aerial and satellite imagery resolutions continue to improve, the suitability of legacy DEM specifications has become a critical concern for national mapping agencies tasked with ensuring consistent positional accuracy across diverse landscapes.

The Chief Directorate of National Geospatial Information (CDNGI) has been acquiring aerial imagery on behalf of the South African State since 1926. In its early years, analogue aerial photography played a critical role in map production (Pinto et al., 2019). The transition to digital photogrammetric workflows in the mid-1990s enabled aerial triangulation and systematic DEM generation, leading to the adoption of a 25 m DEM as the national standard for orthorectification. Since 2008, CDNGI has substantially improved aerial image capture, reducing the ground sample distance (GSD) from 50 cm to 25 cm. Despite these advances, the DEM specification used for orthorectification has remained unchanged, raising concerns about geometric accuracy in complex terrains characterised by steep slopes and pronounced surface discontinuities (Voglino et al., 2025).

At the same time, current DEM production methods at NGI remain labour-intensive, time-consuming, and dependent on expert-driven processes. At the current production rate, achieving comprehensive national DEM coverage would take many years, limiting the agency's ability to respond to growing demands for high-resolution, up-to-date geospatial products. While externally generated photogrammetric DEMs offer a potential alternative, their operational adoption presents challenges related to accuracy, consistency, and suitability for orthorectifying very high-resolution imagery.

Against this backdrop, this study investigates the suitability of photogrammetric DEMs as an operational substitute for legacy elevation data in the orthorectification of 0.25 m aerial imagery. Specifically, it evaluates the performance of a photogrammetric DEM against a LiDAR-derived reference surface across representative terrain types to assess how terrain complexity and spatial resolution influence elevation accuracy.

The study is guided by the following research questions:

1. To what extent can a photogrammetric DEM meet the geometric accuracy requirements for orthorectifying 0.25 m GSD aerial imagery?
2. How does DEM performance vary across different terrain morphologies and spatial resolutions?
3. What are the implications of adopting alternative DEM sources for national-scale mapping workflows at NGI?

Accordingly, the primary aim of this research is to determine an operationally feasible method for DEM generation that balances efficiency and scalability for NGI's evolving national mapping mandate. In so doing, the study seeks to contribute to a timelier and resolution-sensitive framework for DEM generation.

2. METHODOLOGY

2.1.STUDY AREA

The study area comprises three adjacent 10 km by 10 km mapping grids (W56, W57, and W58) located in the Western Cape, South Africa. Grid W56 features rugged mountainous terrain, W57 represents moderately dissected terrain with rolling hills, and W58 consists of low-relief coastal terrain. This gradient in terrain complexity provides a foundation for assessing the impact of terrain morphology and spatial resolution on DEM performance (Breytenbach & Van Niekerk, 2020).

Figure 1: The location of the three study areas in South Africa (Grid W56, W57 and W58)

2.2. DATA DESCRIPTION

2.2.1. The Lidar Digital Elevation Model

LiDAR data acquisition employs active laser ranging, enabling direct measurement of terrain elevations and partial vegetation penetration. The LiDAR DEM accurately captures fine-scale terrain features, providing a robust representation of the ground surface, especially in complex terrains (Aguilar & Mills, 2008; Elaksher et al., 2023). Previous studies have reported that the LiDAR DEM is suitable for applications such as engineering design and hydrological modelling (Choné et al., 2021; Hatta Antah et al., 2021).

For this study, the LiDAR DEM was resampled to 5 m and 10 m resolutions to align with the Photogrammetric DEM comparison, ensuring a consistent evaluation of resolution effects. Furthermore, the LiDAR dataset, provided by the City of Cape Town Municipality, was evaluated against high-accuracy Ground Control Points (GCPs) within the study grids.

2.2.2. The photogrammetric (H1) Digital Elevation Model

The Photogrammetric dataset, also referred to as the H1 dataset in this study, was created from high-resolution aerial imagery that includes RGB and colour-infrared data. This imagery enables the generation of dense photogrammetric point clouds, which capture the three-dimensional structure of the terrain.

These point clouds were processed to produce Digital Surface Models (DSMs), which were subsequently refined to derive Digital Terrain Models (DTMs). Supporting datasets, such as surface roughness rasters and vegetation layers, were used to enhance terrain interpretation and classification accuracy to minimise errors in the generation of the DEM.

2.3. Comparison Of DEMS

The verification approach integrated point-based sampling and raster-based analysis to assess the agreement in elevation between LiDAR and photogrammetric DEMs at matched spatial resolutions. Similar approaches have been used in DEM assessment studies (Thuse et al., 2025). Initially, both DEMs were precisely aligned via spatial overlay within a GIS environment to ensure accurate co-registration. The method is summarised in Figure 2.

A set of 1,048,575 random sample points was then generated across the study areas and used to extract elevation data from both DEMs at identical locations. To ensure the samples were representative of various terrain conditions, the authors manually verified that the points covered flat surfaces, steep slopes, cliffs, and dissected landscapes. The paired elevation values from these points were compiled into an attribute table, which was used to calculate elevation differences, and these differences were then subjected to statistical analyses (Thuse et al., 2024). Statistical metrics such as mean elevation difference, standard deviation, and Root Mean Square Error (RMSE) summarised the agreement and variability between the datasets.

Figure 2: Methodology workflow

Alongside the point-based method, a raster-based verification was conducted through direct DEM comparison. Elevation difference surfaces were created by subtracting the photogrammetric DEM from the LiDAR DEM at the same spatial resolution (Contreras et al., 2017).

Collectively, these complementary techniques offer both localised and continuous spatial insights into DEM performance. The study also demonstrates the practical challenges faced by NGI in operational DEM verification, illustrating how terrain complexity, spatial resolution, and different DEM generation methods significantly impact accuracy and influence decision-making in national mapping workflows.

3. **RESULTS**

The analysis begins with a direct comparison of elevation values between the LiDAR DEM and the H1 DEM across the three study grids at two resolutions (5 m and 10 m).

3.1 Terrain Elevation on Grid W56, W57 and W58 (Lidar and H1 DEMs)

The analysis begins with a direct comparison of elevation values between the LiDAR DEM and the H1 DEM across the three study grids at two resolutions (5 m and 10 m).

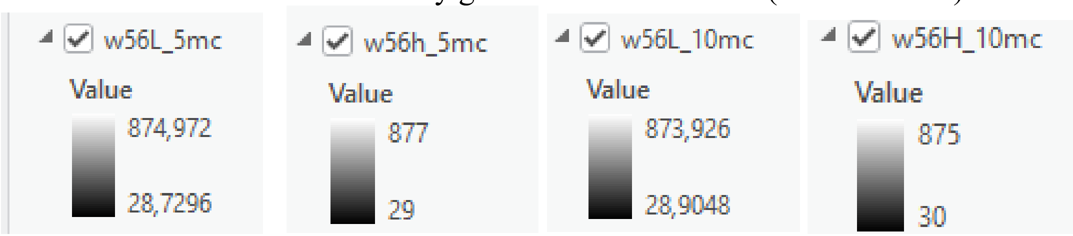

Figure 3: Elevation range between Lider DEM and H1 DEM at Grid W56

In Figure 3, elevation values range from approximately 875 m to 29 m, with minor differences attributed to resampling rather than true terrain discrepancies. The postscripts h and L represent photogrammetric and LiDAR values, respectively.

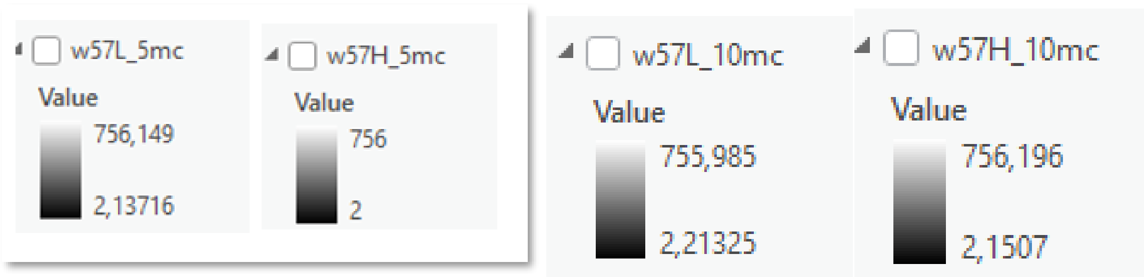

Figure 4: Elevation range between Lider DEM and H1 DEM at Grid W57

In Figure 4, elevation ranges from approximately 756 m to 2 m, showing consistent terrain structures. The postscripts H and L represent photogrammetric and LiDAR values, respectively.

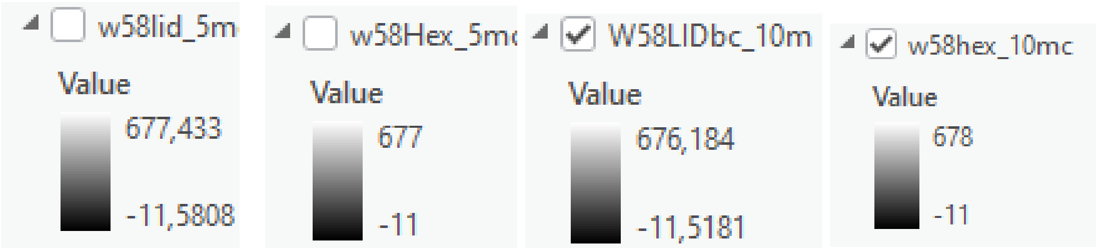

Figure 5: Elevations between Lider DEM and H1 DEM at Grid W58

Elevation values span from approximately 677 m to −11 m, with localized negative elevations in coastal areas. The postscripts Hex and lid represent photogrammetric and LiDAR values, respectively. Across all grids, the LiDAR DEM retains greater precision in the minimum and maximum values, while the H1 DEM presents rounded integer values typical of photogrammetric processing.

3.2 Graphical Analysis of LiDAR and H1 DEM Differences

Elevation difference rasters were generated to assess discrepancies between the LiDAR and H1 DEMs at resolutions of 5 m and 10 m. The approach allows for direct spatial comparison of the two elevation surfaces.

$$\text{Difference } (\Delta h) = \text{LiDAR DEM} - \text{H1 DEM}$$

Positive values indicate locations where the LiDAR DEM is higher than the H1 DEM, while negative values identify areas where the H1 DEM exceeds the LiDAR surface. This approach enables a coherent spatial comparison of the two elevation datasets and aids in interpreting terrain-related variations across the study areas.

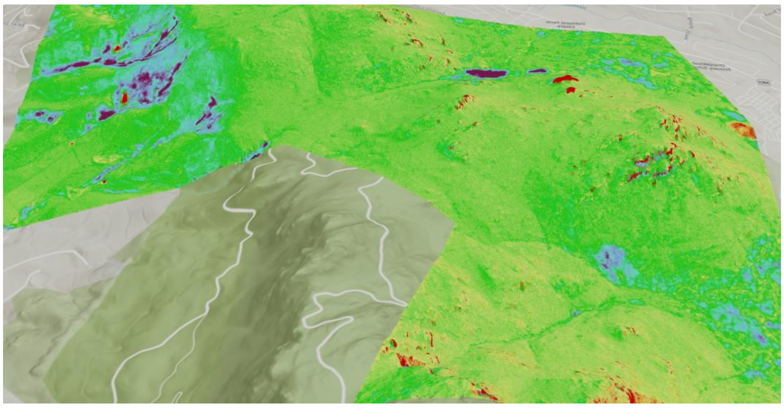
Figure 6: Raster Elevations difference between Lidar DEM and H1 DEM at Grid W56

Figure 6 displays the ranges of the largest elevation differences along the steep edges. The results suggest that rugged terrain can cause discrepancies in the derived elevations.

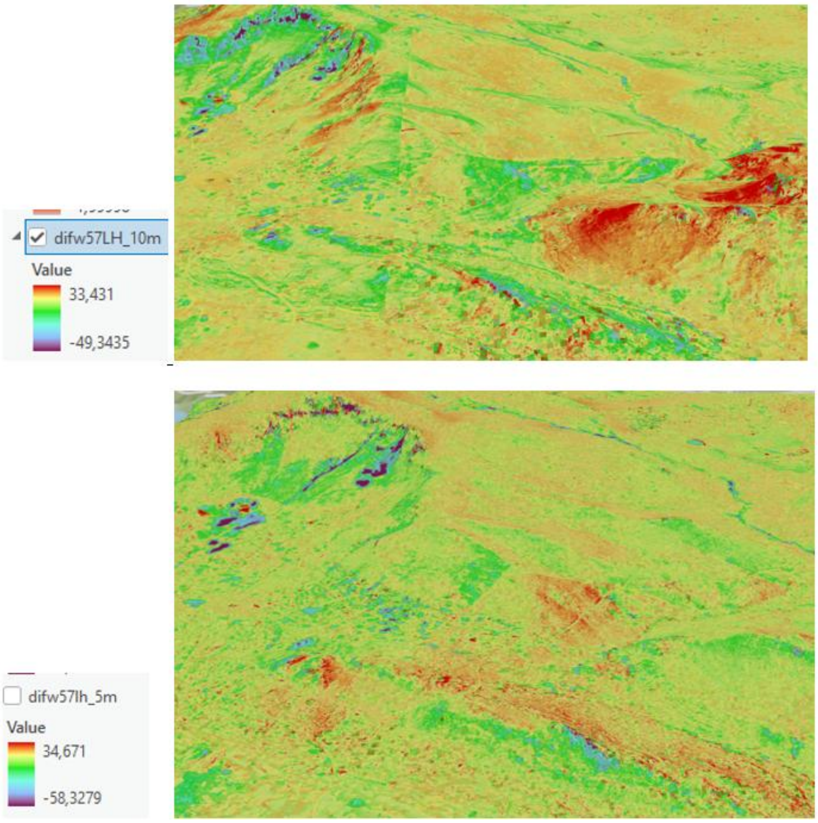

Figure 7: Raster Elevations difference between Lidar and H1 DEM at Grid W57

Indicates strong agreement at 5 m resolution, though coarser resolution at 10 m exaggerates discrepancies.

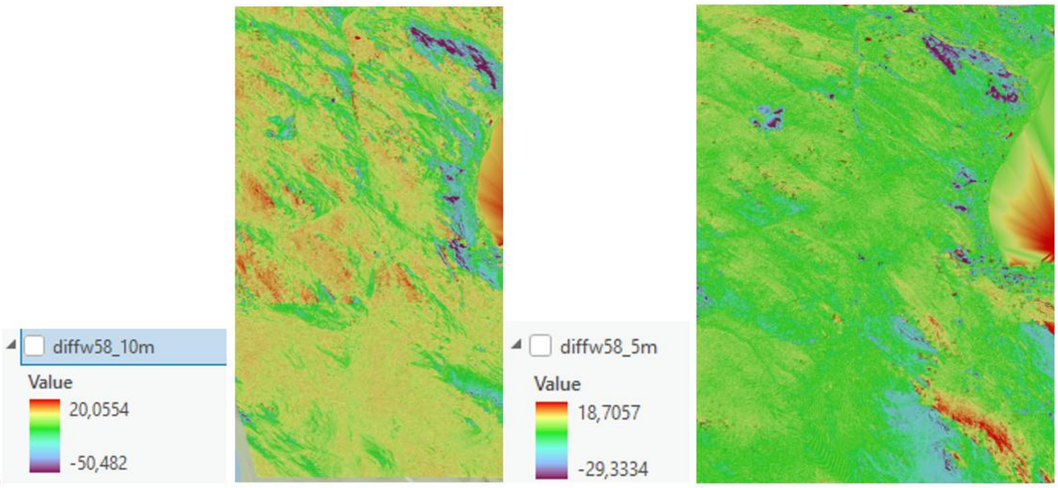

Figure 8: Raster Elevations difference between Lidar and H1 DEM at Grid W58

The figure indicates strong agreement at 5 m resolution, although a coarser 10 m resolution exaggerates elevation discrepancies.

3.2.1 Spatial Areas with Extreme Elevation Differences

Extreme elevation differences between the LiDAR and Photogrammetric DEMs are concentrated in complex terrains across all grids, characterised by steep slopes, escarpments, and dense vegetation.

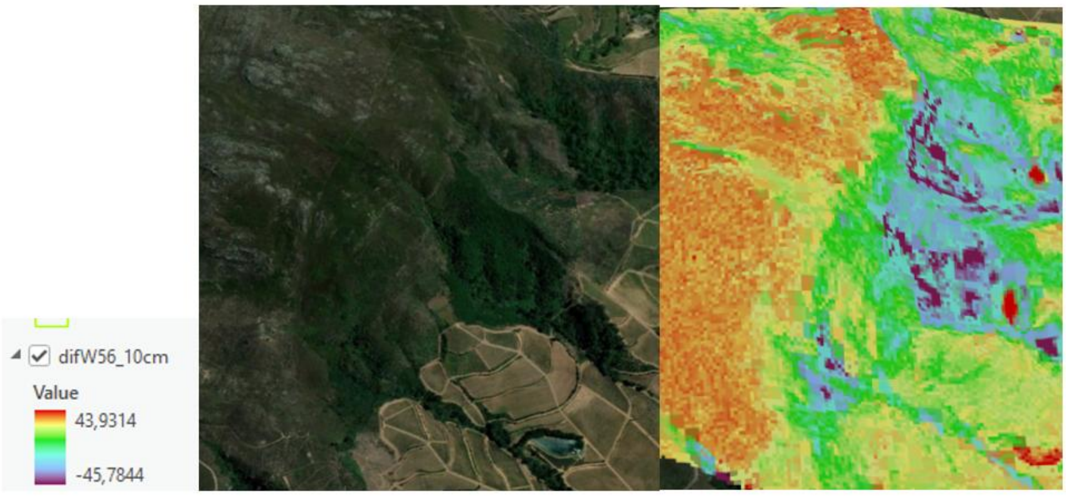

Figure 9: LiDAR–Hexagon DEM difference raster's and Image at Grids W56

Figure 9 shows differences (up to ±45 m) align with rugged terrain and escarpment edges, where LiDAR captures sharp features, whereas the H1 DEM is smoothed.

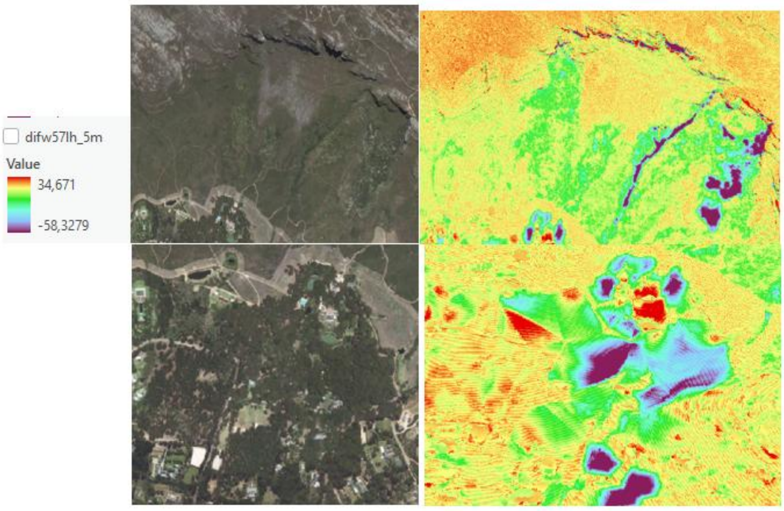

Figure 10: LiDAR–Hexagon DEM difference rasters and Image at Grids W57

Figure 10 shows that discrepancies (+35 m to −58 m) occur along rocky escarpments and in developed areas, with extreme negative values near escarpments and in dense vegetation.

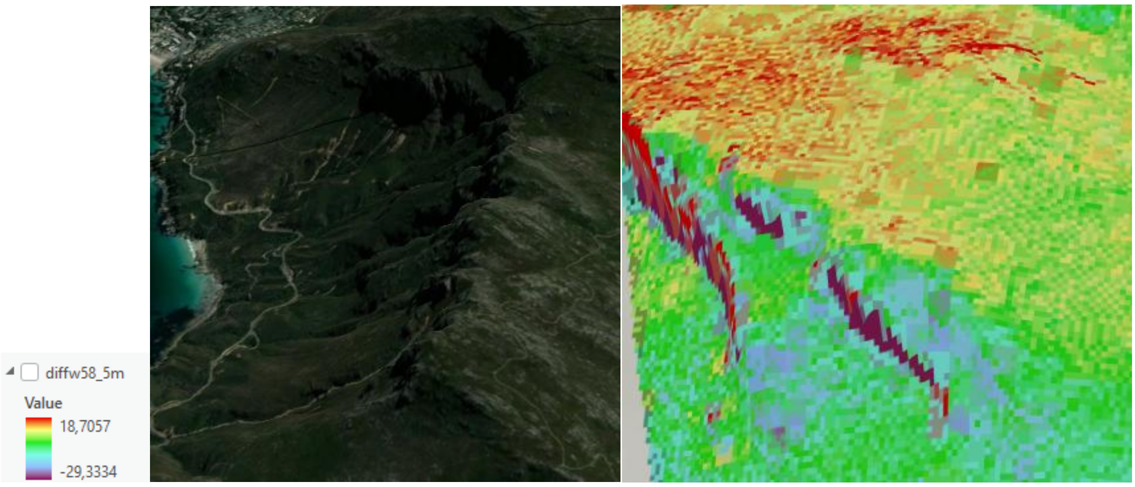

Figure 11: LiDAR–Hexagon DEM difference raster's and Image at Grids W58

Figure 11 shows that differences are confined to coastal cliffs and slope breaks, ranging from +19 m to −29 m, particularly at abrupt transitions.

The patterns of extreme values reflect terrain features and reveal artefacts from resolution effects, posing challenges for DEM verification and highlighting limitations in interpreting elevation differences in complex landscapes.

3.2.2 Statistical Analysis

The tables and figures below show the statistical results from the analysis of the elevations

Table 1

Grid	Resolution	No of points	Mean(m)	Std.Dev(m)	RMSE	Min (m)	Max (m)
W56	10m	472377	-2.440	2.72	3.65	-29.383	47.934
W57	10m	506716	-1.26	1.93	2.31	-52.649	89.594
W58	10m	626660	1.11	1.84	2.14	-49343	33430
W56	5m	619168	-0.459	2.338	2.38	-29.383	47.936
W57	5m	2027007	0.382	1.17	1.23	-58.328	34.671
W58	5m	2507026	0.256	1.12	1.15	-29.33	18.706

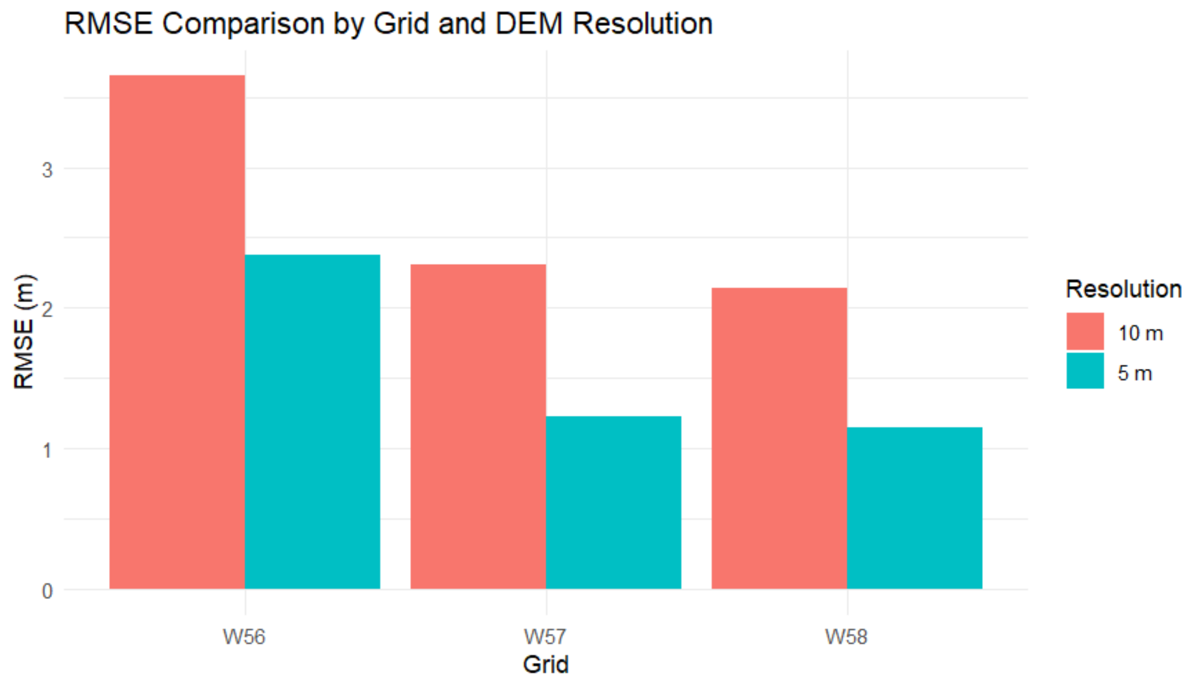

Figure 12: Statistical results of the RMSE analysis

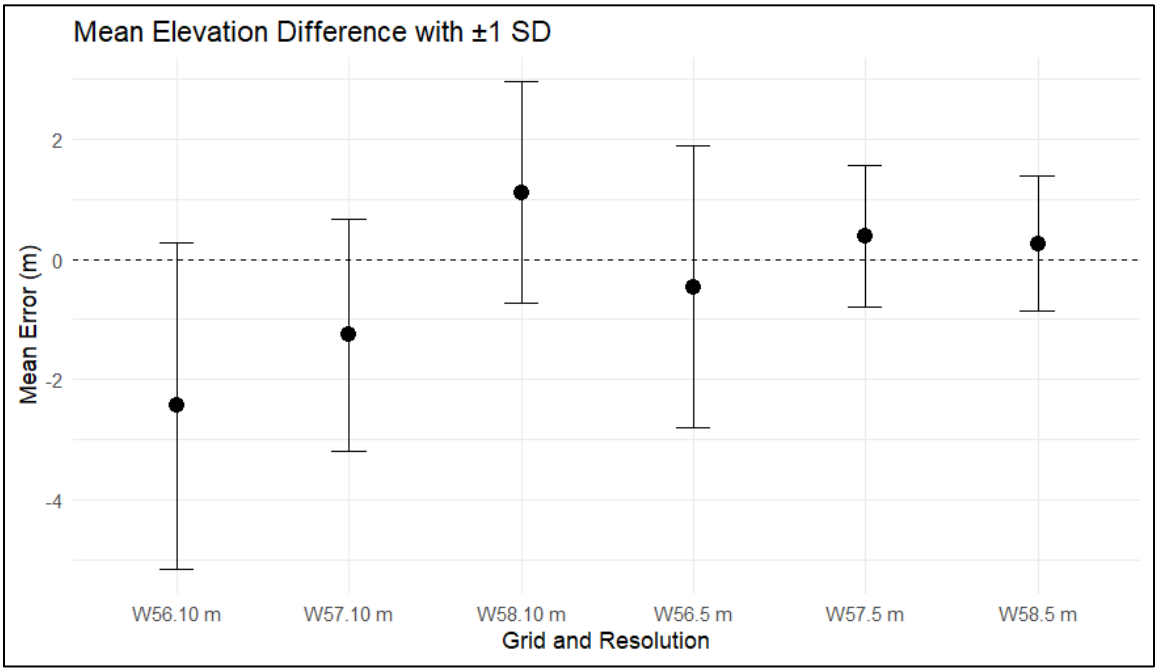

Figure 13: Statistical results of the Mean Error analysis

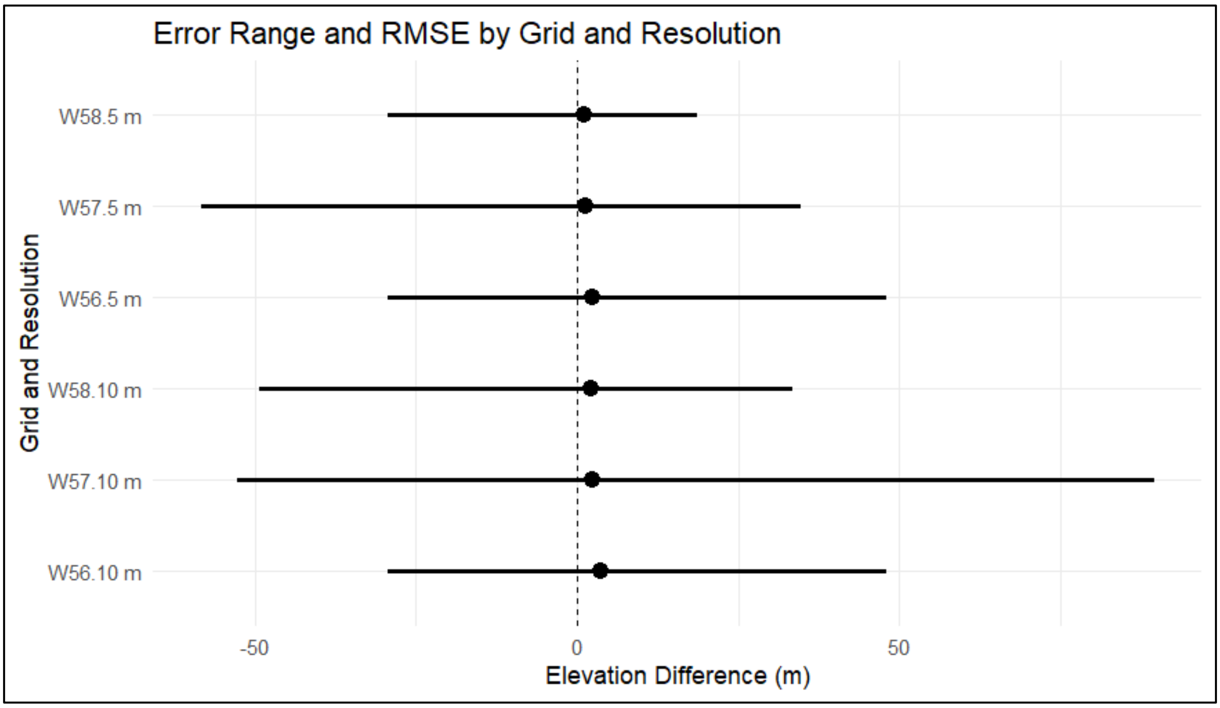

Figure 13: Statistical results of the Mean Error analysis

4 DISCUSSION

In rugged terrain, steep slopes and incised features create significant localized elevation differences between DEMs. These discrepancies mainly arise from differences in DEM generation methods: LiDAR captures sharp terrain features accurately, whereas photogrammetric DEMs tend to smooth surfaces, especially in areas with abrupt elevation changes. As terrain becomes less complex, the correlation between DEMs improves considerably. In low-relief environments, both models align closely, indicating that terrain morphology has a greater impact on DEM differences than the data source itself. Spatial resolution also influences this relationship: at 5 m resolution, both DEMs preserve enough terrain detail for close agreement, while coarser resolutions tend to exaggerate elevation differences along sharp transitions. These patterns emphasise the importance of spatially interpreting elevation discrepancies in relation to terrain form and scale effects.

The results further demonstrate a clear improvement in DEM performance with increased spatial resolution, although the magnitude of this improvement varies with terrain complexity. Across all grids, mean elevation differences remain small, indicating limited systematic vertical bias between datasets. At 10 m resolution, however, noticeable bias persists in both rugged and moderately dissected terrain, and is substantially reduced at 5 m resolution, particularly in W57 and W58. Standard deviation and RMSE values decrease consistently when moving from 10 m to 5 m, with the most pronounced gains observed in moderate and low-relief terrain, where RMSE improves from 2.31 m to 1.23 m in W57 and from 2.14 m to 1.15 m in W58.

In contrast, although accuracy also improves in the rugged W56 grid, RMSE remains comparatively high (2.38 m), underscoring the dominant influence of terrain morphology on elevation error. Large minimum and maximum differences across all grids reflect localised discrepancies associated with steep slopes and terrain discontinuities, reinforcing the limitations of global statistics for DEM evaluation. Overall, the findings confirm that finer-resolution photogrammetric DEMs substantially enhance orthorectification accuracy in moderate-to-low-relief environments, while complex terrain continues to require more specialised elevation-modelling approaches.

5 CONCLUSIONS AND RECOMMENDATIONS

This study compared elevation differences between a LiDAR-derived DEM and the H1 photogrammetric DEM across three terrain grids at resolutions of 5 m and 10 m. The results indicate that photogrammetric DEMs can meet the geometric accuracy requirements for orthorectifying 0.25 m GSD aerial imagery in moderate and low-relief terrains, providing reliable elevation data for high-resolution mapping.

Regarding the second research question, DEM performance is heavily influenced by terrain morphology and spatial resolution. Rugged, steep, and dissected landscapes tend to produce localized elevation discrepancies, while flatter areas show close agreement between DEMs. Additionally, using a finer resolution (5 m) generally reduces errors.

Concerning the third question, adopting photogrammetric DEMs as an alternative to legacy or LiDAR DEMs enhances operational efficiency and suitability for national-scale mapping. However, complex terrains still require expert-driven modelling and selective LiDAR integration. Future efforts should focus on terrain-specific accuracy thresholds and expanding LiDAR incorporation to improve the robustness and scalability of national DEM workflows.

In summary, future work should prioritise enhanced LiDAR integration and establishing terrain-specific accuracy thresholds to support more reliable and scalable national DEM production.

6 REFERENCES

Aguilar, F. J., & Mills, J. P. (2008). Accuracy assessment of lidar-derived digital elevation models. *Photogrammetric Record*, *23*(122), 148–169. https://doi.org/10.1111/j.1477-9730.2008.00476.x

Breytenbach, A., & Van Niekerk, A. (2020). Analysing DEM errors over an urban region across various scales with different elevation sources. *South African Geographical Journal*, *102*(2), 133–169. https://doi.org/10.1080/03736245.2019.1648312

Choné, G., Biron, P. M., Buffin-Bélanger, T., Mazgareanu, I., Neal, J. C., & Sampson, C. C. (2021). An assessment of large-scale flood modelling based on LiDAR data. *Hydrological Processes*, *35*(8). https://doi.org/10.1002/hyp.14333

Contreras, M. A., Staats, W., Yiang, J., & Parrott, D. (2017). Quantifying the Accuracy of LiDAR-Derived DEM in Deciduous Eastern Forests of the Cumberland Plateau. *Journal of Geographic Information System*, *09*(03), 339–353. https://doi.org/10.4236/jgis.2017.93021

Elaksher, A., Ali, T., & Alharthy, A. (2023). A Quantitative Assessment of LIDAR Data Accuracy. *Remote Sensing*, *15*(2), 442. https://doi.org/10.3390/rs15020442

Hatta Antah, F., Khoiry, M. A., Abdul Maulud, K. N., & Abdullah, A. (2021). Perceived usefulness of airborne lidar technology in road design and management: A review. In *Sustainability (Switzerland)* (Vol. 13, Issue 21). MDPI. https://doi.org/10.3390/su132111773

Pinto, A. T., Gonçalves, J. A., Beja, P., & Honrado, J. P. (2019). From archived historical aerial imagery to informative orthophotos: A framework for retrieving the past in long-term socioecological research. In *Remote Sensing* (Vol. 11, Issue 11). MDPI AG. https://doi.org/10.3390/rs11111388

Thuse, T., Musungu, K., & Odera, P. A. (2024). Accuracy assessment of vertical and horizontal coordinates derived from Unmanned Aerial Vehicles over District Six in Cape Town. *South African Journal of Geomatics*, *13*(1), 65–82. https://doi.org/10.4314/sajg.v13i1.5

Thuse, T., Musungu, K., & Odera, P. A. (2025). Evaluating Digital Elevation Models: A Comparison of Terrestrial, UAV, Satellite, and Airborne Sources in District Six, Cape Town. *FIG Working Week 2025 - Collaboration, Innovation and Resilience: Championing a Digital Generation*, 1–19.

Voglino, B., Godone, D., Baldo, M., Bono, B., Luino, F., Bonomelli, R., Colosio, P., Beretta, L., Albertelli, L., & Turconi, L. (2025). Application of Structure from Motion Techniques Using Historical Aerial Images, Orthomosaics, and Aerial LiDAR Point Cloud Datasets for the Investigation of Debris Flow Source Areas. *Remote Sensing*, *17*(22). https://doi.org/10.3390/rs17223658

BIOGRAPHICAL NOTES

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Dr Musungu is a professional land surveyor, geospatial practitioner, and academic based in Cape Town, South Africa. He holds a Doctor of Philosophy in Geomatics and works in the Department of Civil Engineering and Geomatics at the Cape Peninsula University of Technology (CPUT), where he teaches and supervises postgraduate research in GIS, remote sensing, and land surveying. In addition, he contributes to professional development and policy as a member of the provincial committee of the South African Geomatics Institute (SAGI).

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