JEODEZİ VE JEOİNFORMASYON DERGİSİ
JOURNAL OF GEODESY AND GEOINFORMATION
ISSN : 2147-1339
e-ISSN: 2667-8519

Araştırma Makalesi / *Research Article*
Yıl / *Year:* 2025 **Cilt** / *Volume:* 12 **Sayı** / *Issue*: 1
Sayfa / *Page*: 77-88
Dergi No / *Journal No*: 121
Doi: 10.9733/JGG.2025R0006.E

Investigation of the effect of GCP number and distribution on photogrammetric product accuracy in UAV photogrammetry

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Abstract: *Recently, photogrammetric products produced using Unmanned Aerial Vehicles (UAVs) are frequently preferred for disaster management, geological, and meteorological studies, urban studies and military purposes. Obtaining products with UAV photogrammetry provides a significant advantage over ground-based methods in terms of speed and cost. At the same time, the accuracy of the products produced is of particular importance. In this study, the effects of the number of Ground Control Points (GCPs) and GCP network design on accuracy were investigated. In this direction, 12 GCPs with homogeneous distribution in the study area were established and their locations were determined by GNSS measurements. Then, scenarios with different number of GCPs and different network designs were created, and the accuracy of these points were evaluated. As a result, it has been concluded that 5 GCPs homogeneously distributed in the field is sufficient for the products at high accuracy (≤ 10 cm) required in geomatics applications, increasing the number of the GCPs will not benefit the accuracy of the project and this process is disadvantageous in terms of increasing the cost along with the speed.*

Keywords: UAV Photogrammetry, GCP, Network design

İHA fotogrametrisinde YKN sayısı ve dağılımının fotogrametrik ürün doğruluğuna etkisinin araştırılması

Öz: *Son zamanlarda İnsansız Hava Araçları (İHA) kullanılarak üretilen fotogrametrik ürünler afet yönetimi, jeolojik ve meteorolojik araştırmalar, şehircilik çalışmaları ve askeri amaçlar için sıklıkla tercih edilmektedir. İHA fotogrametrisi ile ürün elde etmek hız ve maliyet açısından yersel yöntemlere göre önemli bir avantaj sağlamaktadır. Aynı zamanda üretilen ürünlerin doğruluğu da ayrı bir önem arz etmektedir. Bu çalışmada, Yer Kontrol Noktası (YKN) sayısının ve YKN ağ tasarımının doğruluk üzerindeki etkileri araştırılmıştır. Bu doğrultuda çalışma alanında homojen dağılım gösteren 12 nokta tesis edilerek GNSS ölçümleri ile konumları belirlenmiştir. Ardından, farklı YKN sayısına ve farklı ağ tasarımına sahip senaryolar oluşturularak bu noktaların doğrulukları değerlendirilmiştir. Sonuç olarak, arazide homojen dağılım gösteren 5 YKN'nin geomatik uygulamalarında gereksinim duyulan yüksek doğruluklu (≤ 10 cm) ürünler için yeterli olduğu, YKN sayısını artırmanın projenin doğruluğuna fayda sağlamayacağı ve bu işlemin hız ile birlikte maliyeti artırması bakımından dezavantajlı olduğu sonucuna varılmıştır.*

Anahtar Sözcükler: İHA fotogrametrisi, YKN, Ağ tasarımı

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Geliş Tarihi/Received: 05.02.2025
Kabul Tarihi/Accepted: 03.03.2025

1. Introduction

High-resolution products such as orthoimagery, point clouds and Digital Surface Models (DSM) derived from Unmanned Aerial Vehicle (UAV) photogrammetry are of increasing importance for many different engineering fields that require a complete understanding of topography. These products are produced for a wide variety of purposes and can be produced by many different vehicles such as satellites, airplanes and UAVs. UAVs are emerging as a viable alternative to conventional airborne and satellite sensors due to their lower cost, high temporal and spatial resolution, and flexibility in image acquisition (Harwin & Lucieer, 2012; Hugenholtz et al., 2013; Ozdas et al., 2024; Westoby et al., 2012). In recent years, UAVs can be used effectively and efficiently in many areas such as military purposes, detection and management of natural disasters such as forest fires, earthquakes and landslides, meteorological and geological studies, archaeological field applications, photogrammetric earth modeling and mapping (Mozas-Calvache et al., 2012; Niethammer et al., 2012; Okuyama et al., 2005; Ollero & Merino, 2006; Xiang & Tian, 2011). The use of UAVs in photogrammetric projects has many advantages such as being less affected by meteorological conditions, easy access to inaccessible and risky areas, high location accuracy and fast data processing, and ease of flight. On the other hand, some aspects such as increased wind speed, dust clouds, rainy weather, which affect image quality, and limited time in the air due to battery limitations can be considered as negative (Gencerk, 2016; Hastaoglu et al., 2023).

Ground Control Points (GCPs) are generally used to produce very high accuracy (≤ 5 cm) photogrammetric products, especially in geomatics discipline. On the other hand, in the case of using GNSS-equipped UAVs that allow RTK (Real Time Kinematic) and/or PPK (Post Processing Kinematic) solutions, photogrammetric products with an accuracy (≤ 15 cm) that can be easily used by many different disciplines depending on the Ground Sample Distance (GSD) can be produced.

In the literature, various studies have examined the effect of the distribution and number of GCPs on the positional accuracy of maps produced from UAV-collected data. Indirect georeferencing requires a sufficient number of GCPs with a homogeneous distribution if GCPs are established, measured, and used. However, methods such as Real Time Kinematic (RTK) and Post Processing Kinematic (PPK) in UAV photogrammetry can reduce or even eliminate the use of GCPs depending on the desired accuracy in the project (Ferrer-González et al., 2020; Turk & Ocalan, 2020; Turk et al., 2022). Therefore, if measurements are made with methods such as RTK or PPK, it is very important to investigate the number of GCPs required in the field and their appropriate distribution, since the number of GCPs directly affects labor, time, and cost. There are several studies on this subject in the literature.

Agüera-Vega et al. (2017a) conducted a study on the effect of the number of GCPs on the accuracy of DSM and orthoimagery produced by UAV/RTK method. In this study, 160 images were acquired from a height of 120 meters in an area of 17.64 hectares and the effect of different GCP numbers (4, 5, 6, 7, 8, 9, 10, 15, and 20) on the accuracy was analyzed with the help of Root Mean Square Error (RMSE) values. With 15 and 20 GCPs, RMSExy and standard deviation values for horizontal accuracy were 4.6±0.340 cm and 4.5±0.169 cm, respectively, while RMSEz and standard deviation values for vertical accuracy were 5.8±1.21 cm and 4.7±0.86 cm, respectively. As a result, it was concluded that similar results were obtained in both scenarios, however the most suitable option in terms of factors such as time and cost was 15 GCPs. In general, a decreasing trend was observed in the RMSE values as the number of GCPs increased. However, it was emphasized that there was not a big difference between 15 and 20 GCPs, so 15 GCPs were more preferable.

Martínez-Carricondo et al. (2018) investigated the effects of different GCP distributions on horizontal and vertical accuracies. It was found that the edge distribution and stratified distribution gave the best results. It was found that GCPs should be placed at the edge of the study area to optimize horizontal accuracy; however, this method is not sufficient for vertical accuracy. To improve vertical accuracy, it was suggested to place GCPs in a stratified distribution within the study area at a density of approximately 1.7 GCP/ha. The combination of these two methods was found to be the most appropriate strategy to minimize the total error. In the study, the best horizontal accuracy of 0.035 m was obtained by placing GCPs in an edge distribution and spaced 84 m apart. However, the vertical accuracy increased to 0.062 m in this scenario. On the other hand, the optimal combination for optimizing vertical accuracy was found to be a stratified distribution at a density of 1.7 GCP/ha, with a vertical accuracy of 0.047 m and a horizontal accuracy of 0.045 m. If the GCPs were spaced at 46.7 m intervals according to the edge distribution, the horizontal accuracy was 0.035 m and the vertical accuracy was 0.048 m. These results indicate that the distribution of GCPs should be carefully planned to improve photogrammetric accuracy.

Tomaštík et al. (2017) investigated the effect of different number and distribution of GCPs (4, 5, 7, and 9) installed on the ground on horizontal and vertical accuracies. As a result, they emphasized that the number of GCPs used does not have a significant effect on the accuracy. They stated that there was not a significant difference between using 4 and 9 similarly distributed GCPs in the field and that increasing the number of GCPs too much would negatively affect the effectiveness of the survey. Instead, they stated that the use of more precise methods of measuring and positioning of the GCPs would have a more positive effect on accuracy.

Agüera-Vega et al. (2017b) evaluated the effects of flight height, terrain morphology, and number of GCPs on accuracy. In the study, 60 different photogrammetric scenarios were carried out using five different terrain morphologies, four flight altitudes (50, 80, 100, and 120 m) and three different GCP numbers (3, 5, and 10). The results showed that the horizontal accuracy (RMSEX, RMSEY, RMSEXY) was not significantly affected by flight height or terrain morphology, but the number of GCPs had a significant impact on the accuracy. In terms of horizontal accuracy, the best results were obtained when using 5 or 10 GCPs, especially in flat areas. In terms of vertical accuracy, flight altitude and number of GCPs were found to be important factors, with accuracy decreasing as flight altitude increased. The highest accuracy was obtained with a flight altitude of 50 m and 10 GCPs, where RMSEX, RMSEY, RMSEXY, and RMSEZ values were calculated as 0.038, 0.035, 0.053, and 0.049 m, respectively.

Sanz-Ablanedo et al. (2018) examined the effects of the number and distribution of GCPs on accuracy in a square coal mine area of 1200 ha. As a result of the study, they stated that an increase in the number of GCPs improves accuracy and the importance of a balanced distribution of GCPs in the study area. In this context, they emphasized that the highest accuracy was achieved when the GCPs were evenly distributed over the entire area, and that if the density of GCPs was clustered in the center or edge regions, it gave insufficient results. They mentioned the necessity of using a large number of GCPs (minimum 3 GCPs per 100 images) to achieve high accuracy in large projects.

Oniga et al. (2020) examined the effect of the number of GCPs on accuracy with a low-cost UAV flight at a height of 28 m above ground in an area of 1 hectare. As a result, it was found that increasing the number of GCPs from 4 to 20 reduced the RMSE values by 50%.

Ferrer-González et al. (2020) investigated the effect of the number and distribution of the number of GCPs in the terrain on the accuracy of the photogrammetric product in a corridor-shaped study area with UAV photogrammetry. They emphasized that the horizontal and vertical accuracy improved with the increase in the number of GCPs used in the study and that horizontal accuracy was always better than vertical accuracy. They also stated that even if an RTK capable UAV was used, the use of GCPs was necessary in projects that required higher accuracy.

Deliry and Avdan (2024) emphasized that flight altitude does not affect the horizontal accuracy; however, the vertical accuracy decreases with increasing altitude, the vertical accuracy improves significantly with the increase in the number of GCPs used, and the vertical accuracy is not reliable in DSMs obtained without the use of GCPs.

Liu et al. (2022) evaluated the accuracy of the products obtained by direct georeferencing method. They emphasized that this accuracy improves with the use of GCPs, but this decrease is not significant above a density of 12 GCP/km². In general, they mentioned the positive effects of homogeneous distribution of the GCPs and the establishment of a GCP near the center of the area on the accuracy.

Hastaoglu et al. (2023) emphasized that distribution of GCPs is more important than number of GCPs to achieve the highest accuracy in UAV photogrammetry projects. They emphasized that although the homogeneous distribution of the GCPs that accurately reflects the geometric structure of the study area increases the accuracy, the results are negatively affected by poorly designed GCP networks or those placed only at the field boundaries. They also emphasized that in UAV photogrammetry, increasing the number of GCPs alone will not improve the position accuracy, and that an accurate GCP design that also takes into account the topographic and geometric structure is required.

As can be understood from the above studies, even if measurements are to be made with UAVs equipped with hardware that allows RTK/PPK solution, the installation of a GCP helps to increase the accuracy to higher levels. In addition, it can be difficult to collect photogrammetric data using a large number of GCPs due to time, cost, labor, and accessibility (Zhang et al., 2019). As another comparison, in RTK measurement, if the connection is lost even for a fraction of a second, there may be problems in producing accurate output products. However, the PPK measurement method does not have problem of losing signal connection. Therefore, PPK provides much more reliable results than RTK. In PPK, depending on the accuracy expected from the project, the use of GCP can be reduced or eliminated. As a matter of fact, recent studies have emphasized that high accuracy photogrammetric products can be produced below 10 cm without the need for GCP (Turk & Ocalan, 2020; Turk et al., 2022).

In this study, 12 GCPs were installed in the application area and necessary positioning measurements were made. Afterwards, a flight was performed with a UAV equipped with GNSS hardware capable of PPK solution. Then, the effects of the number of GCPs and their distribution on location accuracy were investigated in different scenarios.

2. Material and Methods

In this study, an area of approximately 6 km^2 within the campus of Sivas Cumhuriyet University with different vegetation, buildings, and topographical features was selected as the study area. In this area, 12 GCPs were installed, and their positions were determined via The Tersus Oscar GNSS receiver and CORS-TR. The receiver supports all GNSS satellite systems and frequencies, enabling high-precision position determination. It is capable of receiving GPS (L1 C/A, L2C, L2P, L5), GLONASS (L1 C/A, L2 C/A), BeiDou (B1, B2, B3, BDS-3), Galileo (E1, E5a, E5b), and QZSS (L1 C/A, L2C, L5) signals and is compatible with SBAS, WAAS, EGNOS, GAGAN, SDCM, and MSAS systems. With the 576-channel capacity, data were obtained from the CORS-TR station with the Network RTK method with a precision of 8mm+0.5ppm horizontally and 15mm+0.5ppm vertically.

In addition, a fixed GNSS reference station was installed approximately in the center of the study area for the solution of the kinematic GNSS data collected by UAV.

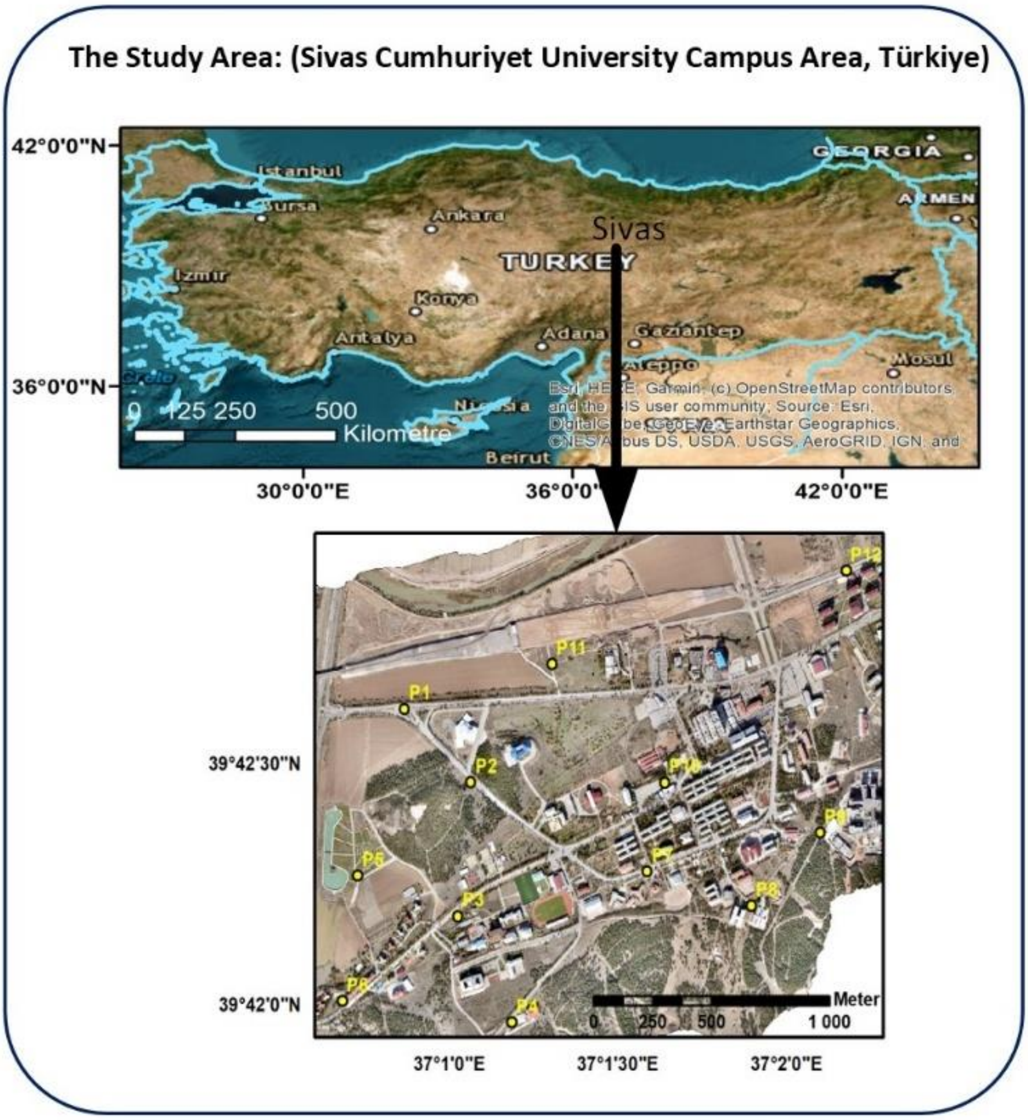

Figure 1: Study area and distribution of GCPs installed

Quantum Systems Trinity F90+ UAV with 42.4 MP (7952 X 5304 pixels) resolution, PPK/GNSS hardware and Sony RX1R II RGB camera with 35.9 mm x 24.0 mm sensor size, f=35mm F2.0 lens type and manual focus vertical take-off and landing (VTOL) capability was used in the study. In the study area, 1770 images were obtained with an average GSD of 3.16 cm, 80% overlap and 60% sidelap parameters during a 1-hour flight. The process steps followed in this study are shown in Fig. 2 and some GCPs installed in the study area are shown in Fig. 3.

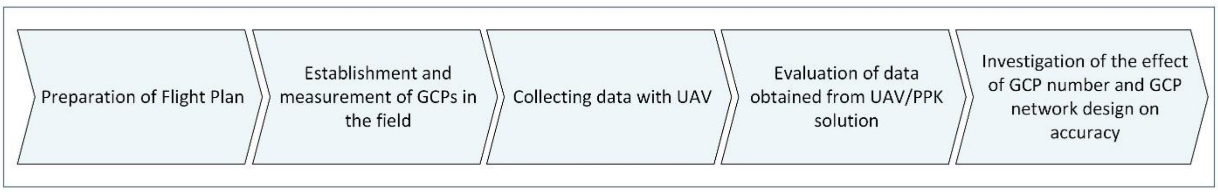

Figure 2: Workflow chart

Figure 3: *Some of the GCPs installed in the study area*

While GCPs contribute to the georeferencing process in photogrammetric studies, Check Points (CPs) are used to test accuracy (Ferrer-González et al., 2020; Tomaštík et al., 2019). In this study, the effect of the number and distribution of GCPs on photogrammetric product accuracy is investigated in 10 different scenarios (Table 1 and Fig. 4).

Table 1: *Scenarios considering the number and distribution of GCPs (H: Homogeneous Distribution and IH: Inhomogeneous Distribution)*

SN	Scenario	GCP	CP
S1	5GCP_H	1,6,8,10,12	2,3,4,5,7,9,11
S2	5GCP_IH	2,3,4,5,6	1,7,8,9,10,11,12
S3	6GCP_H	1,3,6,8,10,12	2,4,5,7,9,11
S4	6GCP_IH	1,2,3,4,5,6	7,8,9,10,11,12
S5	7GCP_H	1,3,6,8,10,11,12	2,4,5,7,9
S6	7GCP_IH	1,2,3,4,5,6,7	8,9,10,11,12
S7	8GCP_H	1,3,6,7,8,10,11,12	2,4,5,9
S8	8GCP_IH	1,2,3,4,5,6,7,11	8,9,10,12
S9	9GCP_H	1,2,3,6,7,8,10,11,12	4,5,9
S10	9GCP_IH	1,2,3,4,5,6,7,10,11	8,9,12

First, kinematic GNSS data obtained using the PPK-equipped UAV were evaluated with the help of static GNSS data. Then, accuracy assessments were performed with Pix4D Mapper v4.4.12 software in line with the UAV photogrammetry workflow.

RMSE values are widely used in accuracy assessment (Cerreta et al., 2023; Štroner et al., 2020; Villanueva & Blanco, 2019). Lower RMSE values indicate that the photogrammetric product is more accurate and precise, i.e. the difference between the model and actual observations is smaller (Cerreta et al., 2023).

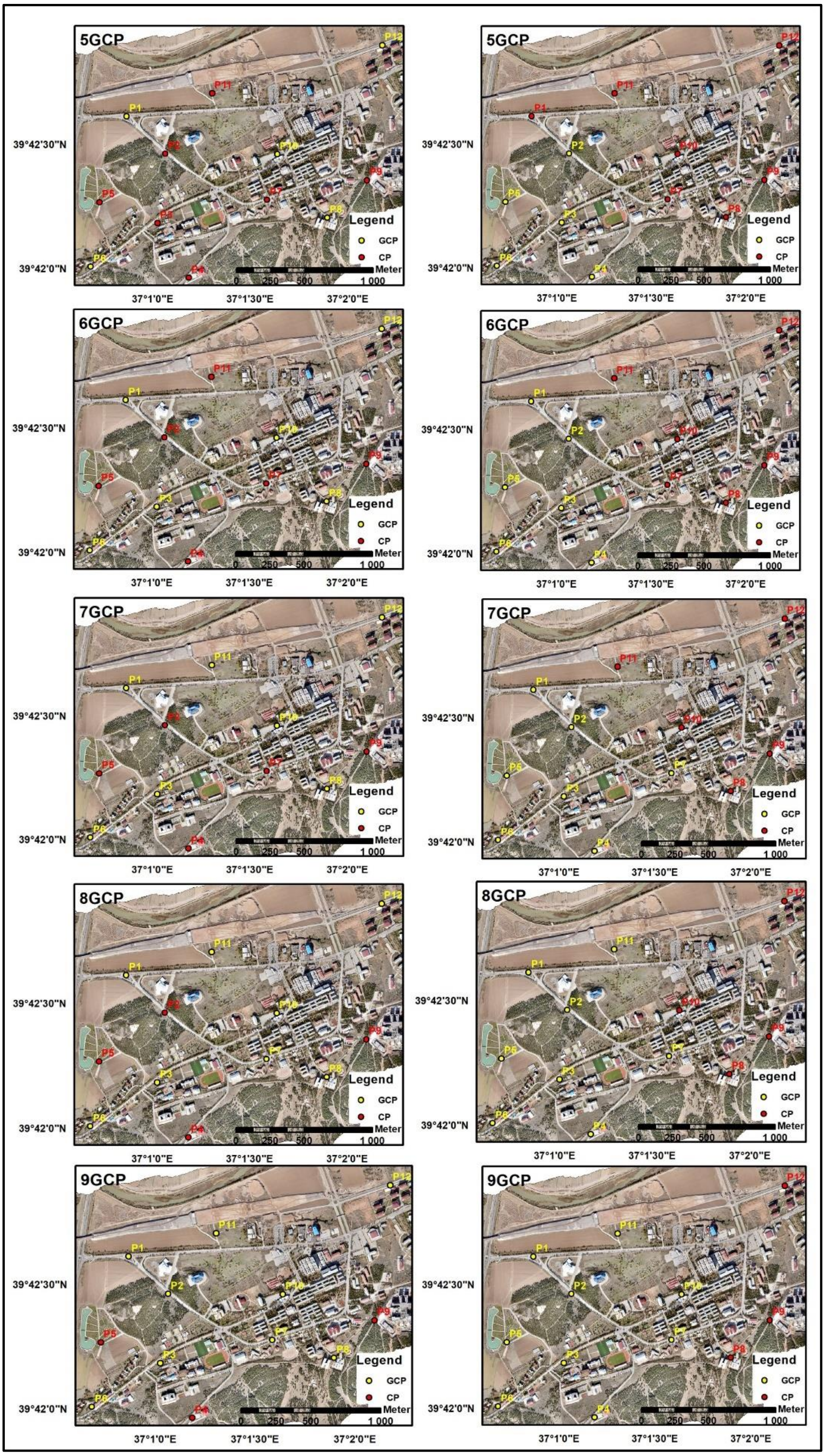

Figure 4: *GCPs installed in different distributions and in different numbers (Left shows homogeneous distribution, right shows inhomogeneous distribution)*

In this study, accuracy was taken into account in three different ways: horizontal, vertical and 3-dimensional (3D). Initially, the coordinate differences for the coordinate components were calculated using the following equations:

$$\begin{bmatrix}\Delta n\\ \Delta e\\ \Delta h\end{bmatrix} = \begin{bmatrix}n_{GNSS} - n_{model}\\ e_{GNSS} - e_{model}\\ h_{GNSS} - h_{model}\end{bmatrix} \quad (1)$$

Where Δn, Δe and Δh are the differences between the reference position and the calculated position for the north, east and ellipsoidal height components in the Gauss Kruger projection plane with a slice width of 3°. The two-dimensional (2D) and 3D error values for each CP were calculated using these differences with the following equation:

$$\begin{bmatrix}\Delta_{2D}\\ \Delta_{3D}\end{bmatrix} = \begin{bmatrix}\sqrt{\Delta n^2 + \Delta e^2}\\ \sqrt{\Delta n^2 + \Delta e^2 + \Delta h^2}\end{bmatrix} \quad (2)$$

Finally, the following equation is used to calculate the RMSE values for coordinate and 2D/3D positioning accuracy:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} {d_i}^2}{n}} \quad (3)$$

Where d_i denotes the coordinate differences (Δn, Δe, and Δh), 2D positioning error (Δ_{2D}) or 3D positioning error (Δ_{3D}) for the i^{th} CP.

3. Results and Discussion

In this study, the network design of the GCPs installed in the field and the effect of the number of GCPs used on the accuracy of the photogrammetric products produced were investigated. In this context, the number of GCPs ranged from 5 to 9 were used and they were positioned according to both homogeneous and non-homogeneous distributions to cover the entire study area. Thus, it was investigated how both the increase in the number of GCPs and the distribution of GCPs in the area affect the accuracy. In other words, the effect of GCP distribution on accuracy was analyzed by designing the same number of GCPs in both homogeneous and inhomogeneous aspects. At the same time, in order to analyze the effect of the number of GCPs on accuracy, the points used in the design of 5 GCPs with homogeneous distribution were kept and new GCPs were added (Table 2). Thus, analyses were performed according to the same point accuracies. The same was done for the inhomogeneous clustered distribution, minimizing the negative impact of the terrain topography, and the direct effect of the number of GCPs on the accuracy was evaluated by considering the RMSE values (Figure 5).

Table 2: *Error values (m) for the GCPs and CPs used (H: Homogeneous Distribution and IH: Inhomogeneous Distribution)*

SN	Scenario	GCP	CP	RMSEx	RMSEy	RMSEz	2DRMSE	3DRMSE
S1	5GCP_H	1,6,8,10,12	2,3,4,5,7,9,11	0.062	0.042	0.033	0.075	0.082
S2	5GCP_IH	2,3,4,5,6	1,7,8,9,10,11,12	0.042	0.069	0.055	0.081	0.098
S3	6GCP_H	1,3,6,8,10,12	2,4,5,7,9,11	0.065	0.038	0.033	0.075	0.082
S4	6GCP_IH	1,2,3,4,5,6	7,8,9,10,11,12	0.046	0.05	0.058	0.068	0.089
S5	7GCP_H	1,3,6,8,10,11,12	2,4,5,7,9	0.065	0.04	0.038	0.076	0.085
S6	7GCP_IH	1,2,3,4,5,6,7	8,9,10,11,12	0.045	0.044	0.063	0.063	0.089
S7	8GCP_H	1,3,6,7,8,10,11,12	2,4,5,9	0.057	0.045	0.036	0.072	0.081
S8	8GCP_IH	1,2,3,4,5,6,7,11	8,9,10,12	0.051	0.043	0.063	0.066	0.092
S9	9GCP_H	1,2,3,6,7,8,10,11,12	4,5,9	0.062	0.04	0.032	0.074	0.08
S10	9GCP_IH	1,2,3,4,5,6,7,10,11	8,9,12	0.055	0.045	0.066	0.071	0.097

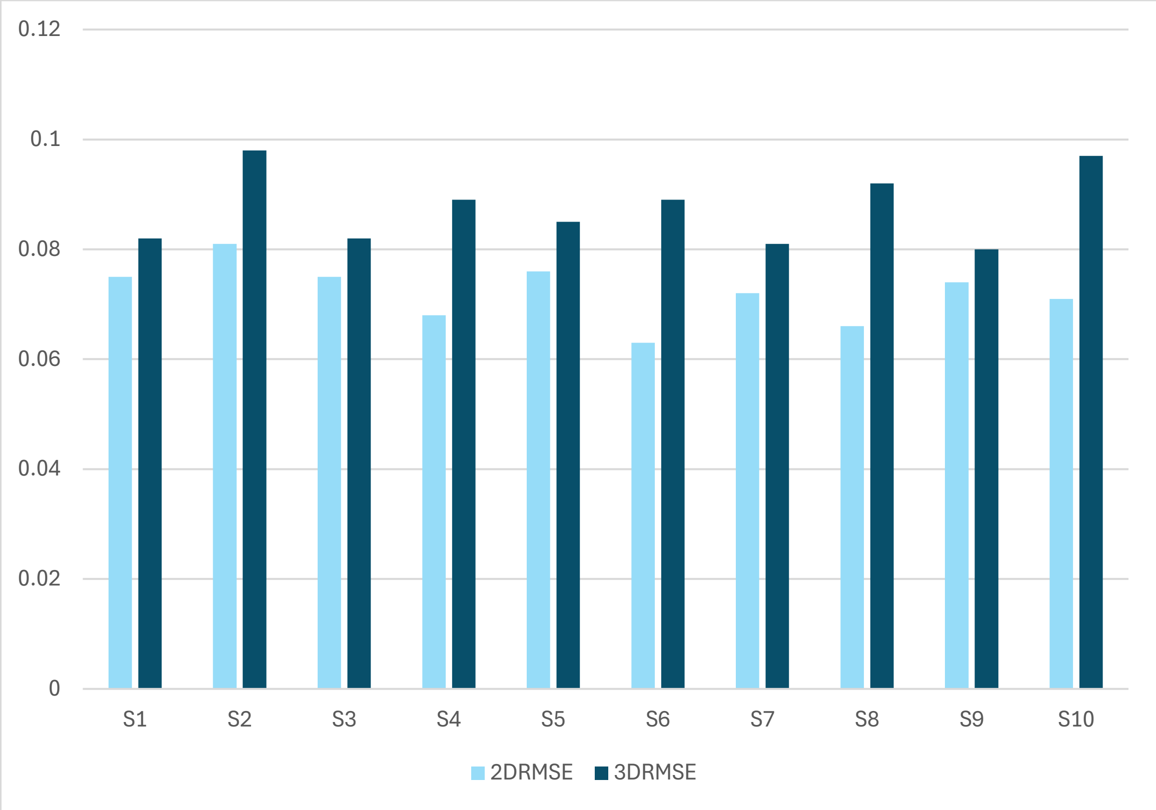

Figure 5: *2D and 3D error values (m) for 10 different GCP scenarios*

When the RMSE values are analyzed in line with the findings obtained, it is seen that the homogeneous distribution of GCPs for the same number of points (homogeneous and inhomogeneous) does not provide a standard accuracy increase in 2D but increases the accuracy in 3D. When homogeneous and inhomogeneous distributions are analyzed, it is observed that the increase in the number of points does not have a standard effect on the accuracy of the product. However, it has been shown that a minimum of 5 GCP facilities, with at least one point in the center and 4 points to cover the corners of the work area, which is basically assumed in photogrammetric projects, creates mm-level differences on the accuracies in homogeneous distribution. The reason for this difference is considered to be the topographical characteristics of each point. On the other hand, no matter how many GCPs between 5 and 9 are used, if the points are not homogeneously distributed, it is observed that both 2D and 3D have irregular RMSE values at cm levels. Also, in terms of 3D location accuracy for the same number of GCPs, homogeneous distributions give better results than inhomogeneous distributions. In this context, since using extra GCPs due to differences at mm level has negative effects in terms of time and cost, it is understood that homogeneous distribution has a more meaningful effect rather than more GCPs in the field.

There are different approaches in the literature regarding the issue addressed by the researchers in this study.

Ferrer-González et al. (2020) evaluated the effect of the number and distribution of GCPs on the accuracy of UAV photogrammetry projects in a corridor-shaped area. By analyzing a 2.1 km long road, it was found that the accuracy increased with the increase in the number of GCPs and planimetric accuracy was better than vertical accuracy. At least 7 GCPs (3.3 GCP/km) were required to achieve $RMSExy \leq 0.031$ m and $RMSEz \leq 0.081$ m accuracy. The best results were obtained with configurations where the GCPs were placed in pairs on both sides of the road in an offset pattern and at the ends of the corridor. In particular, distributions with 9 or 11 GCPs were the best solutions in terms of accuracy (RMSE of 0.028-0.029 m horizontally and 0.055-0.057 m vertically) and fieldwork efficiency. A distribution using 18 GCPs provided similar accuracy, but increased fieldwork time. Therefore, an offset distribution with 9-11 GCPs is recommended to optimize fieldwork without loss of accuracy. However, they emphasized that additional studies are needed to determine whether these findings are valid for different terrain morphologies.

Sanz-Ablanedo et al. (2018), in an area of 1200 hectares with high relief, used more than 2500 photographs and 102 ground points. The results show that the accuracy depends on both the number and the distribution of GCPs. When using a small number of GCPs, the RMSE is about ±5 times the average GSD, while using more than 2 GCPs per 100 images, the RMSE converges to about twice the GSD. As in conventional photogrammetry, the vertical errors in SfM photogrammetry are about 2.5 times larger than the horizontal components. The best accuracy was achieved by evenly distributing the GCPs in a triangular grid, which minimizes the maximum distance to any GCP. In the case of poor distribution, accuracy can be up to twice as low as that of an optimal distribution. In large projects, high accuracy can only be achieved when using at least 3 GCPs per 100 images, and even adding oblique images, high overlap, or diagonal stripes cannot compensate for insufficient GCP utilization.

Agüera-Vega et al. (2017a) stated that in general, there is a tendency to decrease in RMSE values as the number of GCPs increases, but they emphasized that there is no significant difference between 15 and 20 GCPs in an area of approximately 18 ha, and 15 GCPs are optimum when evaluated in terms of labor and cost. Liu et al. (2022) stated that the number of GCPs increases the accuracy up to 12 GCP/km^2, but there is no significant increase after that, but the uniform distribution of the GCPs and their proximity to the center have positive effects on the accuracy. Tomaštík et al. (2017), in their study on determining the accuracy between 4 GCPs and 9 GCPs, stated that the more precise measurement of the installed GCPs has a greater effect on the accuracy rather than the amount of GCPs in similarly distributed GCPs. Agüera-Vega et al. (2017b) stated that although the increase in the number of GCPs increases the horizontal accuracy, the number of GCPs does not affect the vertical accuracy. Martínez-Carricondo et al. (2018) emphasized that the best planimetric (2D) accuracy is obtained if the GCPs are placed at the corners of the study area, while the best 3D accuracy can be obtained if they are at different heights with a stratified distribution. Hastaoglu et al. (2023) emphasized that only increasing the number of GCPs will not improve the location accuracy, and that an accurate GCP design is required by considering the topographical and geometric structure. To summarize, although some researchers in the literature draw attention to the increase in the number of GCPs in terms of accuracy, some researchers believe that this alone will not be sufficient.

In this study conducted in the 6 km^2 Sivas Cumhuriyet University campus area, it is shown that the distribution of at least one GCP in the center and homogeneously distributed in the corners significantly increases the 3D position accuracy of the products produced by UAV photogrammetry, and that higher accuracy results can be obtained if the GCPs are designed in a correct network rather than the number of GCPs.

4. Conclusion

This study was conducted to evaluate the effects of the number and distribution of GCPs on the accuracy of UAV photogrammetry projects. As a result of the analysis, it is emphasized that in order to maximize the accuracy obtained with UAV photogrammetry, it is necessary to ensure a homogeneous distribution of the GCPs in the work area. It was revealed that the homogeneous distribution of GCPs is more important than the number of GCPs. It is observed that if the same number of GCPs are installed, GCPs clustered (inhomogenously) in a certain area provide lower 3D position accuracy than GCPs distributed over the entire area. As a result, it has been determined that in UAV Photogrammetry projects, installing GCPs appropriately distributed in the center and edges of the study area in accordance with the topographical and morphological structure of the terrain increases the accuracy of the product obtained. Thus, it has been revealed that the workload, time and cost burden of installing too many GCPs can be brought to optimum levels with the correct GCP network design.

Acknowledgements

This study was supported by the Scientific and Technological Research Council of Türkiye (Project Grant Number: TÜBİTAK 122Y125) and Sivas Cumhuriyet University (CÜBAP M855).

Author Contribution

Tarık Turk: Conception, Design, Literature review, Data collection, Analysis and interpretation, Writing, Supervision, Review of article. **Berkay Bahadur:** Literature review, Writing, Review of article. **Yasin Demirel:** Literature review, Data collection, Analysis, Writing, Review of article. **Cemali Altuntas:** Literature review, Writing, Review of article. **Taylan Ocalan:** Writing, Review of article.

Declaration of Competing Interests

The authors declare that they have no known relevant competing financial or non-financial interests that could have appeared to influence the work reported in this paper.

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