

ASSESSMENT OF THE IMPACT OF GROUND CONTROL POINT REDUCTION ON THE ACCURACY OF HIGH-RESOLUTION UAV-PPK PRODUCTS

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ABSTRACT. – **Assessment of the Impact of Ground Control Point Reduction on the Accuracy of High-Resolution UAV-PPK Products.** This study evaluates the impact of reducing the number of ground control points (GCPs) on the accuracy of photogrammetric products within a high-resolution UAV-PPK workflow. The experiment was conducted under controlled conditions, using the same study area, imagery, GNSS infrastructure, and processing workflow. Four scenarios were analyzed. Image coordinates were post-processed in TopoSetter, while photogrammetric processing was performed in Pix4Dmapper. The resulting products include dense point clouds, digital surface models (DSM), and orthomosaics, with an average ground sampling distance of 1.32 cm/pixel. The results indicate a limited increase in horizontal RMSE with decreasing GCPs (RMSE XY: 0.025–0.030 m) and a higher sensitivity of vertical RMSE (RMSE Z: 0.026–0.060 m), while remaining within acceptable limits for high-resolution mapping applications. These findings suggest that reducing the number of GCPs does not lead to a significant degradation of geometric accuracy within the analyzed UAV-PPK workflow.

Keywords: UAV-PPK, photogrammetry, ground control points, horizontal accuracy, vertical accuracy.

1. INTRODUCTION

Over the past two decades, the development of UAV platforms has led to a significant transformation in photogrammetry, enabling the rapid and efficient acquisition of high-resolution geospatial products. The use of UAV systems in mapping has become a standard practice across numerous application

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domains, ranging from topography and cadastre to environmental monitoring and terrain surface modeling (Colomina and Molina, 2014). In this context, the georeferencing of image blocks represents a critical component in ensuring the geometric accuracy of the final products, traditionally achieved through the use of an adequate number of ground control points (GCPs), properly distributed across the study area.

Numerous studies have demonstrated that the use of GCPs significantly contributes to the reduction of systematic errors and to the improvement of the geometric accuracy of photogrammetric products, particularly in the case of large image blocks or under conditions of pronounced topographic variation (Agüera-Vega, Carvajal-Ramírez, and Martínez-Carricondo, 2017; Ferrer-González et al, 2020). At the same time, the literature highlights that not only the number, but also the spatial distribution of GCPs directly influences the quality of the results, requiring a balanced configuration to ensure the stability of the photogrammetric block adjustment (Cho, Jeong and Lee, 2025; Seo et al, 2024).

With the integration of high-precision GNSS technologies into UAV platforms, alternative georeferencing solutions have been developed based on real-time kinematic (RTK) and post-processed kinematic (PPK) positioning, which enable the accurate determination of image perspective centers without exclusive reliance on GCPs. Recent studies indicate that these methods can provide image coordinates with centimeter-level accuracy, significantly reducing the need for fieldwork (Martínez-Carricondo, Agüera-Vega and Carvajal-Ramírez, 2023; Štroner et al, 2021). In particular, PPK solutions offer the advantage of independence from real-time data connections, providing increased operational flexibility in remote areas or in regions with limited coverage.

In the recent literature, an increasing number of studies investigate the capability of UAV-PPK workflows to provide results comparable to those obtained through classical GCP-based methods. The results indicate that, under favorable acquisition and processing conditions, geometric accuracy can be maintained at high levels even in the absence of GCPs, although a slight degradation in precision may occur, particularly in the vertical component (Seo et al, 2024; Zhao et al, 2024).

In this context, evaluating the influence of reducing the number of GCPs on the geometric accuracy of photogrammetric products becomes a relevant issue from both scientific and applied perspectives. Although the literature provides promising results regarding the use of UAV-PPK solutions, there remains a need for experimental studies conducted under controlled conditions, allowing for a clear isolation of the effect of GCPs on geometric accuracy.

The present study follows this direction, analysing the impact of reducing the number of ground control points on the planimetric and altimetric accuracy of UAV-PPK photogrammetric products, across four distinct scenarios.

2. MATERIALS AND METHODS

To explicitly evaluate and analyze the influence of ground control, four experimental scenarios were defined, corresponding to the use of 5 GCPs, 3 GCPs, 1 GCP, and 0 GCPs. In all cases, the same set of 8 check points (CPs) was maintained, used exclusively for the assessment of final accuracy.

2.1. Study Area. The study was conducted over a compact area, covering approximately 0.035 km² (3.53 hectares). The selection of a relatively small area aimed to ensure experimental conditions that are as homogeneous and controllable as possible, so that the differences observed between the analyzed scenarios can be primarily attributed to the variation in the number of GCPs rather than to other perturbing factors. The selected area allowed both the execution of a consistent photogrammetric flight and the establishment of a network of ground control and check points appropriately distributed both within the study area and towards its margins.

2.2. Equipment and Data Acquisition. The acquisition of aerial imagery was carried out using a DJI Phantom 4 Pro V2.0, equipped with an external Topodrone PPK system. The camera used within the photogrammetric project is identified in Pix4D reports as model FC6310_8.8_5472x3648 (RGB), specific to high-resolution imaging, suitable for generating final products with high spatial detail.

The determination of the base station coordinates was carried out using a UniStrong G10, and the GNSS observations of both the base and the UAV platform were recorded in RINEX format, in order to enable subsequent post-processing. Flight planning and execution were performed using the Map Pilot Pro application installed on an iPad Pro tablet. An important advantage of this application is the ability to use terrain elevation information during the mission, allowing the UAV platform to maintain a relatively constant distance from the ground surface, rather than from a fixed reference plane, throughout the flight.

The post-processing of image coordinates was carried out in TopoSetter, and the resulting coordinates were subsequently transformed into EPSG:3844 for their integration into the processing workflow. The flight plan was designed for nadir mapping, in a single grid configuration, over a limited area, with the objective of generating a high-resolution orthomosaic and a surface model. The average resolution of the generated products was approximately 1.32 cm/pixel, a value that confirms the high level of detail of the survey.

2.3. GCP Network and Experimental Design. To evaluate the influence of reducing the number of ground control points on the accuracy of photogrammetric products, a comparative experiment was designed based on four distinct processing scenarios: PPK_5GCP, PPK_3GCP, PPK_1GCP, and PPK_0GCP. In all scenarios, the same set of 8 CPs was maintained, used exclusively for result validation and not included in the photogrammetric block adjustment. The spatial distribution of ground control points and check points within the study area is presented in fig. 1.



Fig. 1. Spatial distribution of GCPs and CPs within the study area. *Source: the authors*

2.4. Photogrammetric Processing Workflow. The photogrammetric processing was carried out in Pix4Denterprise 4.5.6, using an identical workflow for all four scenarios. The main processing steps were: Initial Processing, Point Cloud, as well as DSM, Orthomosaic, and Index.

For the initial calibration stage, images geolocated based on externally imported PPK coordinates were used. During initial processing, the image coordinates were assigned an accuracy of 0.05 m in the horizontal component and 0.10 m in the vertical component. These values were kept constant across all scenarios, so that the photogrammetric block was treated under comparable conditions throughout the entire experimental series.

During the point cloud densification stage, the same processing options were maintained for all scenarios. For the reference scenario, the 5 GCP configuration, 11,556,050 densified points were obtained, with an average density of 1,505.5 points/m², while for the 3 GCP scenario, 10,978,088 points were generated, with an average density of 1,549.94 points/m². In the 1 GCP scenario, 9,394,435 densified points were obtained, with an average density of 1,417.33 points/m², whereas for the scenario without GCPs, 11,182,480 points were generated, with an average density of 1,468.13 points/m².

In the final stage, DSMs and the orthomosaic were generated for each scenario, with a resolution of approximately 1.32 cm/pixel. By maintaining the same processing workflow and the same essential settings, the comparison between scenarios was limited to the effect of reducing the number of GCPs. The sequence of processing steps, from data acquisition and PPK coordinate post-processing to photogrammetric processing and final accuracy assessment, is summarized in fig. 2.

2.5. Evaluation Indicators. The evaluation of the results was carried out from both planimetric and altimetric perspectives, based on CPs. For each scenario, the coordinate differences along the three axes were defined as

$$\Delta X_i = X_i - X_{i,\text{ref}}, \Delta Y_i = Y_i - Y_{i,\text{ref}}, \Delta Z_i = Z_i - Z_{i,\text{ref}}$$

where X_i , Y_i , and Z_i are the coordinates determined from the photogrammetric product for point i , while $X_{i,\text{ref}}$, $Y_{i,\text{ref}}$, and $Z_{i,\text{ref}}$ are the corresponding coordinates of the CPs used as reference. The positional accuracy along each coordinate axis was evaluated using

$$\text{RMSE}_X = \sqrt{\frac{1}{n} \sum_{i=1}^n (\Delta X_i)^2}; \text{RMSE}_Y = \sqrt{\frac{1}{n} \sum_{i=1}^n (\Delta Y_i)^2}; \text{RMSE}_Z = \sqrt{\frac{1}{n} \sum_{i=1}^n (\Delta Z_i)^2}$$

where n is the number of CPs. For the horizontal component, the overall planimetric accuracy was additionally expressed by

$$RMSE_{XY} = \sqrt{RMSE_X^2 + RMSE_Y^2}$$

Thus, $RMSE_X$ and $RMSE_Y$ quantify the positional accuracy along the two horizontal coordinate axes, $RMSE_{XY}$ represents the combined planimetric accuracy.

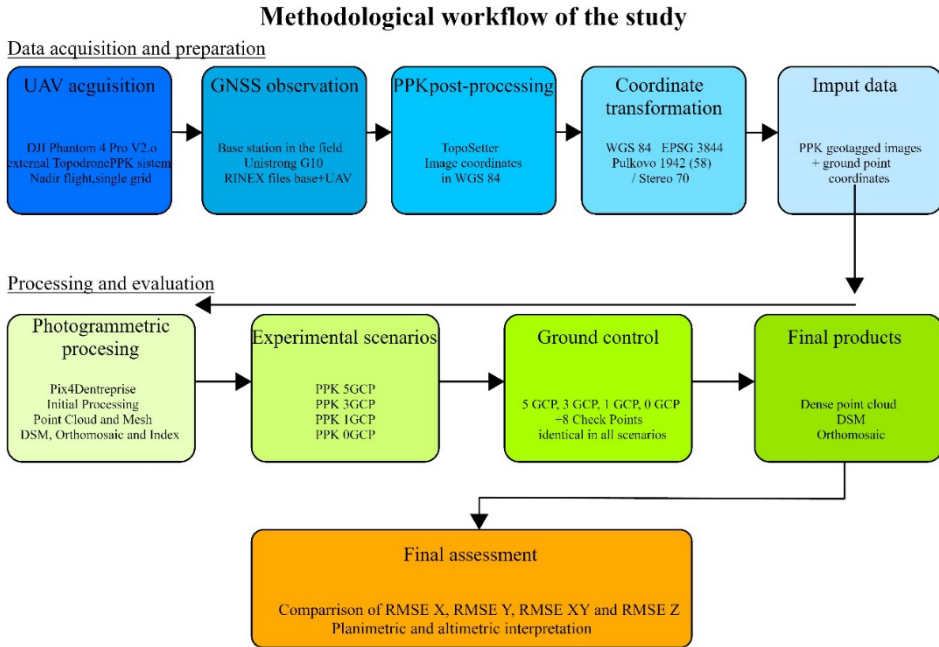


Fig. 2. Methodological workflow of the study. *Source: the authors*

3. RESULTS AND DISCUSSION

3.1. General Behavior of the Photogrammetric Block. The obtained results show that the photogrammetric block exhibited stable behavior across all four analyzed scenarios. In all cases, the average ground sampling distance of the generated products was approximately 1.32 cm/pixel, and the mean reprojection error remained around 0.111 pixels, indicating good internal consistency of the processing and allowing direct comparison of results

between scenarios. In addition, all four configurations led to the generation of complete photogrammetric products, namely dense point clouds, DSMs, and orthomosaics. This result is important from a practical perspective, as it shows that reducing the number of GCPs did not compromise the overall functioning of the processing workflow nor prevent the generation of coherent final products.

3.2. Horizontal Component. The comparison of the values computed at the check points highlights a slight and progressive increase in planimetric error as the number of GCPs is reduced. The synthetic values of geometric accuracy are presented in table 1, while the evolution of the planimetric component, expressed by RMSE XY, is illustrated in fig. 3.

Table 1. Comparative RMSE table. *Source: the authors*

Scenario	No. GCP	No. check points	RMSE X [m]	RMSE Y [m]	RMSE XY [m]	RMSE Z [m]
PPK_5GCP	5	8	0.014678	0.020769	0.025432	0.026066
PPK_3GCP	3	8	0.017368	0.021501	0.027639	0.036411
PPK_1GCP	1	8	0.013093	0.026100	0.029200	0.031787
PPK_0GCP	0	8	0.015519	0.026185	0.030438	0.060266

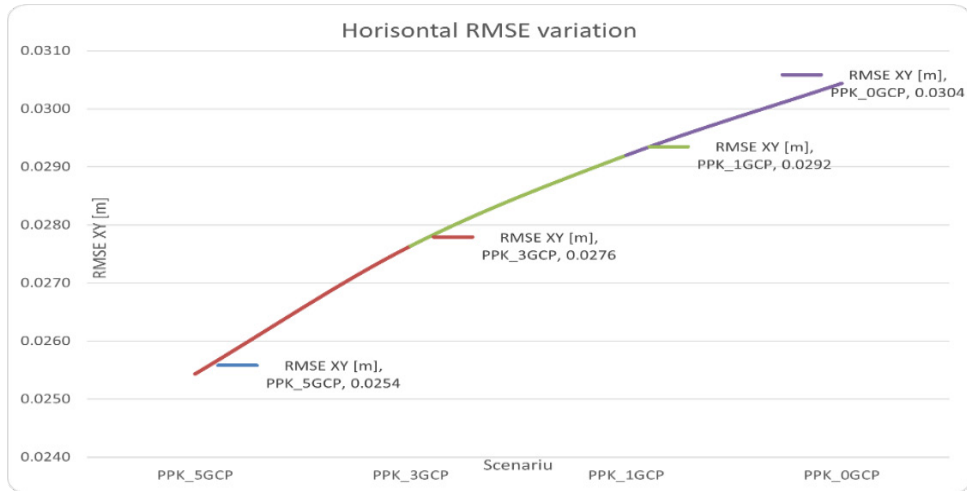


Fig. 3. Variation of RMSE XY across the analyzed scenarios. *Source: the authors*

Figure 3 highlights the slight and progressive increase of the planimetric RMSE XY as the number of ground control points decreases.

For the 5 GCP scenario, the RMSE values at the check points were 0.014678 m along the X axis and 0.020769 m along the Y axis. In the 3 GCP scenario, these values were 0.017368 m along the X axis and 0.021501 m along the Y axis. For the 1 GCP configuration, values of 0.013093 m along the X axis and 0.026100 m along the Y axis were obtained, while for the scenario without GCPs, the values were 0.015519 m along the X axis and 0.026185 m along the Y axis. Based on these values, the planimetric RMSE XY is approximately 0.025 m for the 5 GCP scenario, 0.028 m for the 3 GCP scenario, 0.029 m for the 1 GCP scenario, and 0.030 m for the scenario without GCPs.

The difference between the reference scenario and the scenario without any GCPs is therefore only approximately 0.005 m. This difference is small and indicates a slight planimetric degradation under conditions of progressive reduction of ground control. This result is important, as it suggests that, within the analyzed experimental framework, image geolocation based on PPK provides a sufficiently robust basis for maintaining very good planimetric accuracy even in the absence of GCPs.

It is nevertheless observed that the 3 GCP scenario provides the best balance between the reduction of field effort and the preservation of an accuracy level close to that of the reference scenario. From a practical perspective, the difference between 0.025 m and 0.028 m is small, and can be considered acceptable in numerous high-detail topographic and cartographic applications. Therefore, the 3 GCP scenario can be interpreted as an optimized solution in which the reduction in the number of ground control points does not produce significant compromises in the final geometric quality (Agüera-Vega, Carvajal-Ramírez and Martínez-Carricondo, 2017; Ferrer-González et al, 2020; Seo et al, 2024).

3.3. Vertical Component. The analysis of the vertical component also highlighted very good results across all scenarios. The RMSE Z values were 0.026066 m for the 5 GCP scenario, 0.03641 m for the 3 GCP scenario, 0.031787 m for the 1 GCP scenario, and 0.060266 m for the scenario without GCPs. These results complement the overall interpretation of accuracy and show that the vertical component also provided very good values in all four scenarios, even under conditions of progressive reduction of ground control points. Figure 4 confirms that the vertical component also yielded very good results in all scenarios, with RMSE Z values remaining between approximately 0.026 m and 0.060 m.

The results obtained from the Pix4D reports show that the differences between scenarios are small at the planimetric level, with RMSE XY values ranging approximately between 0.025 m and 0.03 m, while the analysis of the vertical component also highlighted very good results across all scenarios, with RMSE Z values ranging approximately between 0.026 m and 0.060 m.

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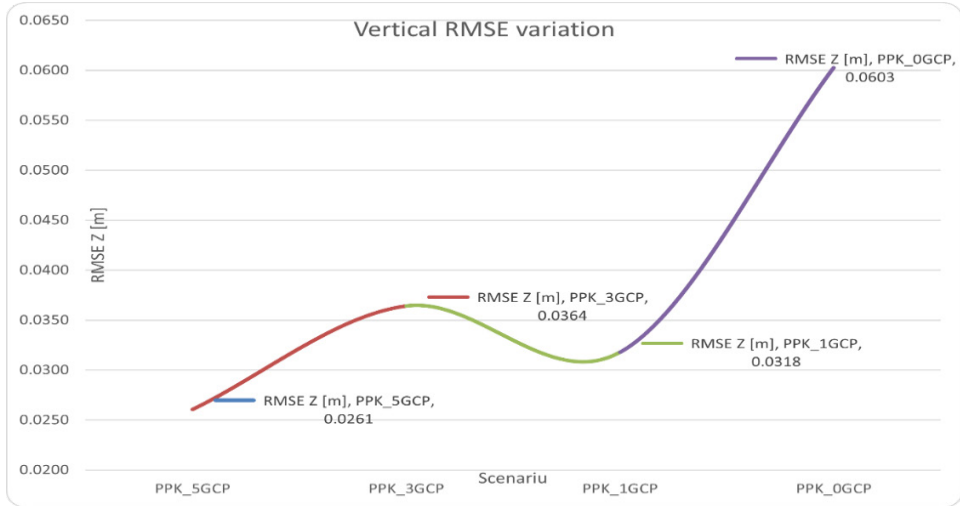


Fig. 4. Variation of RMSE Z across the analyzed scenarios. *Source: the authors*

3.4. Practical Significance of the Results. Viewed as a whole, the results support the idea that the performance of a high-resolution UAV-PPK workflow depends not only on the existence of a GCP network, but also on the quality of image georeferencing, the stability of the photogrammetric block, flight planning, and the maintenance of consistent processing settings (Martínez-Carricondo, Agüera-Vega and Carvajal-Ramírez, 2023; Štroner et al, 2021). In this case, the progressive reduction of GCPs did not produce major disruptions in the geometric behavior of the project, but only moderate variations in error values.

From an applied perspective, the 3 GCP scenario stands out as the most balanced. It provides an accuracy level very close to that of the reference scenario, but with reduced field effort, which may translate into time savings and increased efficiency of survey operations.

At the same time, the results of the 1 GCP and 0 GCP scenarios show that the UAV-PPK workflow has a high potential to support reliable products even under conditions of minimal ground control. This is not to say that GCPs are unnecessary, but rather that their role can be recalibrated depending on the specific requirements of the project.

For this reason, the use of a UAV-PPK workflow can represent an efficient solution not only for reducing fieldwork, but also for maintaining a high level of confidence in the geometric quality of the final products.

4. CONCLUSIONS

The study analysed the impact of reducing the number of GCPs on the geometric accuracy of photogrammetric products obtained through a high-resolution UAV-PPK workflow, under controlled experimental conditions.

The results highlight that the progressive reduction in the number of GCPs leads to a limited degradation of planimetric accuracy, with the variations observed between scenarios being small and without major implications for the geometric consistency of the products. This reduced variation indicates that PPK-based georeferencing can ensure a high level of reliability even under conditions of minimal ground control.

Regarding the vertical component, the results confirm a higher sensitivity to the reduction of GCPs; however, the obtained values remain within acceptable limits for high-resolution mapping applications. This behavior is consistent with the specialized literature and highlights the need for a differentiated evaluation between the horizontal and vertical components (Martínez-Carricondo, Agüera-Vega and Carvajal-Ramírez, 2023; Štroner et al, 2021; Zhao et al, 2024).

From an applied perspective, the 3 GCP scenario provides an optimal balance between field effort and positional accuracy, suggesting that dense GCP networks are not always necessary in UAV-PPK workflows.

Overall, the study confirms the potential of UAV-PPK technology to support efficient and accurate mapping processes, contributing to the optimization of workflows by reducing dependence on field measurements (GNSS and total stations), without significant compromises in geometric quality. However, the results must be interpreted in relation to the analyzed experimental conditions, and the extension of the conclusions to larger areas or to different topographic contexts requires further investigation.

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