# Assessing the number and placement of ground control points in low-cost UAV photogrammetry

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**Abstract.** This study examines the impact of the number and placement of Ground Control Points (GCPs) on the accuracy of photogrammetric results using low-cost UAVs. The relevance of this research stems from the growing popularity and applicability of UAV photogrammetry, particularly in areas with diverse terrains and requirements for precise spatial data. The experiment leverages modern photogrammetric techniques, including Structure from Motion (SfM) algorithms, to analyze how GCP configurations affect error distribution and model accuracy.

The study's first phase focused on evaluating the influence of GCP placement at varying heights. A photogrammetric survey was conducted at the Kyiv Hippodrome, utilizing terrestrial laser scanning (TLS) to establish high-precision coordinates for control points. The data acquisition involved the DJI Phantom 4 Pro V2 UAV, with multiple flight missions capturing images at 30-degree camera deviations from the nadir. Points were systematically analyzed by alternating their roles as GCPs and Control Points (CPs). The results demonstrated that errors significantly increased when CPs were located further from the UAV camera, emphasizing the need for proximity in GCP placement.

The second phase analyzed how GCP configurations and quantities influence photogrammetric model accuracy. By forming 12 groups of GCPs, each varying in distribution and number, the study identified optimal setups for minimizing errors. Groups with evenly distributed points across the survey area, comprising at least eight GCPs, exhibited the lowest root mean square errors (RMSE). Conversely, configurations with GCPs concentrated along a single side or solely on the survey area's edges resulted in substantial inaccuracies.

Key findings reveal that an effective GCP placement strategy involves prioritizing proximity to the UAV camera and achieving even distribution across the surveyed area. Additionally, configurations with fewer than eight GCPs tend to suffer from sharp declines in accuracy. The research underscores the importance of balancing GCP quantity and placement for achieving reliable photogrammetric outputs in low-cost UAV applications.

**Keywords**: UAV photogrammetry, Ground Control Points, TLS, accuracy optimization, DJI Phantom 4.

## INTRODUCTION

Understanding the impact of the number and placement of Ground Control Points (GCPs) on photogrammetry results is undeniable. Their usage forms the foundation of classical digital photogrammetry, which is based on strict mathematical operations. However, modern UAV photogrammetry has distinct differences, utilizing Structure from Motion (SfM) algorithms, requiring different overlap areas for images, and working with images taken at larger tilt and rotation angles. Thus, with the growing popularity and applications of low-cost UAV photogrammetry, scientists worldwide increasingly seek to understand the influence of GCP configuration and quantity on results. Recent studies in this field can be conditionally divided into several groups.

The studies in first group emphasize the importance of optimal GCP distribution for enhancing the accuracy of UAV photogrammetry. Zhao et al. [1] found that strategic GCP placement significantly improves photogrammetric accuracy in challenging environments like glaciers. Villanueva and Blanco [2] concluded that well-planned GCP configurations enhance survey accuracy using Structure from Motion (SfM) techniques. Smith and Doe [3] demonstrated that uneven GCP distribution can lead to substantial errors in photogrammetric outputs, while Brown and Green [4] highlighted the need for tailored GCP configurations based on specific survey requirements.

Research in in second group focuses on the impact of GCP quantity on the accuracy of photogrammetric products. Lee and Park [5] showed that increasing the number of GCPs generally improves the accuracy of Digital Elevation Models (DEMs) derived from UAV data. Wang and Liu [6] identified an optimal number of GCPs for achieving high-resolution outputs without redundancy. Kim and Choi [7] found that a minimal number of well-placed GCPs can still produce accurate mapping results, reducing the need for excessive GCPs. Garcia and Lopez [8] concluded that the quantity of GCPs directly impacts the quality of photogrammetric products, with diminishing returns beyond a certain point.

The third group includes research explore various strategies for effective GCP placement in different environments. Johnson and Miller [9] suggested that strategic GCP placement in urban areas can mitigate issues such as signal obstruction and multipath errors. Davis and White [10] emphasized the importance of GCP placement in forested regions to account for canopy cover and terrain variability. Patel and Singh [11] recommended specific GCP placement techniques for agricultural fields to enhance crop monitoring and mapping accuracy. Martinez and Gonzalez [12] highlighted effective GCP placement strategies for coastal areas, considering factors like tidal changes and shoreline dynamics.

The fourth group includes research aimed at discusses recent technological advancements in GCP application for UAV photogrammetry. Robinson and Evans [13] discussed advancements in GCP technology, including high-precision GNSS receivers. Thompson and Harris [14] explored the integration of Real-Time Kinematic (RTK) and Post-Processed Kinematic (PPK) methods with GCPs to enhance survey accuracy. Nguyen and Tran [15] demonstrated how GNSS technology can improve the accuracy and efficiency of GCP deployment. Wilson and Clark [16] highlighted innovations in GCP deployment, such as automated GCP placement and real-time monitoring.

The studies in last group present practical applications and case studies of GCP use in UAV photogrammetry. Adams and Baker [17] presented a case study on the use of GCPs in UAV surveys of archaeological sites, showing improved accuracy in mapping historical features. Carter and Foster [18] illustrated the practical applications of GCPs in disaster management, particularly in post-disaster damage assessment. Edwards and Hall [19] showed how GCPs are utilized in environmental monitoring to track changes in ecosystems over time. Foster and Green [20] discussed the implementation of GCPs in UAV photogrammetry for infrastructure inspection, highlighting improvements in defect detection and maintenance planning. Paper [21] discusses the use of low-cost UAVs for monitoring of excavation works.

The aim of this work is to determine the impact on the results of low-cost UAV photogrammetry of both the number of GCPs and their configuration.

## PURPOSE AND METHODS

To achieve the research objective, a network of points with defined coordinates and varying vertical and horizontal placement was proposed for the study area. UAV photography was conducted in this area, and during the photo processing stage, various configurations of control and reference points were used to evaluate changes and error distribution in the photogrammetric model depending on the number and placement of GCPs.

The experiment utilized the Kyiv Hippodrome structure, specifically its roof and the surrounding area. The building's overall dimensions are 170 m in length, 30 m in width, and 15 m in height (Figure 1).

**Figure 1.** General view of the building and roof of the Kyiv Hippodrome.

Coordinates were obtained using terrestrial laser scanning (TLS) with the FARO Focus S120 scanner, involving 75 scanning stations, 33 of which were conducted on the roof. The average distance between scanning points did not exceed 20 m. The scanning quality of individual points was 4 mm, with a point density of at least 3 mm per 10 m. The average number of control points between neighboring scans was 7, and the root mean square error (RMSE) of the scanning was 6.1 mm.

UAV imaging was conducted using the DJI Phantom 4 Pro V2 across six missions with a camera nadir deviation of 30 degrees. Unfortunately, not all missions were completed due to the presence of tall trees near the structure at the planned flight height of 20–25 meters (Figure 2).

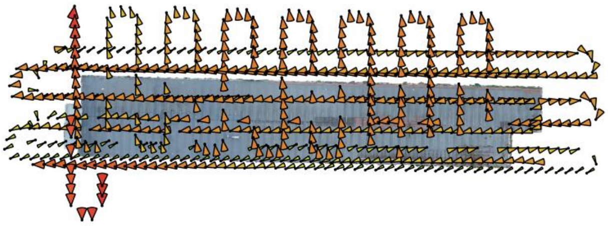

**Figure 2.** A diagram illustrating the UAV's flight path while photographing the roof. The apex of the triangle marks the image's position, and the triangle's extension shows the direction of the photo.

GCPs on the roof were marked with black-and-white signs on A4 sheets, while distinctive markings were selected at the base of the structure. Image processing was performed using Agisoft Metashape. More details about this facility were presented at the conference [22].

The first part of the study focused on determining the impact of using GCPs at different heights. Here, groups of points on the roof and around the structure were alternately used. Initially, the roof points were employed as GCPs, with control points (CPs) around the structure marked on distinctive outlines (Figure 3).

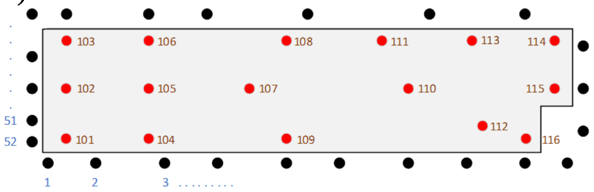

**Figure 3.** Schematic representation of CPs (black) and GCPs(red) points.

The next step involves swapping the reference and control points. The accuracy assessment of the control and reference points from the UAV survey results was conducted based on the differences with the coordinates of the corresponding points obtained via TLS.

The second part of the study focuses on determining the impact of the configuration and quantity of GCPs. By selecting only, the points on the roof of the structure, which showed minimal discrepancies compared to the coordinates obtained from laser scanning, it becomes possible to examine the influence of GCP placement on the accuracy of the resulting photogrammetric model. Twelve groups of reference points were formed for this purpose

(Table 1):

**Table 1.** Group GCPs

| Group number | Name GCPs |
|---|---|
| 1 | 101, 103, 104, 106, 108, 109, 111, 112, 113, 114, 115 |
| 2 | 101, 103, 105, 108, 109, 110, 114, 116 |
| 3 | 102, 104, 106, 107, 112, 113, 115 |
| 4 | 101, 103, 107, 114, 116 |
| 5 | 101, 103, 107, 108, 109, 114, 116 |
| 6 | 104, 105, 106, 107, 108, 109, 110, 111 |
| 7 | 103, 106, 108, 111, 113, 114 |
| 8 | 102, 105, 107, 108, 109, 110, 115 |
| 9 | 102, 105, 108, 109, 110, 115 |
| 10 | 102, 108, 109, 115 |
| 11 | 101, 103, 114, 116 |
| 12 | 103, 104, 108, 112, 114 |

The study provides an example of only one schematic diagram of the arrangement of reference and control points for the first variant (Fig. 4).

**Figure 4.** Schematic diagram of the arrangement of GCPs (red) and CPs (black) for the first listed variant.

## RESULTS AND EXPLANATIONS

According to the results of the first part of the study, the results of the accuracy assessment for the first combination of GCPs and CPs at different heights were obtained. (Table 2).

**Table 2.** RMSE points if GCPs on the roof

| | RMSEx (m) | RMSEy (m) | RMSEz (m) |
|---|---|---|---|
| GCPs | 0.005 | 0.004 | 0.013 |
| CPs | 0.443 | 0.274 | 0.441 |

Based on the results, we can conclude that there are large errors in the observation results (Fig 5).

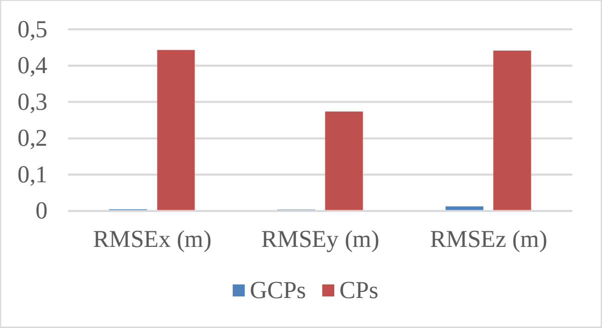

**Figure 5.** RMSE distribution points if GCPs on the roof.

At this stage, most of the errors are observed in the CPs located on the ground at a greater distance from the UAV camera. Let us attempt to swap the GCPs and CPs (Table 3).

**Table 3.** RMSE points if GCPs on the ground

| | RMSEx (m) | RMSEy (m) | RMSEz (m) |
|---|---|---|---|
| GCPs | 0.397 | 0.064 | 0.152 |
| CPs | 0.111 | 0.171 | 0.328 |

In this case, a similar pattern was not observed; the errors were not concentrated in the points on the roof that were used as CPs (Fig. 6).

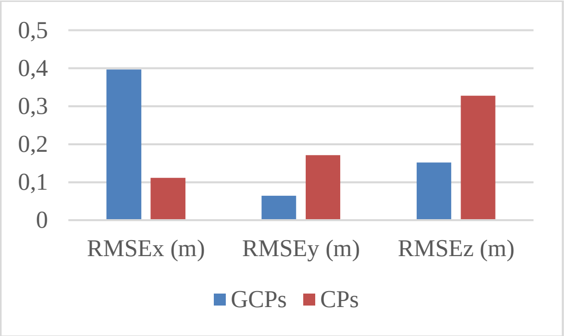

**Figure 6.** RMSE distribution points if GCPs on the ground.

The results of the second part of the study, focusing on the configuration and quantity of GCPs, are presented in Table 4.

**Table 4.** RMSE of the roof points depending on their combination

| Group number | Name point | RMSEx (mm) | RMSEy (mm) | RMSEz (mm) |
|---|---|---|---|---|
| | Reference | 5.4 | 7.9 | 7.9 |
| 1 | GCPs | 6.2 | 8.4 | 9.8 |
| | CPs | 6 | 9.8 | 8.6 |
| 2 | GCPs | 5.5 | 9.1 | 10.8 |
| | CPs | 6.6 | 9.9 | 8.9 |
| 3 | GCPs | 6.4 | 8 | 9.8 |
| | CPs | 6.2 | 12.3 | 13.2 |
| 4 | GCPs | 6.2 | 10.4 | 14 |
| | CPs | 7.8 | 12.3 | 18.2 |
| 5 | GCPs | 5.2 | 10.5 | 11 |
| | CPs | 6.9 | 6.8 | 9.9 |
| 6 | GCPs | 4.5 | 5.7 | 6.4 |
| | CPs | 11.5 | 23.5 | 22.7 |
| 7 | GCPs | 6 | 10.7 | 52.1 |
| | CPs | 12.7 | 58.6 | 2325.6 |
| 8 | GCPs | 3.6 | 9.9 | 7.5 |
| | CPs | 7.9 | 10.1 | 13.3 |
| 9 | GCPs | 4 | 9.7 | 8.7 |
| | CPs | 7.6 | 10.4 | 13.6 |
| 10 | GCPs | 4.6 | 11.3 | 10.9 |
| | CPs | 7.1 | 9.8 | 14.5 |
| 11 | GCPs | 7.7 | 2.3 | 13.6 |
| | CPs | 10.8 | 21.6 | 39.6 |
| 12 | GCPs | 6.8 | 10.3 | 10.6 |
| | CPs | 7.7 | 11.2 | 16.4 |

It was proposed to investigate changes in accuracy using as a reference the results obtained from processing all roof points as GCPs, where residual errors were determined after assigning the points coordinates based on TLS results.

Immediately, significant errors can be observed for combination 7, where the reference points were placed along one side of the roof. For further analysis, the results of this experiment were excluded from the overall series. All other data were converted into differences between the RMSE of the current experiment and the RMSE of the reference points and presented as a percentage (Table 5).

**Table 5.** RMSE of the roof points depending on their combination

| Group number | Name point | RMSE x (%) | RMSE y (%) | RMSE z (%) |
|---|---|---|---|---|
| 1 | GCPs | 15 | 6 | 24 |
| | CPs | 9 | 23 | 7 |
| 2 | GCPs | 2 | 12 | 33 |
| | CPs | 22 | 23 | 9 |
| 3 | GCPs | 15 | 1 | 21 |
| | CPs | 13 | 56 | 54 |
| 4 | GCPs | 13 | 21 | 46 |
| | CPs | 38 | 42 | 74 |
| 5 | GCPs | -3 | 21 | 17 |
| | CPs | 29 | -10 | 19 |
| 6 | GCPs | -13 | -32 | -15 |
| | CPs | 136 | 271 | 230 |
| 8 | GCPs | -14 | 3 | 0 |
| | CPs | 68 | 22 | 72 |
| 9 | GCPs | -17 | 18 | 6 |
| | CPs | 54 | 26 | 65 |
| 10 | GCPs | -11 | 33 | 22 |
| | CPs | 36 | 17 | 61 |
| 11 | GCPs | 32 | -57 | 39 |
| | CPs | 70 | 602 | 233 |
| 12 | GCPs | 13 | 11 | 7 |
| | CPs | 34 | 32 | 80 |

By highlighting in the table the values where the error increased by more than 50%, it is possible to identify groups of reference points whose placement and quantity should be avoided.

## CONCLUSIONS

From the RMSE analysis results for combinations of roof and ground points, it can be concluded that ground-level points exhibited significant errors that could affect the final photogrammetry results. Points further away from the UAV camera introduced considerably more errors compared to closer points. Therefore, when selecting GCP locations, preference should be given to points closer to the camera, with less emphasis on the number of points.

From the second part of the study, groups with significant errors were identified (Groups

6, 7, 8, and 11). Thus, it is advisable to avoid points located only in the central part of the object, along one side of the object, or solely on the edges of the survey area.

The best-performing groups were Groups 1, 2, and 5, which had the smallest errors. These groups included evenly distributed points across the survey area, with at least eight points, comprising half of the total points in the survey territory. In Groups 3 and 9, errors increased by almost 50%, which could be associated with a reduction of a few GCPs. Such a sharp drop in accuracy due to fewer points should be considered. Groups 4, 10, and 12 can be categorized as cases where height errors are not critical for work, as they lead to a pronounced increase in vertical errors.

Summarizing the results, it is recommended to use GCPs as close as possible to the camera, evenly distributed across the territory, with at least eight GCPs.

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## Оцінка кількості та конфігурації наземних контрольних точок у недорогій БПЛА фотограмметрії

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**Анотація**. Дослідження присвячене впливу кількості та розміщення наземних контрольних точок (GCPs) на точність фотограмметричних результатів із використанням недорогих БПЛА. Актуальність цієї роботи зумовлена зростаючою популярністю та застосуванням БПЛА у фотограмметрії, особливо в областях з різноманітним рельєфом і високими вимогами до точності просторових даних. У дослідженні використовуються сучасні фотограмметричні методи, зокрема алгоритми Structure from Motion (SfM), для аналізу впливу конфігурації GCP на розподіл помилок і точність моделей.

Перша частина роботи зосереджена на оцінці впливу розташування GCP на різних висотах. Фотограмметрична зйомка виконувалася на території Київського іподрому, використовуючи наземне лазерне сканування (TLS) для встановлення координат контрольних точок із високою точністю. Збір даних проводився за допомогою БПЛА DJI Phantom 4 Pro V2 під час кількох польотних місій із відхиленням камери на 30 градусів від надиру. Точки послідовно аналізувалися шляхом чергування їхніх ролей як GCP і контрольних точок (CP). Результати показали, що помилки значно зростають, коли CP розташовані далі від камери БПЛА, що підкреслює необхідність близького розміщення GCP.

Друга частина роботи аналізує, як конфігурація та кількість GCP впливають на точність фотограмметричних моделей. Сформовано 12 груп GCP, кожна з яких відрізняється розподілом і кількістю точок, для виявлення оптимальних варіантів мінімізації помилок. Групи з рівномірним розподілом точок по всій площі знімання, що включають не менше восьми GCP, продемонстрували найменші середньоквадратичні похибки (RMSE). Натомість конфігурації, де GCP розташовані лише вздовж одного боку або виключно на краях зони знімання, призводять до суттєвих неточностей.

Ключові висновки свідчать, що ефективна стратегія розташування GCP передбачає пріоритетне наближення точок до камери БПЛА та рівномірний розподіл по території знімання. Крім того, конфігурації з менш ніж вісьмома GCP, як правило, страждають від різкого зниження точності. У дослідженні підкреслюється важливість збалансованого підходу до кількості та розташування GCP для досягнення надійних фотограмметричних результатів у застосуваннях із недорогими БПЛА.

**Ключові слова:**фотограмметрія БПЛА, наземні контрольні точки, TLS? оптимізація точності DJI Phantom 4.