

# Optimization of GCP configuration for UAS-based SfM-MVS photogrammetry

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## Funding information:

This research was supported by the Slovak Research and Development Agency under contract KEGA grant no. 018TUKE-4/2026, 011TUKE-4/2024, grant no. APVV-18-0351 and Interreg grant #mountgreenfra - HUSK/2302/1.2/060.

## How to cite this article:

Topitzer, B., Kovanič, Ľ., Peťovský, P., Sokolová, E., Blišťan, P. and Tokarčík, O. (2026), Optimization of GCP configuration for UAS-based SfM-MVS photogrammetry, *Acta Montanistica Slovaca*, Volume 31 (2), 391–412

## DOI:

<https://doi.org/10.46544/AMS.v31i2.06>

## Abstract

Research focuses on optimizing the number and placement of ground control points (GCPs) for SfM-MVS photogrammetry carried out using unmanned aerial systems (UAS). It examines the influence of both the number and spatial distribution of GCPs on the resulting accuracy. Evaluations were performed for two typologically different areas—a square area and a line area. The aim of this article is to evaluate, based on practical measurements, the achieved accuracy of UAS-based photogrammetric surveying under different numbers and configurations of GCPs. Subsequently, individual cases are compared, and an optimal solution is determined. The accuracy of each photogrammetric measurement is assessed using the root mean square error (RMSE) at GCPs and check points (CPs). Horizontal and vertical accuracy are evaluated separately. Data were collected independently for each area using two different UAS platforms. For each area, six different GCP configurations were processed, including one configuration with complete exclusion of GCPs. Multicriteria decision analysis showed that the optimal solution is to place GCPs at the corners and center of a square area, and at the beginning, middle, and end of a line area. A configuration without GCPs proved insufficient to ensure vertical accuracy. Our approach enables more precise identification of how the number and spatial distribution of GCPs affect the georeferencing process and the resulting accuracy.

## Keywords

UAS, SfM-MVS, GCP, RMSE, photogrammetry, accuracy, optimization



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## 1. Introduction

UAS combined with photogrammetric methods has become a common tool in recent years for detailed area mapping, digital terrain model generation, orthophotos, and 3D object models. Their wide application in geodesy, cartography, civil engineering, environmental analysis, and land management is driven primarily by their ability to rapidly acquire high-resolution data at relatively low operational cost. UAS-based surveying is used across various fields and disciplines, such as mining (Wang et al., 2024; Padró et al., 2019), cadastre (Šafář et al., 2021; Kurczynski et al., 2016), industry (Ajayi et al., 2021; Sookram et al., 2021), geology (Giordan et al., 2020; Jacko et al., 2021), archaeology (Fiz et al., 2022; Schroder et al., 2021), architecture (Benko et al., 2026; Marčič et al., 2024), agriculture (Merz et al., 2022; Balawejder et al., 2023), as well as for monitoring natural processes in the landscape, including slope stability assessment (Akçay, 2015; Beltramone et al., 2024), geohazards (Jacko et al., 2026; Andresen et al., 2023), and landslides (Jakopeć et al., 2023; Gantimurova et al., 2021).

Advances in sensor technology, navigation systems, and data-processing algorithms have significantly increased the efficiency and accessibility of UAS photogrammetry. Despite these developments, geometric accuracy remains a key factor that fundamentally influences the applicability of the acquired data in professional and technical applications. The accuracy of photogrammetric outputs largely depends on the data georeferencing method (Kyriou et al., 2021), with the number, position, and spatial distribution of GCPs playing a crucial role (Guan et al., 2019). GCPs serve as reference points with precisely determined coordinates, enabling stabilization of the photogrammetric block within a real-world coordinate system and reduction of systematic errors (Famiglietti et al., 2024). However, surveying is time-consuming and logistically demanding, so practitioners often minimize the number of points or exclude them entirely, especially in smaller and less complex areas. The relevance of the topic is underscored by the increasing use of UAS equipped with precise positioning through Real-Time Kinematic (RTK) and Post-Processed Kinematic (PPK) techniques, which claim to achieve high accuracy even with a limited number of GCPs (Štroner et al., 2020). In this context, there is a need to objectively assess the extent to which the reduction or absence of GCPs (Štroner et al., 2021) is acceptable and which spatial distribution of GCPs is most effective in terms of accuracy. The study (Forlani, 2018) evaluates the quality of DSM models generated from UAS flights georeferenced using an onboard RTK GNSS system. The results confirm that direct georeferencing can achieve accuracy comparable to the traditional GCP approach. The study is relevant for optimizing flight parameters and GCP placement. Article (Zeybek, 2021) examines the accuracy of direct georeferencing of UAS images with onboard GNSS. Findings show that combining modern GNSS systems with UAS enables high accuracy without extensive use of GCPs. This research provides a basis for decision-making regarding the use of GCPs.

Ferrer et al. (2020) evaluate UAS photogrammetry accuracy in corridor mapping, focusing on the number and distribution of GCPs. The results indicate that optimal performance is achieved when GCPs are evenly distributed along both sides of the corridor, with their geometric arrangement being more important than their total number. The study highlights the specific characteristics of linear areas in terms of sensitivity to point distribution. Ridha et al. (2025) analyze the optimization of GCP placement in slope stability mapping using UAS photogrammetry. The results show that an appropriate combination of the number and spatial distribution of GCPs significantly improves model accuracy and deformation detection. The study confirms the importance of proper GCP design for geohazard applications. Cho et al. (2025) focus on designing an optimal GCP distribution for high-accuracy 3D mapping using UAS. The findings show that a uniform distribution of points, including their placement in both peripheral and central parts of the area, leads to the highest accuracy. Agüera-Vega et al. (2017) evaluate the influence of the number of GCPs on the accuracy of UAS-based photogrammetric mapping. The results indicate that increasing the number of GCPs improves accuracy, but only up to a certain threshold, beyond which the benefit diminishes. The study emphasizes the need to optimize the number of points in terms of efficiency. Martínez-Carricondo et al. (2018) analyze the accuracy of UAS photogrammetry under different GCP configurations and quantities. The results confirm that not only the number, but especially the spatial distribution of GCPs has a crucial impact on the final model accuracy. Zhong et al. (2025) investigate how GCP reliability and distribution affect the accuracy of 3D models generated from UAS photogrammetry. The findings show that low-quality or poorly distributed GCPs can significantly reduce accuracy, even when more points are used.

Many existing studies focus primarily on evaluating the accuracy of the resulting digital models or orthophotos, while accuracy at the GCP and CP levels is often secondary. This article focuses on optimizing the number and placement of GCPs in UAS photogrammetry, with an emphasis on accuracy assessment using RMSE at GCPs and independent CPs. The analysis is based on real field measurements carried out in two typologically different areas—a small-scale square area and a line area with flat terrain characteristics. This selection of study areas minimizes the influence of pronounced terrain morphology and enables a focus on the effect of GCP configuration on resulting georeferencing accuracy. Data acquisition for each area was carried out independently using two different UAS platforms, thereby also considering the influence of the employed platform on the achieved accuracy. For each area, six different GCP configurations were processed, representing commonly used as well as minimized approaches in practice. One of the configurations involved the complete exclusion of GCPs,

which made it possible to assess the limits of accuracy achieved solely based on onboard positioning. The novelty and practical benefit of this contribution lie in the systematic evaluation of extensive datasets to assess the influence of the number and spatial distribution of GCPs on accuracy, expressed as RMSE at GCPs and CPs. This approach enables a more precise identification of the direct impact of GCP configuration on the georeferencing process. The results show that the optimal solution is placing GCPs at the corners and center of the square area, or at the beginning, middle, and end of the line area, while the solution without GCPs proved insufficient, particularly for ensuring vertical accuracy.

The article evaluates the accuracy of UAS photogrammetry based on the area type, GCP configuration, and selected flight parameters. The second chapter provides a detailed description and characterization of the study area. Subsequently, the Materials and Methods chapter describes and defines the tested cases for square and line areas, the signalization and geodetic surveying of GCPs and CPs, as well as the implementation of UAS photogrammetric measurements. The Results section calculates the resulting RMSE values and analyzes RMSE for individual area types, UAS platforms, and flight altitudes, based on which it proposes an optimal solution separately for square and line areas. Finally, the article concludes by interpreting the results in the context of current knowledge and comparing them with approaches presented by other authors who have addressed similar issues in their studies.

## 2. Study Area

In terms of shape, areas used for photogrammetric mapping are generally divided into two basic types: square areas and line areas. Research areas were selected in a locality near Košice (Fig. 1). The study area is situated in close proximity to Košice Airport, which means that the airspace in this area falls within the CTR Košice up to an altitude of 5,000 ft (approximately 1,500 m), where stricter regulations apply to UAS operations. Operation of UAS within this area therefore requires permission from Košice Airport. The line area within the study site is approximately 800 m long and 50 m wide. The square area is approximately 260 m on a side. Both areas are flat, with no significant elevation differences and no vegetation cover. In our study area, the maximum elevation is 196.8 m and the minimum elevation is 193.1 m. The average elevation is 195.64 m, and the mean slope is 0.45%.

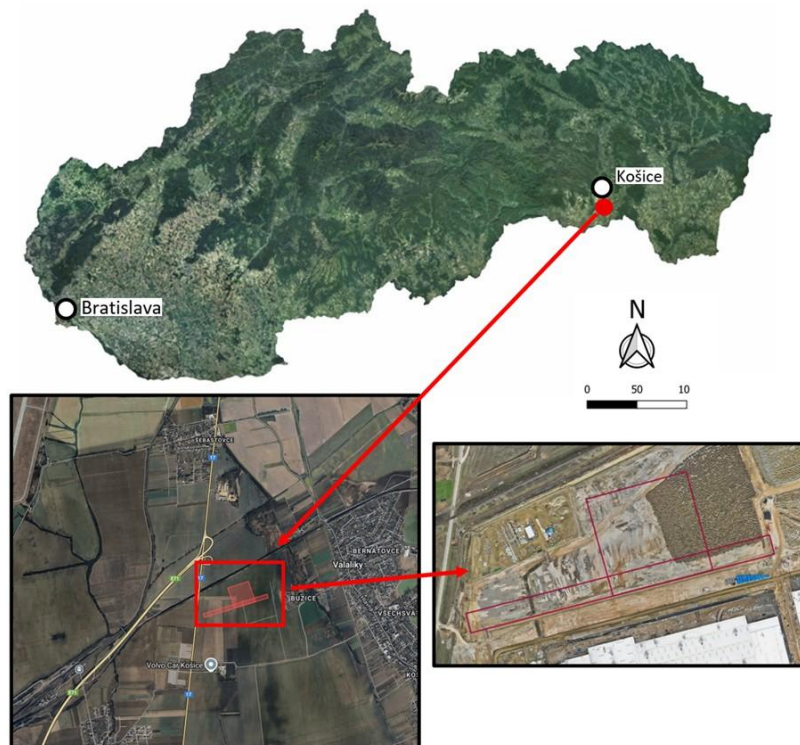


Figure 1. Study area.

## 2. Materials and Methods

This article analyzes how the number and spatial distribution of GCPs affect the accuracy of UAS photogrammetry and identifies an optimal solution. The proposed methodology involves aerial image acquisition over two different types of areas using various GCP configurations. For a more detailed analysis, we carried out the flights independently using two different UAS platforms and at three different flight altitudes above ground

level (AGL). The data were processed in Agisoft Metashape software, and accuracy was evaluated based on the RMSE of GCPs and CPs. The methodological workflow is illustrated in Tab. 1.

**Table 1.** Description of Datasets.

| <b>Territory type</b> | <b>UAS</b>             | <b>Flight height [m]</b> | <b>GCP distribution</b> |
|-----------------------|------------------------|--------------------------|-------------------------|
| Square area           | DJI Matrice 350 RTK    | 110                      | Test Case 1             |
|                       |                        | 90                       | Test Case 2             |
| Line area             | DJI Mavic 3 Enterprise | 70                       | Test Case 3             |
|                       |                        |                          | Test Case 4             |
|                       |                        |                          | Test Case 5             |
|                       |                        |                          | Test Case 6             |

To achieve the objective, appropriate surveying instruments, tools, and equipment were used. The coordinates of GCPs and CPs were measured using a GNSS set (Trimble R2) with a Trimble TSC5 controller. The coordinates and heights were adjusted using terrestrial measurements with a total station (TS). All photogrammetric surveys were conducted independently using two UAS platforms - DJI Matrice 350 RTK and the DJI Mavic 3 Enterprise in all combinations of heights AGL and all test cases as follows.

### 3.1. Test Cases

This chapter presents a set of six independent experiments conducted on a square area and a line area, representing different types of surveyed scenes. Within each case, various configurations for the placement and spatial distribution of GCPs were designed and applied, considering the specific characteristics of the respective area. This chapter aims to establish a comparable framework for evaluating how the number and distribution of GCPs affect the accuracy and quality of the resulting outputs. GCPs and CPs were selected as independent point sets, and CPs were excluded from model adjustment.

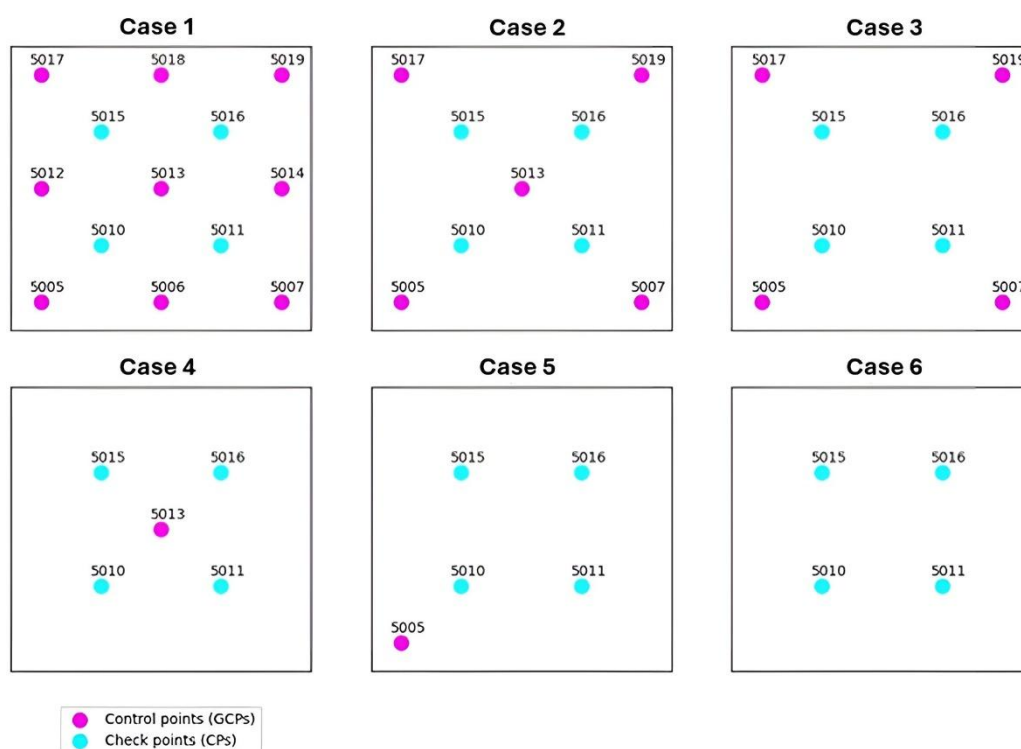


**Figure 2.** Test cases for square area.

#### 3.1.1. Square area

For the square area, 13 points were selected. To assess the achieved accuracy, it is important to use some points as CPs that are not included in the alignment calculations and serve only to compare their real-world positions with their positions in the aligned images. Out of all points in the square area, 9 were selected as GCPs and 4 points as CPs. Six test cases were considered, where subsets of the original 9 GCPs were chosen to represent different numbers and spatial distributions of GCPs. In the first test case, all 9 GCPs arranged in a regular 3×3 grid

were used, with an average distance of 99.107 m between two neighboring GCPs. In the second case, only 4 GCPs at the corners of the area and one GCP in the center were used. In the third case, only the 4 corner GCPs were used; in the fourth case, only one GCP in the center; in the fifth case, only one GCP at a corner of the area; and in the sixth and final case, no GCPs were used for image alignment, and the images were aligned solely based on the UAV positions recorded using RTK technology. Fig. 2 shows a graphical representation of the tested cases, including point numbers, where purple points represent GCPs and blue points represent CPs. To capture changes in achieved accuracy, we used the same 4 CPs in every test case and added no additional points from the original GCP set. This approach ensures that varying the number and distribution of GCPs does not bias the overall RMSE calculated on CPs, allowing an objective evaluation of the effect of GCP number and distribution on CP accuracy.

### 3.1.2. Line area

A similar strategy to that used for the square area was applied to the line area. From a practical point of view, three points (5005, 5006, 5007) were common to both tested areas. In total, nine points were placed at regular intervals along the line. Of these nine points, five were used as GCPs and four (every second point) as CPs. The average distance between two neighboring GCPs was 183.312 m. Again, six cases with different numbers and distributions of GCPs were tested. In the first case, all five GCPs were used. In the second case, the first, middle, and last GCPs were used. In the third case, only the first and last GCPs were used. In the fourth case, only the middle GCP was used. In the fifth case, only the first GCP was used, and in the sixth case, no GCPs were used. Fig. 3 shows a graphical representation of the individual test cases, with point numbering.

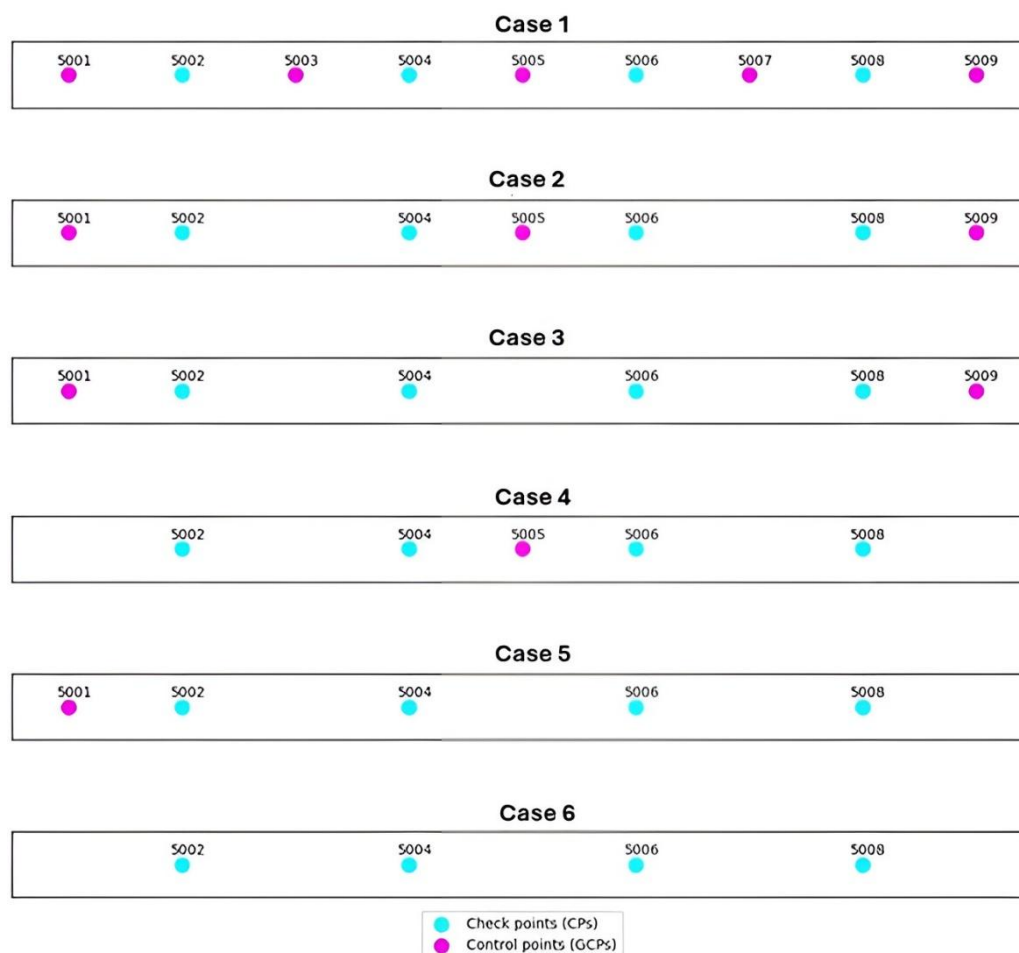


Figure 3. Test cases for line area.

### 3.2. Signalization and surveying of GCPs and CPs

The points were signalized in the field using artificial targets. Two types of signalization targets were used, one with dimensions of 50×50 cm and another with dimensions of 30×30 cm (Fig. 4). In total, 19 signalization targets were placed. The targets were temporarily stabilized using metal nails. For the line area, 9 targets for GCPs and CPs were placed at regular intervals along the line. For the square area, 9 targets were arranged in a regular grid for GCPs, and 4 targets were placed approximately at the center of each resulting quadrilateral to serve as

CPs. To ensure accurate target placement according to the planned layout, their positions were staked out using the GNSS RTN method.

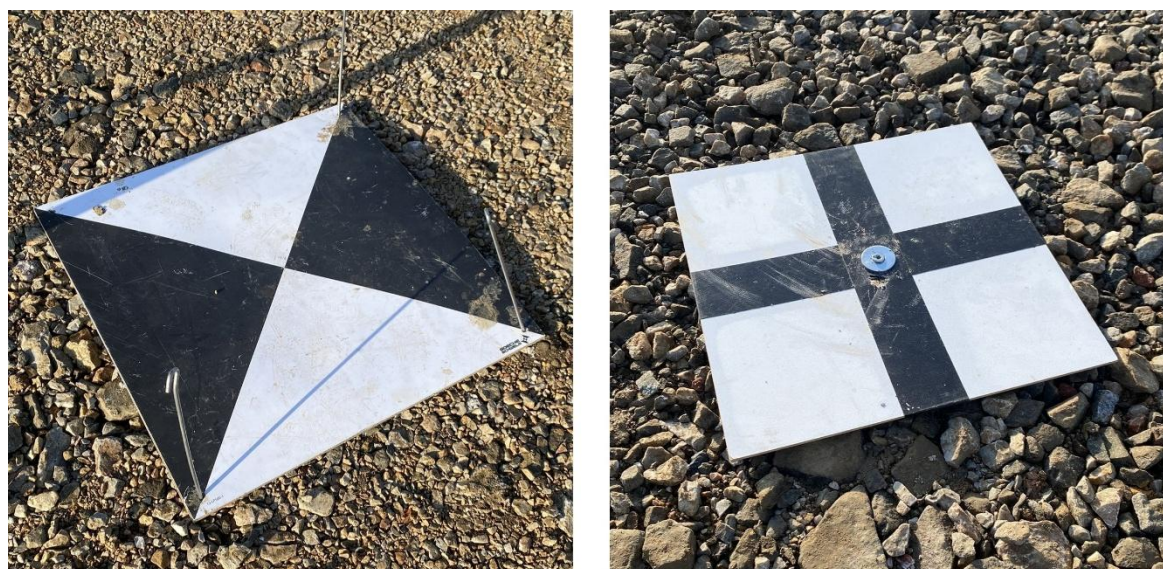


Figure 4. Signalization targets 50×50 cm (left) and 30×30 cm (right).

The points' positions were determined using a GNSS set (Trimble R2) with a Trimble TSC5 controller. The Trimble R2 is a standard GNSS receiver designed for geodetic surveying applications. It receives dual-frequency signals from GPS, GLONASS, Galileo, BeiDou, and QZSS satellite systems. The technical parameters of the GNSS set Trimble R2 are listed in Tab. 2. Measurements were carried out in topographic point survey mode, with the observation time at each point set to 15 minutes. The antenna was mounted on a tripod. The position of each point was determined based on three independent measurements. Measurements were conducted using the fast static method, connected to the Slovak Real-time Positioning Service (SKPOS) – national active geodetic reference network. The estimated accuracy of coordinate determination for the temporarily stabilized GCPs and CPs was 0.005 m in position and 0.010 m in height. After adjustment using terrestrial measurements with a TS, the accuracy of the GCP and CP points reached an RMSE of 2 mm for both  $m_{xy}$  and  $m_z$ .

Table 2. Technical parameters of the GNSS set Trimble R2 (www1)

|                              |                                     |                                                        |
|------------------------------|-------------------------------------|--------------------------------------------------------|
| <b>Weight</b>                | 1.08 kg (receiver only)             |                                                        |
| <b>Number of channels</b>    | 220                                 |                                                        |
| <b>Operating Temperature</b> | -20 °C to +55 °C                    |                                                        |
| <b>Frequency Range</b>       | GPS, GLONASS, Galileo, BeiDou, QZSS |                                                        |
| <b>Accuracy</b>              | RTK Positioning                     | Horizontal: 10 mm + 1 ppm<br>Vertical: 20 mm + 1 ppm   |
|                              | Network RTK                         | Horizontal: 10 mm + 1 ppm<br>Vertical: 20 mm + 1 ppm   |
|                              | Static and Fast Static              | Horizontal: 3 mm + 0.5 ppm<br>Vertical: 5 mm + 0.5 ppm |

### 3.3. Measurement by photogrammetric method

Photogrammetric measurements in the study area were carried out using the UAS DJI Matrice 350 RTK (Fig. 5a) and the UAS DJI Mavic 3 Enterprise (Fig. 5b). Other technical parameters of the UAS used are listed in Tab. 3.

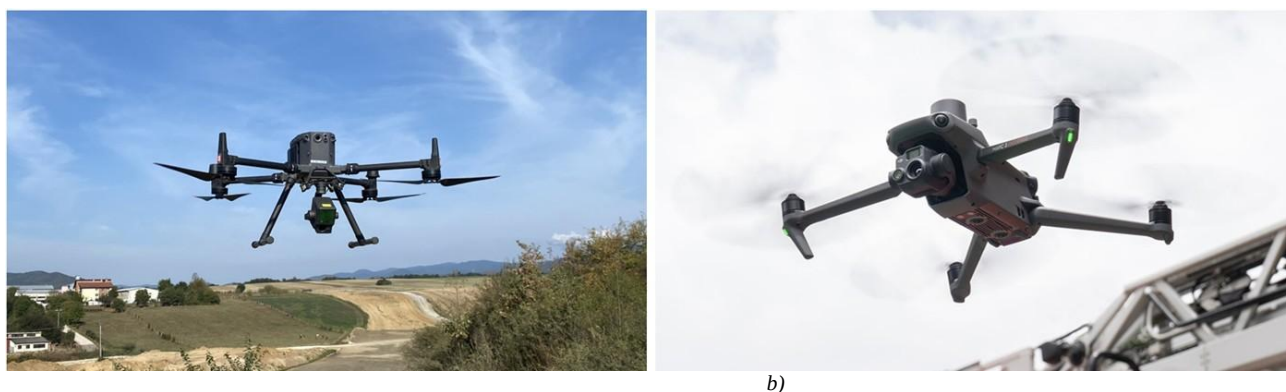


Figure 5. UAS DJI Matrice 350 RTK (a), UAS DJI Mavic 3 Enterprise (b).

Table 3. Comparison of technical parameters of both UAS (www2, www3, www4, www5, www6)

| UAS Specification                  | DJI Matrice 350 RTK         | DJI Mavic 3 Enterprise   |
|------------------------------------|-----------------------------|--------------------------|
| <b>Aircraft</b>                    |                             |                          |
| <b>Weight</b>                      | 3.77 kg (without batteries) | 915 g                    |
| <b>Max. Ascent/Descent Speed</b>   | 6 m/s and 5 m/s             | 6 m/s and 6 m/s          |
| <b>Max. Flight Speed</b>           | 23 m/s                      | 15 m/s                   |
| <b>RTK module</b>                  | Yes                         | Yes                      |
| <b>Max. flight time</b>            | 55 min                      | 45 min                   |
| <b>Wind speed resistance</b>       | 12 m/s                      | 12 m/s                   |
| <b>Operating Temperature Range</b> | - 20°C to + 50°C            | - 10°C to + 40°C         |
| <b>Sensor</b>                      |                             |                          |
| <b>Sensor</b>                      | DJI Zenmuse L1              | 4/3" CMOS                |
| <b>Type of sensor</b>              | Lidar + camera              | Camera                   |
| <b>Effective Pixels</b>            | 20 MPx                      | 20 MPx                   |
| <b>Camera</b>                      | DJI 24 mm F2.8              | DJI 24 mm F2.8           |
| <b>Active Pixels</b>               | 5472 × 3648 pixels (3:2)    | 5280 × 3956 pixels (4:3) |
| <b>Gimbal Pitch</b>                | - 120° to + 30°             | - 90° to + 35°           |
| <b>Battery</b>                     |                             |                          |
| <b>Type</b>                        | Li-ion                      | Li-ion                   |
| <b>Capacity</b>                    | 5880 mAh                    | 5000 mAh                 |
| <b>Voltage</b>                     | 44.76 V                     | 7.2 V                    |

The flight plans for all flights were created in the DJI Pilot 2 application. Two different types of areas were surveyed: square area and line area. Each area was surveyed at three different flight heights: 110 m, 90 m, and 70 m, set relative to the take-off point. These flight heights were selected to approximate the most commonly used flight heights in photogrammetric surveys of square and linear structures. The flight heights correspond to GSD values of 3, 2.5, and 2 cm/pixel. For all flight plans, a longitudinal image overlap of 80% and a side image overlap of 75% were used. Additional flight plan specifications are provided in Tab. 4. Fig. 6 shows an example flight plan from the DJI Pilot 2 application.

Table 4. Flight plans parameters.

| Flight plan | UAS         | Camera     | Area   | Flight Height s [m] | GSD [cm/pixel] | Longitudinal overlap | Side overlap | Area size [m <sup>2</sup> ] | Flight speed [m/s] | Number of images | Estim. mission time |
|-------------|-------------|------------|--------|---------------------|----------------|----------------------|--------------|-----------------------------|--------------------|------------------|---------------------|
| 1           | Matrice 350 | Zenmuse L1 | Square | 110                 | 3              | 80%                  | 75%          | 78589.4                     | 8.7                | 108              | 4 m 28 s            |
| 2           | Matrice 350 | Zenmuse L1 | Square | 90                  | 2.5            | 80%                  | 75%          | 78589.4                     | 7.1                | 169              | 6 m 38 s            |
| 3           | Matrice 350 | Zenmuse L1 | Square | 70                  | 2              | 80%                  | 75%          | 78589.4                     | 5.5                | 262              | 9 m 54 s            |
| 4           | Matrice 350 | Zenmuse L1 | Line   | 110                 | 3              | 80%                  | 75%          | 81330.8                     | 8.7                | 140              | 5 m 52 s            |
| 5           | Matrice 350 | Zenmuse L1 | Line   | 90                  | 2.5            | 80%                  | 75%          | 81330.8                     | 7.1                | 171              | 6 m 58 s            |
| 6           | Matrice 350 | Zenmuse L1 | Line   | 70                  | 2              | 80%                  | 75%          | 81330.8                     | 5.5                | 217              | 8 m 47 s            |
| 7           | Mavic 3E    | M3E Wide   | Square | 110                 | 3              | 80%                  | 75%          | 78589.4                     | 8.5                | 103              | 4 m 58 s            |
| 8           | Mavic 3E    | M3E Wide   | Square | 90                  | 2.5            | 80%                  | 75%          | 78589.4                     | 7.5                | 138              | 6 m 5 s             |
| 9           | Mavic 3E    | M3E Wide   | Square | 70                  | 2              | 80%                  | 75%          | 78589.4                     | 6.5                | 235              | 9 m 10 s            |
| 10          | Mavic 3E    | M3E Wide   | Line   | 110                 | 3              | 80%                  | 75%          | 65064.6                     | 8.5                | 126              | 5 m 58 s            |
| 11          | Mavic 3E    | M3E Wide   | Line   | 90                  | 2.5            | 80%                  | 75%          | 65064.6                     | 7.5                | 153              | 6 m 36 s            |
| 12          | Mavic 3E    | M3E Wide   | Line   | 70                  | 2              | 80%                  | 75%          | 65064.6                     | 6.5                | 195              | 7 m 34 s            |

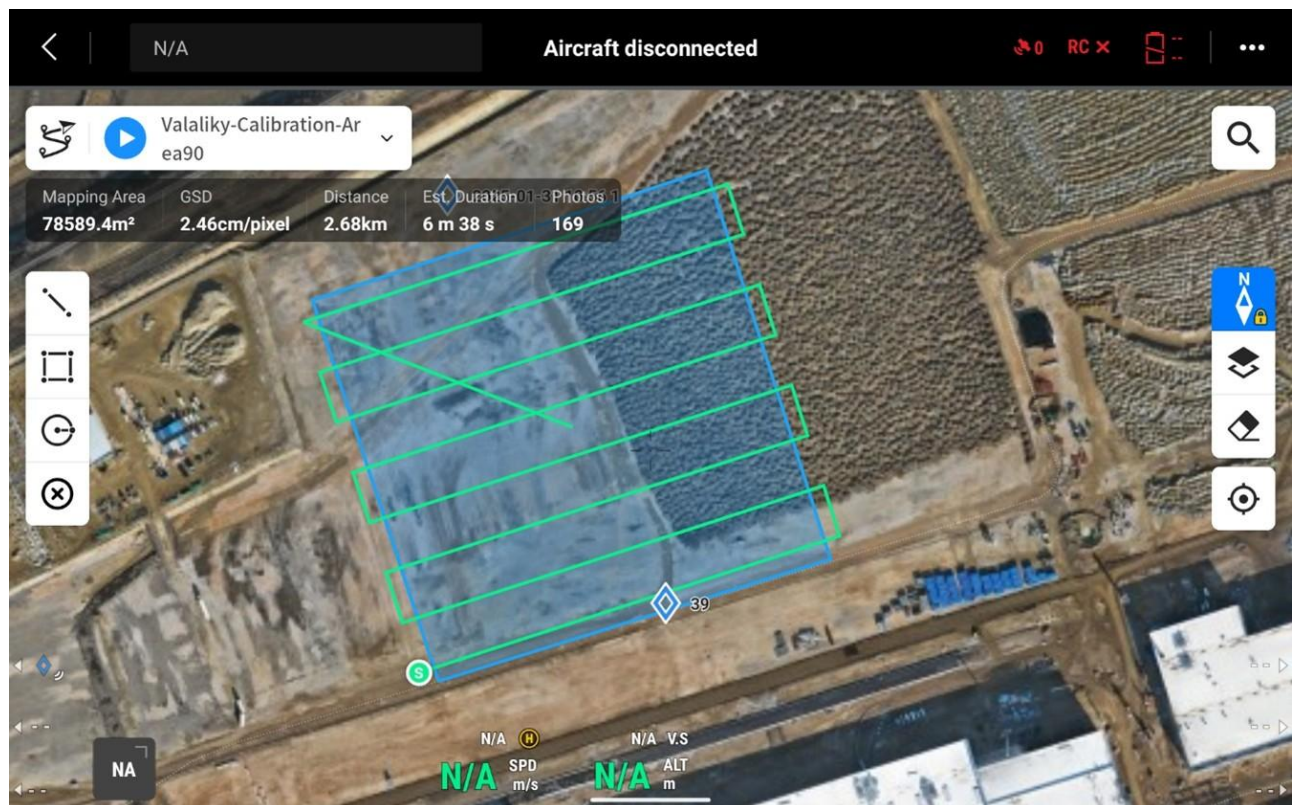


Figure 6. Example of a flight plan from the DJI Pilot 2 application.

### 3. Results

The captured images were processed using Agisoft Metashape Professional software, v. 2.2.1. A total of 12 flight missions were conducted. Each flight mission was processed with 6 different GCP configurations, resulting in 72 image-processing projects in total. For accuracy analysis of the resulting model, it is sufficient to proceed only to the image alignment step. Subsequent creation of final products—such as dense point clouds, DEMs, mesh models, or orthophotomosaics—is not required for this analysis. This decision was made to focus on accuracy assessment and reduce time-intensive processing effort. The same methodology was applied to each project, including identical software settings and a uniform processing workflow. The accuracy of photogrammetric measurements can be evaluated only using independent reference measurements, which were not included in the previous processing steps. In general, the term accuracy is used to evaluate quality. It can be quantified, for example, using the RMSE. RMSE expresses the difference between measured and reference values, or, in the case of a photogrammetric model, the difference between the coordinates of a point estimated by the software during processing and the actual coordinates of that point measured in the field. RMSE for the individual coordinates  $x$ ,  $y$ ,  $z$  is defined as follows (Luhmann et al., 2020):

$$RMSE_x = \sqrt{\frac{\sum_{i=1}^n (x_{oi} - x_{mi})^2}{n}} \quad (1)$$

$$RMSE_y = \sqrt{\frac{\sum_{i=1}^n (y_{oi} - y_{mi})^2}{n}} \quad (2)$$

$$RMSE_z = \sqrt{\frac{\sum_{i=1}^n (z_{oi} - z_{mi})^2}{n}} \quad (3)$$

where  $x_{oi}$ ,  $y_{oi}$ ,  $z_{oi}$  are the coordinates of the  $i$ -th point estimated from the model,  $x_{mi}$ ,  $y_{mi}$ ,  $z_{mi}$  are the coordinates of the  $i$ -th point measured in the field, and  $n$  is the number of points for which RMSE is calculated. In some cases, horizontal and vertical point accuracy is assessed separately. Then, the horizontal RMSE is calculated as follows:

$$RMSE_{xy} = \sqrt{\frac{\sum_{i=1}^n [(x_{oi} - x_{mi})^2 + (y_{oi} - y_{mi})^2]}{n}} = \sqrt{RMSE_x^2 + RMSE_y^2} \quad (4)$$

Equivalently, for the overall RMSE, the following applies:

$$RMSE = \sqrt{RMSE_x^2 + RMSE_y^2 + RMSE_z^2} \quad (5)$$

The most important processing results are the RMSE values at the CPs, presented in the following tables (Tab. 5, Tab. 6).

Table 5. RMSE of CPs for DJI Matrice 350 RTK.

| Square area          |                |                |                |                             |                  | Line area            |                |                           |                           |                            |              |
|----------------------|----------------|----------------|----------------|-----------------------------|------------------|----------------------|----------------|---------------------------|---------------------------|----------------------------|--------------|
| Flight height: 110 m |                |                |                |                             |                  | Flight height: 110 m |                |                           |                           |                            |              |
| Case                 | RMSE<br>x (cm) | RMSE<br>y (cm) | RMSE<br>z (cm) | RMSE <sub>x</sub><br>y (cm) | RMS<br>E<br>(cm) | Case                 | RMSE<br>x (cm) | RMSE <sub>y</sub><br>(cm) | RMSE <sub>z</sub><br>(cm) | RMSE <sub>xy</sub><br>(cm) | RMSE<br>(cm) |
| Case 1               | 0.418          | 1.652          | 1.004          | 1.704                       | 1.978            | Case 1               | 0.879          | 1.872                     | 1.819                     | 2.068                      | 2.754        |
| Case 2               | 0.441          | 1.924          | 1.010          | 1.974                       | 2.217            | Case 2               | 1.130          | 2.539                     | 0.856                     | 2.779                      | 2.908        |
| Case 3               | 0.429          | 1.976          | 1.046          | 2.022                       | 2.276            | Case 3               | 1.394          | 3.251                     | 1.435                     | 3.537                      | 3.817        |
| Case 4               | 0.817          | 3.039          | 1.398          | 3.147                       | 3.444            | Case 4               | 1.537          | 4.014                     | 0.520                     | 4.299                      | 4.330        |
| Case 5               | 0.681          | 3.108          | 1.431          | 3.182                       | 3.489            | Case 5               | 1.835          | 4.885                     | 1.027                     | 5.218                      | 5.318        |
| Case 6               | 0.818          | 3.274          | 1.836          | 3.375                       | 3.842            | Case 6               | 2.068          | 5.530                     | 3.059                     | 5.904                      | 6.649        |

| Flight height: 90 m |                |                |                |                             |                  |
|---------------------|----------------|----------------|----------------|-----------------------------|------------------|
| Case                | RMSE<br>x (cm) | RMSE<br>y (cm) | RMSE<br>z (cm) | RMSE <sub>x</sub><br>y (cm) | RMS<br>E<br>(cm) |
| Case 1              | 0.420          | 2.059          | 1.390          | 2.102                       | 2.519            |
| Case 2              | 0.398          | 2.243          | 1.365          | 2.278                       | 2.656            |
| Case 3              | 0.382          | 2.302          | 1.321          | 2.333                       | 2.682            |
| Case 4              | 0.472          | 2.649          | 1.895          | 2.690                       | 3.291            |
| Case 5              | 0.416          | 2.710          | 1.763          | 2.741                       | 3.259            |
| Case 6              | 0.501          | 2.715          | 8.736          | 2.761                       | 9.162            |

| Flight height: 70 m |                |                |                |                             |                  |
|---------------------|----------------|----------------|----------------|-----------------------------|------------------|
| Case                | RMSE<br>x (cm) | RMSE<br>y (cm) | RMSE<br>z (cm) | RMSE <sub>x</sub><br>y (cm) | RMS<br>E<br>(cm) |
| Case 1              | 1.001          | 2.890          | 1.463          | 3.058                       | 3.391            |
| Case 2              | 1.052          | 3.092          | 1.425          | 3.266                       | 3.563            |
| Case 3              | 1.054          | 3.138          | 1.422          | 3.311                       | 3.603            |
| Case 4              | 1.265          | 3.492          | 1.645          | 3.714                       | 4.062            |
| Case 5              | 1.211          | 3.423          | 1.530          | 3.631                       | 3.941            |
| Case 6              | 1.269          | 3.556          | 1.586          | 3.776                       | 4.096            |

| Flight height: 90 m |                |                           |                           |                            |              |
|---------------------|----------------|---------------------------|---------------------------|----------------------------|--------------|
| Case                | RMSE<br>x (cm) | RMSE <sub>y</sub><br>(cm) | RMSE <sub>z</sub><br>(cm) | RMSE <sub>xy</sub><br>(cm) | RMSE<br>(cm) |
| Case 1              | 0.542          | 0.377                     | 1.931                     | 0.661                      | 2.041        |
| Case 2              | 0.614          | 0.355                     | 1.008                     | 0.709                      | 1.233        |
| Case 3              | 0.658          | 0.390                     | 1.694                     | 0.765                      | 1.859        |
| Case 4              | 0.766          | 0.886                     | 0.740                     | 1.171                      | 1.386        |
| Case 5              | 0.651          | 0.388                     | 1.707                     | 0.758                      | 1.868        |
| Case 6              | 0.793          | 0.989                     | 17.786                    | 1.268                      | 17.831       |

| Flight height: 70 m |                |                           |                           |                            |              |
|---------------------|----------------|---------------------------|---------------------------|----------------------------|--------------|
| Case                | RMSE<br>x (cm) | RMSE <sub>y</sub><br>(cm) | RMSE <sub>z</sub><br>(cm) | RMSE <sub>xy</sub><br>(cm) | RMSE<br>(cm) |
| Case 1              | 0.377          | 0.706                     | 1.765                     | 0.800                      | 1.938        |
| Case 2              | 0.372          | 0.847                     | 0.820                     | 0.925                      | 1.236        |
| Case 3              | 0.321          | 1.016                     | 1.427                     | 1.066                      | 1.781        |
| Case 4              | 0.379          | 1.260                     | 0.868                     | 1.316                      | 1.577        |
| Case 5              | 0.298          | 1.333                     | 0.847                     | 1.366                      | 1.608        |
| Case 6              | 0.403          | 1.575                     | 9.471                     | 1.626                      | 9.609        |

Table 6. RMSE of CPs for DJI Mavic 3 Enterprise.

| Square area          |                |                |                |                             |                  |
|----------------------|----------------|----------------|----------------|-----------------------------|------------------|
| Flight height: 110 m |                |                |                |                             |                  |
| Case                 | RMSE<br>x (cm) | RMSE<br>y (cm) | RMSE<br>z (cm) | RMSE <sub>x</sub><br>y (cm) | RMS<br>E<br>(cm) |
| Case 1               | 1.703          | 1.943          | 1.613          | 2.584                       | 3.046            |
| Case 2               | 1.937          | 2.196          | 1.537          | 2.928                       | 3.307            |
| Case 3               | 2.055          | 2.281          | 1.419          | 3.070                       | 3.382            |
| Case 4               | 2.308          | 3.086          | 2.701          | 3.853                       | 4.706            |
| Case 5               | 2.570          | 3.423          | 1.915          | 4.281                       | 4.690            |
| Case 6               | 2.593          | 3.382          | 4.606          | 4.262                       | 6.275            |

| Line area            |                |                |                |                             |              |
|----------------------|----------------|----------------|----------------|-----------------------------|--------------|
| Flight height: 110 m |                |                |                |                             |              |
| Case                 | RMSE<br>x (cm) | RMSE<br>y (cm) | RMSE<br>z (cm) | RMSE <sub>x</sub><br>y (cm) | RMSE<br>(cm) |
| Case 1               | 0.234          | 1.323          | 1.632          | 1.344                       | 2.114        |
| Case 2               | 0.256          | 1.703          | 0.732          | 1.722                       | 1.871        |
| Case 3               | 0.259          | 2.082          | 1.239          | 2.098                       | 2.437        |
| Case 4               | 0.211          | 2.289          | 1.070          | 2.299                       | 2.536        |
| Case 5               | 0.281          | 3.096          | 1.009          | 3.109                       | 3.268        |
| Case 6               | 0.390          | 3.474          | 28.023         | 3.496                       | 28.241       |

| Flight height: 90 m |                |                |                |                             |                  |
|---------------------|----------------|----------------|----------------|-----------------------------|------------------|
| Case                | RMSE<br>x (cm) | RMSE<br>y (cm) | RMSE<br>z (cm) | RMSE <sub>x</sub><br>y (cm) | RMS<br>E<br>(cm) |
| Case 1              | 0.342          | 1.550          | 1.396          | 1.587                       | 2.114            |
| Case 2              | 0.334          | 1.627          | 1.547          | 1.661                       | 2.269            |
| Case 3              | 0.343          | 1.642          | 1.483          | 1.678                       | 2.239            |
| Case 4              | 0.478          | 2.116          | 1.484          | 2.169                       | 2.628            |
| Case 5              | 0.378          | 1.813          | 1.624          | 1.852                       | 2.463            |
| Case 6              | 0.463          | 2.161          | 5.486          | 2.210                       | 5.915            |

| Flight height: 70 m |                |                |                |                             |                  |
|---------------------|----------------|----------------|----------------|-----------------------------|------------------|
| Case                | RMSE<br>x (cm) | RMSE<br>y (cm) | RMSE<br>z (cm) | RMSE <sub>x</sub><br>y (cm) | RMS<br>E<br>(cm) |
| Case 1              | 0.606          | 1.635          | 1.337          | 1.744                       | 2.198            |
| Case 2              | 0.600          | 1.696          | 1.274          | 1.799                       | 2.205            |
| Case 3              | 0.595          | 1.726          | 1.272          | 1.826                       | 2.225            |
| Case 4              | 0.780          | 1.789          | 1.275          | 1.952                       | 2.331            |
| Case 5              | 0.743          | 1.802          | 1.369          | 1.949                       | 2.381            |
| Case 6              | 0.777          | 1.817          | 2.438          | 1.976                       | 3.139            |

| Flight height: 90 m |                |                |                |                             |              |
|---------------------|----------------|----------------|----------------|-----------------------------|--------------|
| Case                | RMSE<br>x (cm) | RMSE<br>y (cm) | RMSE<br>z (cm) | RMSE <sub>x</sub><br>y (cm) | RMSE<br>(cm) |
| Case 1              | 0.494          | 1.055          | 2.239          | 1.165                       | 2.524        |
| Case 2              | 0.578          | 1.341          | 1.333          | 1.461                       | 1.978        |
| Case 3              | 0.670          | 1.477          | 2.006          | 1.622                       | 2.580        |
| Case 4              | 0.715          | 1.606          | 1.372          | 1.757                       | 2.229        |
| Case 5              | 0.831          | 2.135          | 2.298          | 2.291                       | 3.245        |
| Case 6              | 0.895          | 2.146          | 6.842          | 2.325                       | 7.226        |

| Flight height: 70 m |                |                |                |                             |              |
|---------------------|----------------|----------------|----------------|-----------------------------|--------------|
| Case                | RMSE<br>x (cm) | RMSE<br>y (cm) | RMSE<br>z (cm) | RMSE <sub>x</sub><br>y (cm) | RMSE<br>(cm) |
| Case 1              | 0.593          | 1.416          | 1.226          | 1.535                       | 1.965        |
| Case 2              | 0.739          | 1.910          | 0.359          | 2.048                       | 2.079        |
| Case 3              | 0.884          | 2.397          | 0.481          | 2.555                       | 2.600        |
| Case 4              | 1.176          | 3.103          | 1.107          | 3.319                       | 3.498        |
| Case 5              | 1.280          | 3.969          | 0.362          | 4.170                       | 4.186        |
| Case 6              | 1.573          | 4.390          | 5.290          | 4.663                       | 7.052        |

From the processing results, graphs showing the achieved RMSE in horizontal position and in height for CPs across the different cases, areas, flight heights, and UAS used were created. Cases 1–6 for the square area and the line area are matched, as they were designed to be equivalent. For example, case 3 for the square area uses GCPs in the corners of the area, while case 3 for the line area uses GCPs at the start and end of the area. The other cases are also equivalent in this way. For this reason, all cases are presented together in a single graph. To maintain

clarity, we use abbreviations: M350 for the UAS DJI Matrice 350 RTK and M3e for the UAS DJI Mavic 3 Enterprise. Fig. 7 shows the achieved RMSE in horizontal position.

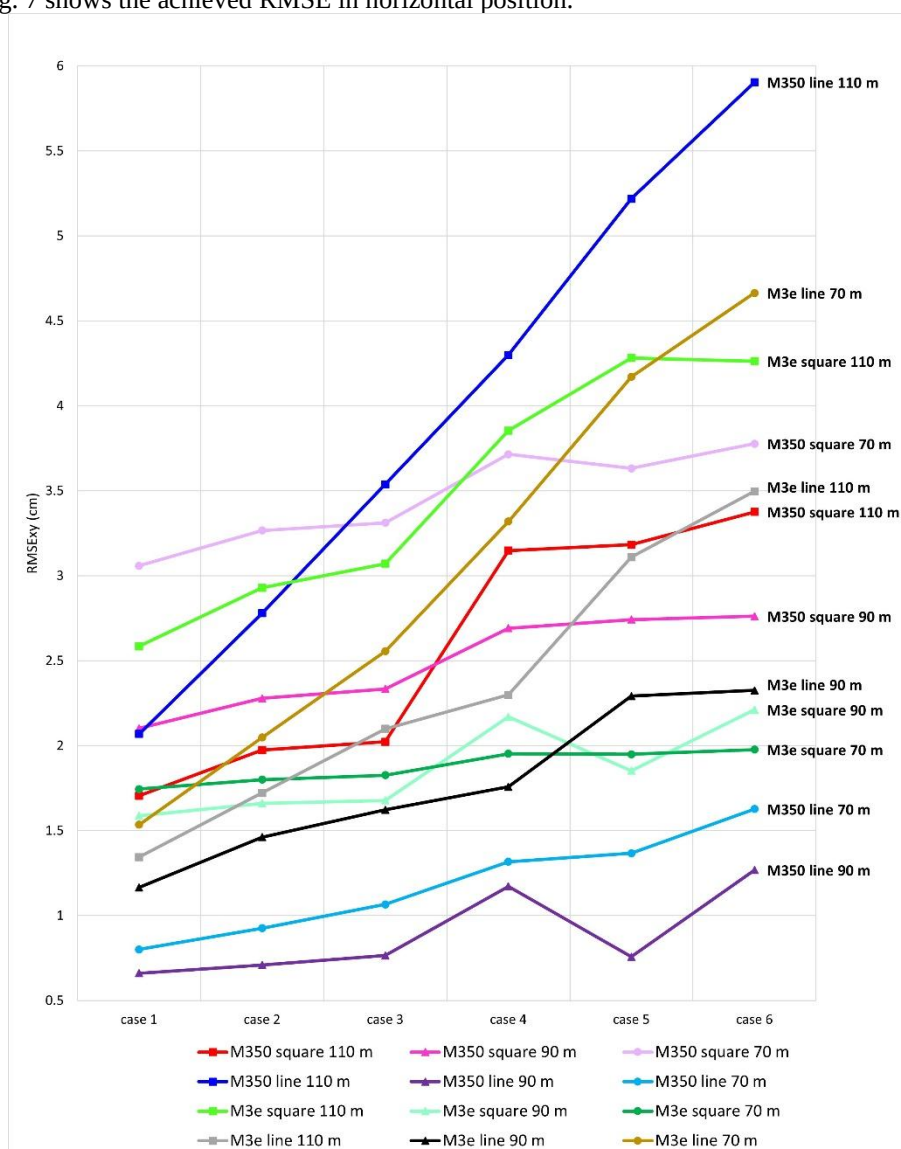
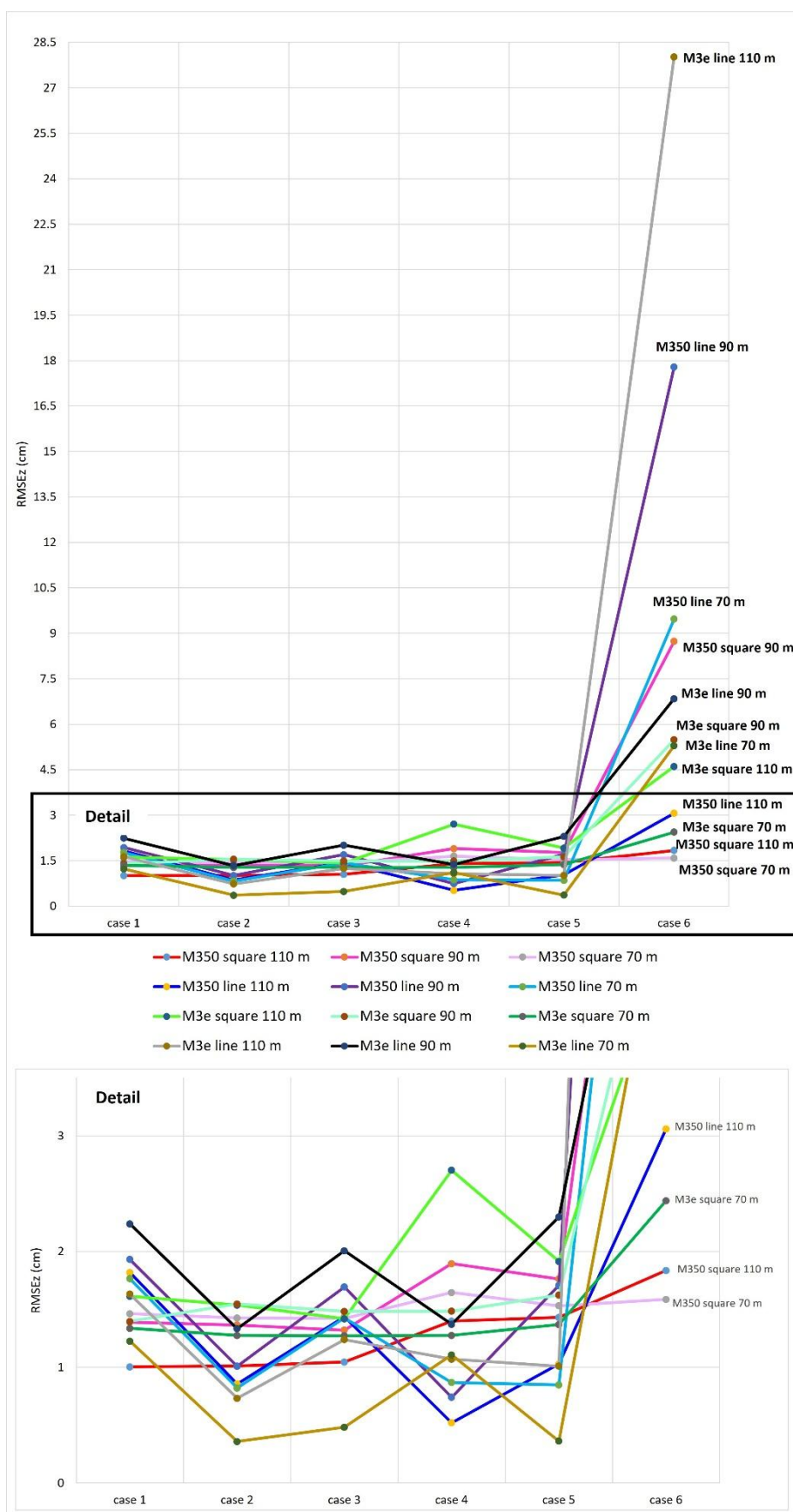


Figure 7. Root Mean Square Error in horizontal position – RMSExy.

From the depiction of horizontal accuracy development for the individual cases, it is evident that RMSExy tends to increase in all tested cases as the number of GCPs decreases or their distribution worsens. RMSExy ranges from approximately 0.7 to 3.1 cm for case 1 and from roughly 1.3 to 5.9 cm for case 6. The most accurate results were achieved with the UAS DJI Matrice 350 RTK over the line area at a flight height of 90 m, while the least accurate results were obtained for the same UAS over the line area at 110 m. Differences in horizontal accuracy for GCP configurations 1, 2, and 3 are not significant, with RMSExy ranging from 0.7 cm to 3.5 cm across all tests. For the remaining GCP configurations, accuracy deteriorates. This outcome confirms that placing GCP at the corners of the square area or at the start and end of the line area achieves higher accuracy. Comparing only configurations 1, 2, and 3 shows that adding GCP at the centers of the sides, at the center of the square area, or along the line does not significantly improve accuracy. For configurations 4, 5, and 6, the spread of RMSExy is larger, ranging from 0.8 cm to 5.9 cm. In these cases, it can be observed that with RTK-equipped UAS, horizontal accuracy without GCP (case 6) reaches a level comparable to that achieved with a single GCP (cases 4 and 5). Differences between square and line areas also become noticeable in these cases. The graph showing the achieved RMSE in height at the CPs for each case is presented in Fig. 8.



Regarding the development of RMSE<sub>z</sub> for the individual tested cases, the graph shows that for cases 1 to 5, the vertical accuracy remains approximately constant, with RMSE<sub>z</sub> values ranging from 0.4 to 2.7 cm. In general, vertical accuracy is lower than horizontal accuracy; however, in this instance, this is not the case because the test areas lacked terrain variability. Both the square and line areas were flat, with no significant elevation differences, resulting in higher vertical accuracy than is usually observed in photogrammetric measurements. This also explains why vertical accuracy does not deteriorate with fewer GCPs or poorer GCP distribution. A difference becomes noticeable in case 6, where no GCPs were used for image alignment. In this case, most tested scenarios show a significant deterioration of RMSE<sub>z</sub>, reaching up to 28 cm for the UAS DJI Mavic 3 Enterprise over the line area at a flight height of 110 m. The large elevation error under pure RTK direct georeferencing is mainly due to the absence of GCPs, which otherwise eliminate residual systematic errors. While RTK improves camera positioning, it does not fully compensate for vertical inaccuracies, GNSS-related errors, and calibration uncertainties. As a result, these uncorrected errors propagate into the elevation component, leading to significantly higher RMSE<sub>z</sub> values. Conversely, in some instances of case 6, vertical accuracy of 1.6 to 3 cm was still achieved, which may also be influenced by the flatness of the area.

#### 4.1. Analysis of RMSE for the different types of areas

The following graphs show RMSE separately for the square area (Fig. 9) and for the line area.

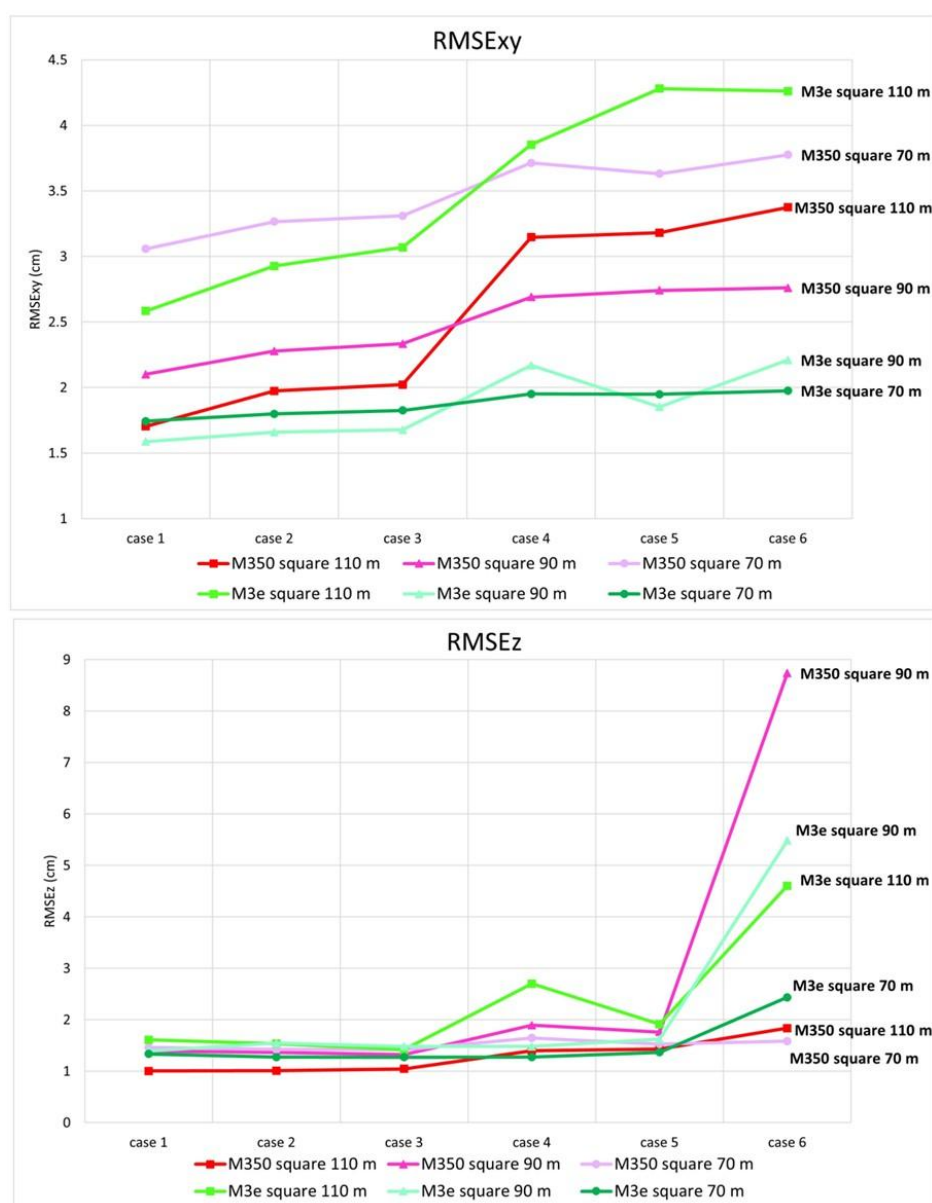


Figure 9. RMSE in horizontal position and in height for the square area.

For the square area, a more pronounced jump in horizontal accuracy can be observed between cases 3 and 4. As mentioned in the previous subsection, horizontal accuracy for cases 1 to 3 remains largely unchanged. These cases share the placement of GCPs at the corners of the area. For cases 4 to 6, horizontal accuracy also does not change significantly, indicating that if only one GCP is used, its placement does not matter, and even omitting it does not cause a major decrease in horizontal accuracy. However, it significantly deteriorates vertical accuracy. Fig. 10 shows RMSE in horizontal position and in height for the line area.

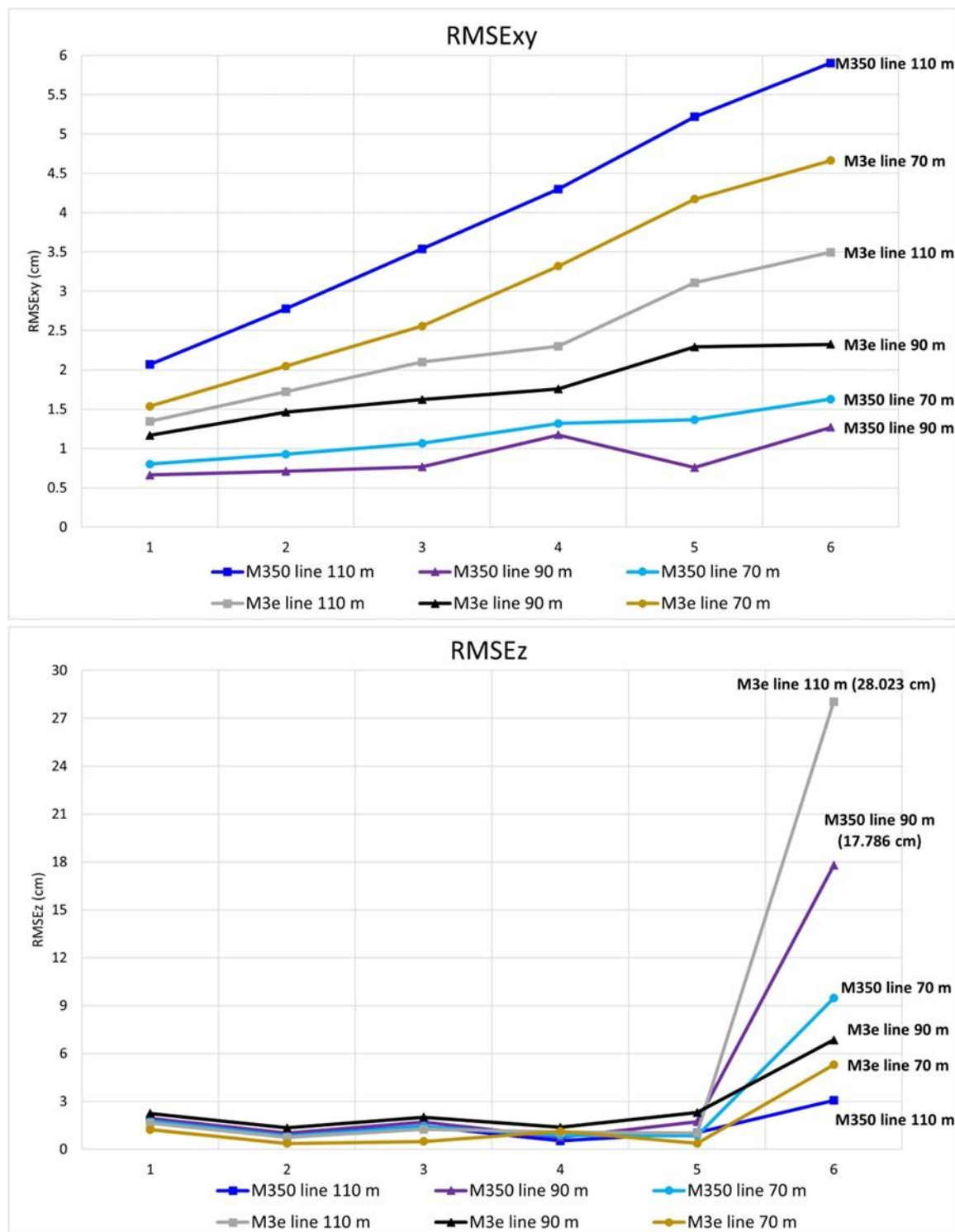


Figure 10. RMSE in horizontal position and in height for the line area.

For the line area, horizontal accuracy steadily decreases from case 1 to case 6. This indicates that for cases 1 to 3, more GCPs yield more accurate results. For cases 4 to 6, placing GCPs in the middle of the area is more

effective than placing them at the beginning or end. When no GCPs are used, horizontal accuracy worsens slightly, but not dramatically. However, vertical accuracy deteriorates significantly in case 6.

When comparing the achieved horizontal accuracy between the square area and the line area, the graphs show that the number and distribution of GCPs have a greater impact on horizontal accuracy in the line area. In the line area, lower numbers or poorly distributed GCPs lead to a more pronounced decrease in accuracy than in the square area. For vertical accuracy, cases 1 to 5 show no significant differences between the square and line areas. For case 6 (without GCPs), the line area showed worse results, with a maximum of 28 cm for the UAS DJI Mavic 3 Enterprise at a flight height of 110 m. In the square area, vertical accuracy was better, with the worst result being 8.7 cm at a flight height of 90 m using UAS DJI Matrice 350 RTK.

#### 4.2. Analysis of RMSE by individual UAS and flight heights

This subsection analyzes RMSE values separately for each UAS and flight height, based on the results presented in Tab. 5 and Tab. 6. The aim is to evaluate each UAS's accuracy and assess the effect of flight height on the quality and precision of the acquired data. For the DJI Matrice 350 RTK UAS, the best horizontal RMSE of 0.66 cm was achieved for the line area at a flight height of 90 m in case 1. The worst horizontal RMSE of 5.9 cm was recorded for the line area at a flight height of 110 m in case 6. The best vertical RMSE of 0.5 cm for the UAS DJI Matrice 350 RTK was achieved in the line area, at a flight height of 110 m, in case 4, while the worst vertical RMSE of 17.8 cm occurred in the line area, at a flight height of 90 m, in case 6. For the UAS DJI Mavic 3 Enterprise, the best horizontal RMSE of 1.2 cm was achieved in the line area, at a flight height of 90 m, in case 1, and the worst horizontal RMSE of 4.7 cm was recorded in the line area, at a flight height of 70 m, in case 6. The best vertical RMSE of 0.36 cm for the UAS DJI Mavic 3 Enterprise was achieved in the line area, at a flight height of 70 m, in case 2, while the worst vertical RMSE of 28 cm was observed in the line area, at a flight height of 110 m, in case 6. The results show that the variability across tests is lower for the UAS DJI Mavic 3 Enterprise than for the UAS DJI Matrice 350 RTK. Regarding vertical accuracy, both UAS achieve approximately the same level of precision.

The following results show the RMSE achieved at each flight height. At a flight height of 110 m, the best horizontal RMSE of 1.3 cm was achieved for the line area, using the UAS DJI Mavic 3 Enterprise, in case 1. The worst horizontal RMSE of 5.9 cm was recorded for the line area, using the UAS DJI Matrice 350 RTK, in case 6. At the same flight height of 110 m, the best vertical RMSE of 0.5 cm was achieved for the line area, using the UAS DJI Matrice 350 RTK, in case 4, while the worst vertical RMSE of 28 cm occurred for the line area, using the UAS DJI Mavic 3 Enterprise, in case 6. At a flight height of 90 m, the UAS DJI Matrice 350 RTK achieved the best horizontal RMSE of 0.66 cm for the line area in case 1. The worst horizontal RMSE of 2.8 cm was recorded for the square area, using the UAS DJI Matrice 350 RTK, in case 6. At the same flight height, the best vertical RMSE of 0.7 cm was achieved for the line area, using the UAS DJI Matrice 350 RTK, in case 4, and the worst vertical RMSE of 17.8 cm was recorded for the line area, using the UAS DJI Matrice 350 RTK, in case 6. At a flight height of 70 m, the UAS DJI Matrice 350 RTK achieved the best horizontal RMSE of 0.8 cm for the line area in case 1. The worst horizontal RMSE of 4.7 cm occurred for the line area, using the UAS DJI Mavic 3 Enterprise, in case 6. At the same flight height, the best vertical RMSE of 0.36 cm was achieved for the line area, using the UAS DJI Mavic 3 Enterprise, in case 2, while the worst vertical RMSE of 9.5 cm was recorded for the line area, using the UAS DJI Matrice 350 RTK, in case 6.

The comparison of horizontal RMSE shows that the most accurate horizontal results were achieved at a flight height of 90 m. At this height, the differences between cases 1 to 6 are also the smallest. In contrast, at a flight height of 110 m, the achieved accuracy deteriorates more rapidly from case 1 to case 6. This indicates that a decreasing number and poorer distribution of GCPs have the least impact at a flight height of 90 m and the greatest impact at 110 m. Comparing the resulting vertical RMSE, flight height has no significant effect on vertical accuracy.

#### 4.3. Determining the Optimal Solution

To determine the optimal number and distribution of GCPs, it is necessary to evaluate square and line areas separately, as they differ in character and the measurement results also indicate differences. To identify the most suitable solution, a multicriteria decision-making analysis was applied, which allows optimization based on multiple criteria. In this method, the first criterion, with a weight of 0.67, was achieving the highest possible accuracy (i.e., the lowest possible RMSE), and the second criterion, with a weight of 0.33, was the number of GCPs used. The alternatives were the individual GCP distribution cases (case 1 to case 6). The weights of the individual criteria were determined based on their order of importance (most important – accuracy = 1, second most important – number of GCPs = 2), according to the following relationship (Malczewski et al., 2015):

$$w_k = \frac{n - p_k + 1}{\sum_{k=1}^n (n - p_k + 1)} \quad (6)$$

where  $w_k$  is the weight of the  $k$ -th criterion ( $k = 1, 2, \dots, n$ ),  $n$  is the number of criteria, and  $p_k$  is the order of importance of the  $k$ -th criterion.

In the evaluation, we used average RMSE values from measurements using individual UAS at different flight heights, as well as the number of GCP used in cases 1 to 6. These values were normalized to a scale from 0 to 1 using the following relation for criterion minimization:

$$v(x_{ik}) = \frac{\max_i\{x_{ik}\} - x_{ik}}{\max_i\{x_{ik}\} - \min_i\{x_{ik}\}} \quad (7)$$

where  $v(x_{ik})$  is the normalized value of the  $i$ -th alternative ( $i = 1, 2, \dots, m$ ) for the  $k$ -th criterion ( $k = 1, 2, \dots, n$ ),  $m$  is the number of alternatives,  $n$  is the number of criteria,  $x_{ik}$  is the original value,  $\min_i\{x_{ik}\}$  and  $\max_i\{x_{ik}\}$  are the minimum and maximum values from the set of all alternatives for the  $k$ -th criterion. The overall evaluation of a given alternative was calculated as a weighted sum of the normalized values as follows:

$$V(X_i) = \sum_{k=1}^n w_k v(x_{ik}) \quad (8)$$

where  $V(X_i)$  is the overall evaluation of the  $i$ -th alternative ( $i = 1, 2, \dots, m$ ),  $w_k$  is the weight of the  $k$ -th criterion ( $k = 1, 2, \dots, n$ ) and  $v(x_{ik})$  is the normalized value of the  $i$ -th alternative for the  $k$ -th criterion. The alternative with the highest overall evaluation is considered the most suitable.

#### 4.3.1. Square area

For the square area, Tab. 7 presents the horizontal and vertical RMSE values and their average for the individual measurements, which then enter the calculation of the overall evaluation for each case.

Table 7. Horizontal and vertical RMSE values for the square area.

| UAS:           | Matrice 350             | Matrice 350             | Matrice 350             | Mavic 3e                | Mavic 3e                | Mavic 3e                |              |
|----------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|--------------|
| Flight height: | 110 m                   | 90 m                    | 70 m                    | 110 m                   | 90 m                    | 70 m                    |              |
|                | RMSE <sub>xy</sub> (cm) | RMSE <sub>xy</sub> (cm) | RMSE <sub>xy</sub> (cm) | RMSE <sub>xy</sub> (cm) | RMSE <sub>xy</sub> (cm) | RMSE <sub>xy</sub> (cm) | Average (cm) |
| Case 1         | 1.704                   | 2.102                   | 3.058                   | 2.584                   | 1.587                   | 1.744                   | 2.130        |
| Case 2         | 1.974                   | 2.278                   | 3.266                   | 2.928                   | 1.661                   | 1.799                   | 2.318        |
| Case 3         | 2.022                   | 2.333                   | 3.311                   | 3.070                   | 1.678                   | 1.826                   | 2.373        |
| Case 4         | 3.147                   | 2.690                   | 3.714                   | 3.853                   | 2.169                   | 1.952                   | 2.921        |
| Case 5         | 3.182                   | 2.741                   | 3.631                   | 4.281                   | 1.852                   | 1.949                   | 2.939        |
| Case 6         | 3.375                   | 2.761                   | 3.776                   | 4.262                   | 2.210                   | 1.976                   | 3.060        |
|                | RMSE <sub>z</sub> (cm)  | RMSE <sub>z</sub> (cm)  | RMSE <sub>z</sub> (cm)  | RMSE <sub>z</sub> (cm)  | RMSE <sub>z</sub> (cm)  | RMSE <sub>z</sub> (cm)  | Average (cm) |
| Case 1         | 1.004                   | 1.390                   | 1.463                   | 1.613                   | 1.396                   | 1.337                   | 1.367        |
| Case 2         | 1.010                   | 1.365                   | 1.425                   | 1.537                   | 1.547                   | 1.274                   | 1.360        |
| Case 3         | 1.046                   | 1.321                   | 1.422                   | 1.419                   | 1.483                   | 1.272                   | 1.327        |
| Case 4         | 1.398                   | 1.895                   | 1.645                   | 2.701                   | 1.484                   | 1.275                   | 1.733        |
| Case 5         | 1.431                   | 1.763                   | 1.530                   | 1.915                   | 1.624                   | 1.369                   | 1.605        |
| Case 6         | 1.836                   | 8.736                   | 1.586                   | 4.606                   | 5.486                   | 2.438                   | 4.115        |

The following tables (Tab. 8, Tab. 9) present the overall evaluations of the individual cases in terms of horizontal and vertical accuracy. The overall evaluation is a numerical value from 0 to 1, calculated according to equation (7), where a value closer to 1 indicates a more suitable alternative with respect to the selected criteria.

Table 8. Overall evaluation in terms of horizontal RMSE for the square area.

| Criterion: | Horizontal RMSE <sub>xy</sub> [cm] |             |        | Number of GCP |             |        | Overall score | Rank |
|------------|------------------------------------|-------------|--------|---------------|-------------|--------|---------------|------|
|            | Value                              | Norm. value | Weight | Value         | Norm. value | Weight |               |      |
| Case 1     | 2.130                              | 1.000       | 0.67   | 9             | 0.000       | 0.33   | 0.667         | 3.   |
| Case 2     | 2.318                              | 0.798       | 0.67   | 5             | 0.444       | 0.33   | 0.680         | 1.   |
| Case 3     | 2.373                              | 0.738       | 0.67   | 4             | 0.556       | 0.33   | 0.677         | 2.   |
| Case 4     | 2.921                              | 0.150       | 0.67   | 1             | 0.889       | 0.33   | 0.396         | 4.   |
| Case 5     | 2.939                              | 0.130       | 0.67   | 1             | 0.889       | 0.33   | 0.383         | 5.   |
| Case 6     | 3.060                              | 0.000       | 0.67   | 0             | 1.000       | 0.33   | 0.333         | 6.   |

**Table 9.** Overall evaluation in terms of vertical RMSE for the square area.

| Criterion: | Vertical RMSEz [cm] |             |        | Number of GCP |             |        | Overall score | Rank |
|------------|---------------------|-------------|--------|---------------|-------------|--------|---------------|------|
|            | Value               | Norm. value | Weight | Value         | Norm. value | Weight |               |      |
| Case 1     | 1.367               | 0.986       | 0.67   | 9             | 0.000       | 0.33   | 0.657         | 5.   |
| Case 2     | 1.360               | 0.988       | 0.67   | 5             | 0.444       | 0.33   | 0.807         | 4.   |
| Case 3     | 1.327               | 1.000       | 0.67   | 4             | 0.556       | 0.33   | 0.852         | 3.   |
| Case 4     | 1.733               | 0.854       | 0.67   | 1             | 0.889       | 0.33   | 0.866         | 2.   |
| Case 5     | 1.605               | 0.900       | 0.67   | 1             | 0.889       | 0.33   | 0.896         | 1.   |
| Case 6     | 4.115               | 0.000       | 0.67   | 0             | 1.000       | 0.33   | 0.333         | 6.   |

From the calculations in Tab. 8, case 2 provides the most suitable distribution and number of GCPs to achieve the lowest horizontal RMSE while minimizing the number of GCPs, with an overall score of 0.680. Case 3 (0.677) and case 1 (0.667) also achieved similarly high scores. Following these, with considerably lower scores, are case 4 (0.396), case 5 (0.383), and case 6 (0.333). Based on these calculations, the optimal solution for the number and distribution of GCPs for a square area is to place four GCPs at the corners of the area, complemented by one GCP at its center (case 2). Alternative solutions could include case 3, which uses only the four corner GCPs, or case 1, which uses all nine GCPs.

Based on the calculations in Tab. 9, case 5 is the most suitable solution for achieving the minimum vertical RMSE while minimizing the number of GCPs, with an overall score of 0.896. Case 4 (0.866), case 3 (0.852), and case 2 (0.807) also achieved comparably high scores. Following these are case 1 (0.657) and case 6 (0.333). From this, it can be concluded that a single GCP is sufficient to ensure high vertical accuracy. However, it should be noted that the measurements were carried out on a flat area with a homogeneous surface, so in more complex terrain, the requirements for the number and placement of GCPs could differ. It is also evident that completely omitting GCPs (case 6) significantly reduces the achieved vertical accuracy.

#### 4.3.2. Line area

For the line area, Tab. 10 shows the horizontal and vertical RMSE values and their averages for individual measurements, which are then used to calculate the overall evaluation for each case.

**Table 10.** Horizontal and vertical RMSE values for the line area.

| UAS:           | Matrice 350 | Matrice 350 | Matrice 350 | Mavic 3e    | Mavic 3e    | Mavic 3e    |              |
|----------------|-------------|-------------|-------------|-------------|-------------|-------------|--------------|
| Flight height: | 110 m       | 90 m        | 70 m        | 110 m       | 90 m        | 70 m        |              |
|                | RMSExy (cm) | RMSExy (cm) | RMSExy (cm) | RMSExy (cm) | RMSExy (cm) | RMSExy (cm) | Average (cm) |
| Case 1         | 2.068       | 0.661       | 0.800       | 1.344       | 1.165       | 1.535       | 1.262        |
| Case 2         | 2.779       | 0.709       | 0.925       | 1.722       | 1.461       | 2.048       | 1.607        |
| Case 3         | 3.537       | 0.765       | 1.066       | 2.098       | 1.622       | 2.555       | 1.941        |
| Case 4         | 4.299       | 1.171       | 1.316       | 2.299       | 1.757       | 3.319       | 2.360        |
| Case 5         | 5.218       | 0.758       | 1.366       | 3.109       | 2.291       | 4.170       | 2.819        |
| Case 6         | 5.904       | 1.268       | 1.626       | 3.496       | 2.325       | 4.663       | 3.214        |
|                | RMSEz (cm)  | RMSEz (cm)  | RMSEz (cm)  | RMSEz (cm)  | RMSEz (cm)  | RMSEz (cm)  | Average (cm) |
| Case 1         | 1.819       | 1.931       | 1.765       | 1.632       | 2.239       | 1.226       | 1.769        |
| Case 2         | 0.856       | 1.008       | 0.820       | 0.732       | 1.333       | 0.359       | 0.851        |
| Case 3         | 1.435       | 1.694       | 1.427       | 1.239       | 2.006       | 0.481       | 1.380        |
| Case 4         | 0.520       | 0.740       | 0.868       | 1.070       | 1.372       | 1.107       | 0.946        |
| Case 5         | 1.027       | 1.707       | 0.847       | 1.009       | 2.298       | 0.362       | 1.208        |
| Case 6         | 3.059       | 17.786      | 9.471       | 28.023      | 6.842       | 5.290       | 11.745       |

The following tables (Tab. 11, Tab. 12) present the overall evaluations of the test cases in terms of horizontal and vertical accuracy. As with the square area, the closer the overall evaluation is to 1, the more suitable the alternative is for the chosen criteria.

**Table 11.** Overall evaluation in terms of horizontal RMSE for the line area.

| Criterion: | Horizontal RMSExy [cm] |             |        | Number of GCPs |             |        | Overall score | Rank |
|------------|------------------------|-------------|--------|----------------|-------------|--------|---------------|------|
|            | Value                  | Norm. value | Weight | Value          | Norm. value | Weight |               |      |
| Case 1     | 1.262                  | 1.000       | 0.67   | 5              | 0.000       | 0.33   | 0.667         | 2.   |
| Case 2     | 1.607                  | 0.823       | 0.67   | 3              | 0.400       | 0.33   | 0.682         | 1.   |
| Case 3     | 1.941                  | 0.652       | 0.67   | 2              | 0.600       | 0.33   | 0.635         | 3.   |
| Case 4     | 2.360                  | 0.437       | 0.67   | 1              | 0.800       | 0.33   | 0.558         | 4.   |

|        |       |       |      |   |       |      |       |    |
|--------|-------|-------|------|---|-------|------|-------|----|
| Case 5 | 2.819 | 0.202 | 0.67 | 1 | 0.800 | 0.33 | 0.402 | 5. |
| Case 6 | 3.214 | 0.000 | 0.67 | 0 | 1.000 | 0.33 | 0.333 | 6. |

**Table 12.** Overall evaluation in terms of vertical RMSE for the line area.

| Criterion: | Vertical RMSEz [cm] |             |        | Number of GCPs |             |        | Overall score | Rank |
|------------|---------------------|-------------|--------|----------------|-------------|--------|---------------|------|
|            | Value               | Norm. value | Weight | Value          | Norm. value | Weight |               |      |
| Case 1     | 1.769               | 0.916       | 0.67   | 5              | 0.000       | 0.33   | 0.611         | 5.   |
| Case 2     | 0.851               | 1.000       | 0.67   | 3              | 0.400       | 0.33   | 0.800         | 4.   |
| Case 3     | 1.380               | 0.951       | 0.67   | 2              | 0.600       | 0.33   | 0.834         | 3.   |
| Case 4     | 0.946               | 0.991       | 0.67   | 1              | 0.800       | 0.33   | 0.928         | 1.   |
| Case 5     | 1.208               | 0.967       | 0.67   | 1              | 0.800       | 0.33   | 0.911         | 2.   |
| Case 6     | 11.745              | 0.000       | 0.67   | 0              | 1.000       | 0.33   | 0.333         | 6.   |

The calculations in Tab. 11 indicate that case 2 provides the most suitable number and distribution of GCPs to achieve the minimum horizontal RMSE while minimizing their number, with an overall evaluation of 0.682. This variant includes three GCPs placed at the start, middle, and end of the line. Alternative solutions are case 1 (0.667) and case 3 (0.635). Case 4 (0.558) had slightly lower overall evaluations, followed by case 5 (0.402) and case 6 (0.333).

Based on the calculations in Tab. 12, a single GCP is sufficient to ensure high vertical accuracy. The most suitable solution was case 4 (0.928), which consists of one GCP placed at the center of the line. Case 5 (0.911) also achieved a comparably high overall evaluation, with the GCP located at the start of the line. This is followed by case 3 (0.834), case 2 (0.800), case 1 (0.611), and case 6 (0.333). As with the square area, omitting GCPs significantly degrades vertical accuracy.

## 5. Discussion

This article presents a comprehensive evaluation of UAS photogrammetric accuracy, with particular emphasis on the influence of terrain type, GCP configuration, the UAS platform used, and flight height. Its distinctiveness lies primarily in a combined approach that analyzes both square and line areas within a unified methodology, enabling direct comparison of photogrammetric model behavior under different geometric conditions. Most existing studies focus on a single area type or analyze only one accuracy factor, most commonly the number of GCPs. A key contribution of this article is the systematic analysis of multiple test cases with different GCP placement and distribution configurations, consistently applied to both square and line areas. This approach improves understanding of how terrain geometry affects RMSE and which GCP configurations are most suitable in terms of accuracy and efficiency. Moreover, accuracy assessment was carried out using independent CPs, thereby eliminating the risk of accuracy overestimation highlighted by several studies. A limitation of this study is the relatively small number of control points (CPs) used for accuracy assessment, with only four points evaluated in both square and linear test areas. From a statistical perspective, such a limited sample size reduces the robustness of the RMSE calculation and increases sensitivity to potential outliers or random errors at individual points. Therefore, the reported RMSE values should be interpreted with caution, particularly in terms of absolute accuracy. However, it is important to note that the primary objective of this study was not to establish absolute accuracy metrics with high statistical confidence, but rather to perform a comparative analysis between different UAV platforms, flight configurations, and georeferencing approaches. In this context, consistently using the same CP configuration across all experimental scenarios ensures comparable results.

Several studies investigate how the number and distribution of GCPs affect the accuracy of photogrammetric measurements. Shylesh et al. (2023) evaluate the impact of the number, quality, and spatial distribution of GCPs on the positional accuracy of UAS photogrammetric results over a square area in a built-up environment. The authors concentrate not only on the number of GCPs but primarily on their horizontal and vertical distribution within the area, as well as on the influence of errors in their geodetic surveying. The study aims to identify optimal GCP configurations that achieve high accuracy with minimal fieldwork demands. The research tests multiple GCP configurations, with the number of points ranging from a zero-GCP variant to configurations with eleven GCPs. Various placement scenarios were evaluated, particularly GCPs located at the corners of the area, along its boundaries, in the central part, and at different vertical elevation levels. The accuracy of the results was assessed using RMSE calculated from a large number of independent CPs, enabling an objective comparison of individual variants. The results show that increasing the number of GCPs generally improves accuracy; however, this relationship is not linear. Some configurations with four to five suitably distributed GCPs achieved RMSE values comparable to those of variants with significantly more GCPs. An important finding is the positive effect of the vertical distribution of GCPs, which particularly improved vertical accuracy. This article confirms that an appropriate spatial distribution of GCPs strongly affects the resulting accuracy, while optimal point placement can compensate for a higher number of less suitably positioned GCPs. This is supported by the results we obtained for

configurations with sufficient area coverage (cases 1–3). Horizontal accuracy ranged from about 0.7 to 3.5 cm, whereas for unsuitable configurations or in the absence of GCPs, the RMSE increased to around 5.9 cm. Based on our findings, it is evident that the importance of GCP distribution is particularly pronounced in linear objects. In contrast to the referenced study, we also identified the influence of area type and flight altitude, providing a more comprehensive perspective on optimizing GCP configuration under different conditions.

Article (Zhang et al., 2022) addresses the optimization of GCP distribution for UAS photogrammetry in situations where GCPs cannot be placed directly within the mapped area but only along its boundary or perimeter. The authors note that, in practice, terrain is often difficult to access, making it important to identify GCP arrangements that ensure the highest possible positional accuracy even without placing points in the area's interior. In the study, 88 different GCP configurations were created and evaluated for a square area of approximately 18 ha. Each configuration differed in the number of points and their spatial distribution around the area, while the resulting accuracy was assessed using RMSE calculated for CPs. The results showed that the best accuracy (RMSE = 0.15 m) was achieved by configurations in which GCPs were evenly distributed around the entire area, providing the best spatial effect. If it was not possible to place GCPs around the full perimeter, satisfactory accuracy was also achieved by configurations with GCPs evenly distributed along one half of the area or arranged in a uniformly distributed triangular pattern (RMSE = 0.18 m and 0.43 m, respectively). In contrast, configurations in which all GCPs lay along a single straight line resulted in significantly worse accuracy (RMSE = 2.10 m), confirming that the spatial distribution of points in two dimensions is more important than their number alone. The article emphasizes that when designing GCPs for UAS photogrammetry in inaccessible terrain, it is crucial to ensure a good geometric distribution that minimizes georeferencing errors even without placing points in the center of the area. Our research confirms these conclusions, particularly the finding that the number of GCPs alone is not decisive; their spatial distribution is key. Our results show that with an appropriate layout (corner points or beginning–middle–end configuration), sufficient horizontal accuracy can be achieved. At the same time, we demonstrated that high accuracy can be obtained even without placing points in the center of the area, provided that the GCPs are sufficiently distributed along the perimeter.

Liu et al. (2022) evaluate the accuracy of direct georeferencing of UAS images using RTK/PPK while examining how the number and spatial distribution of GCPs influence the quality of the resulting products. The authors used a FEIMA D2000 multicopter UAS equipped with RTK/PPK to acquire positional data for photogrammetric processing and created several projects with different GCP configurations incorporated into the bundle adjustment. The accuracy of the results was evaluated using RMSE at independent CPs and by comparing point cloud models using the M3C2 method. The results showed that direct georeferencing can significantly increase data acquisition efficiency without requiring a large number of GCPs, with measured horizontal and vertical RMSE values of 0.041 m and 0.087 m, respectively. As the number of GCPs increased and their distribution became denser and more uniform, RMSE values improved; however, beyond a certain density (e.g., 10–12 GCP/km<sup>2</sup>), additional points did not lead to a significant reduction in error. The authors recommend a uniform distribution of GCPs, including at least one point at the center of the area, to improve the models' vertical accuracy. At the same time, the study confirms that direct georeferencing of UAS data using RTK/PPK can achieve acceptable positional accuracy suitable for various applications, thereby reducing dependence on time-consuming field surveying of GCPs. The results of this study are largely consistent with our findings and confirm the importance of combining direct georeferencing with a well-designed GCP configuration. Although the authors achieved an accuracy of approximately 0.090 m using RTK/PPK, our results indicate that an optimal GCP distribution can achieve significantly higher accuracy, around 3.1 cm. At the same time, both studies confirm that the absence of GCPs primarily leads to a significant decrease in vertical accuracy.

Ferrer-González et al. (2020) evaluate the accuracy of photogrammetric results when mapping corridor or line areas, emphasizing how many GCPs are required and how they should be spatially distributed to achieve optimal results. The authors conducted multiple photogrammetric projects in which the number and distribution of GCPs in the bundle adjustment varied, and they evaluated the results using RMSE and multiscale M3C2 point cloud comparisons. The findings indicate that optimal accuracy is achieved with configurations comprising approximately 9 to 11 GCPs, placed alternately on both sides of the line area in an offset or “zick-zack” arrangement, with pairs of GCPs located at both ends of the corridor. These configurations offer the best compromise between fieldwork effort and the quality of the resulting products compared to other possible GCP layouts. The results therefore confirm that not only the number of GCPs, but above all their correct spatial distribution along a linear area, is crucial for achieving high accuracy in UAS photogrammetry. Conclusions similar to ours highlight the importance of proper GCP distribution, particularly in linear areas. In our case, we also confirmed that inappropriate or one-sided GCP placement significantly reduces overall model accuracy. The authors recommend configurations with 9 to 11 GCPs, whereas our results indicate that comparable accuracy can be achieved with a smaller number of points. This, however, depends on the optimal spatial distribution of the GCPs.

Sanz-Ablanedo et al. (2018) evaluate the geometric accuracy of digital surface models (DSM) and orthophotos derived from UAS and SfM photogrammetry. The authors assessed the number and placement of

GCPs used for georeferencing. The study area covered more than 1200 ha, included over 100 GCPs, and involved processing more than 2500 images, providing a robust dataset for comprehensive experiments. The authors generated up to 3465 different GCP combinations within the bundle adjustment and evaluated model accuracy using both GCPs and independent CPs. The analysis clearly showed that increasing the number of GCPs improves accuracy, while also highlighting that a uniform spatial distribution of GCPs is as important as their number. The findings of this study are consistent with our results, particularly in showing that increasing the number of GCPs improves accuracy; however, this effect is not continuous, as beyond a certain number of points the improvement becomes negligible. At the same time, the study confirms that an even spatial distribution of GCPs is key, since inappropriate configurations in our case led to decreased accuracy, as supported by the authors of the referenced study.

The selection of the five reference articles was not random, but deliberately reflects the main thematic axes addressed in this research. The first group of studies focuses on how the number, quality, and spatial distribution of GCPs affect the accuracy of UAS photogrammetry. These studies provide both a theoretical and experimental foundation for analyzing the GCP configurations used in this article and enable comparison of findings across different terrain types and processing methodologies. The results of the present study confirm their conclusions that proper geometric distribution of GCPs is often more important than their number. The second group of selected articles addresses specific cases, such as mapping areas with limited accessibility for GCP placement or mapping line areas. These studies are directly relevant to the present work, as line areas exhibit different error behavior and are more sensitive to unsuitable GCP distributions. The results presented in this article confirm that, for linear areas, increased attention must be paid to both the longitudinal and transverse distribution of GCPs, consistent with the recommendations published in the referenced studies.

Overall, the discussion shows that the results align with current trends in UAS photogrammetry while extending them with practical insights from comparing square and line areas within a single experimental framework. The article thus not only confirms existing knowledge but also offers new recommendations for GCP design and flight-parameter selection based on the characteristics of the mapped area, increasing its practical applicability.

#### 4. Conclusions

This article analyzes the achieved accuracy of photogrammetric measurements with different numbers and configurations of GCPs. Horizontal and vertical accuracy are assessed separately based on RMSE values, and optimal solutions for the number and placement of GCPs are identified. The aim was to investigate this issue for both square and line areas. Two different UAS platforms were available for measurements and were used to perform independent surveys for all investigated cases. Data acquisition was carried out at three flight heights—110 m, 90 m, and 70 m—since these heights are among the most commonly used in practical applications. Analysis in our study area showed that, for a square area, the optimal solution is to place four GCPs at the corners and one at the center. For a shorter linear area, the optimal configuration appears to be three GCPs positioned at the beginning, middle, and end of the area. As an optimal GCP configuration, we propose a layout covering the corners and the center for square areas, while for linear areas, a distribution of GCPs along the beginning, middle, and end of the area is recommended. The required number of GCPs should be adapted to the size and geometry of the mapped area. These findings are consistent with previous studies addressing this topic. However, it should be emphasized that the measurements were conducted over a relatively small area compared to typical real-world applications and on predominantly flat terrain. The RMSE analysis for individual UAS platforms and flight heights confirmed that platform choice and flight parameters directly affect resulting accuracy. Lower flight heights generally led to improved accuracy, albeit at the cost of increased demands on data acquisition and processing. At the same time, the results showed that modern UAS systems can achieve comparable accuracy with appropriate GCP configurations, opening opportunities to optimize workflows for specific application requirements. The article provides new insights, particularly in comparing UAS photogrammetric accuracy across different types of areas within a unified experimental framework. The results extend existing knowledge and highlight the need to adapt GCP design and flight parameters to the characteristics of the mapped area. Future research could focus on integrating direct georeferencing and conducting more extensive analyses across areas of varying size, shape, and topographic complexity.

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