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GEOGRAPHY

Accuracy of High Resolution Digital Cartographic Products with Elevation Control Points

Acurácia de Produtos Cartográficos Digitais de Alta Resolução com Pontos de Controle em Elevação

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Abstract

The use of Unmanned aerial vehicles (UAVs) as a tool for image acquisition has been applied in several fields, some applications require cartographic products with high accuracy. With this comes the need for planning the acquisition of images and distribution of control points (GCP) so that digital products meet the required level of accuracy. The aim of this work was to investigate whether the quantity of control points as well as their distribution in different altitude planes in elevated ground can improve the accuracy of the generated cartographic products. RGB images captured by an onboard camera with a resolution of 20 MP were used. Images were captured by a multirotor UAV with an overlap of 80% (front and side) and estimated GSD of 0.017 m. The surveyed area of 5.5 ha overflown area had 31 targets surveyed with GNSS RTK, 21 defined as checkpoints (CP) and 12 as ground control points (GCP), which were used in image processing to generate orthomosaic. We evaluated the accuracy of the generated products based on the PEC-PCD. The results showed that when using only 2 GCPs the altimetric errors are high, being the single configuration that did not fit the PEC-PCD scale 1: 1,000 class A. With 5 GCPs we obtained the best RMSE in altimetry (0.026 m). With 6 GCPs we obtained the best RMSE in planimetry (0.046 m). Altimetry is the most sensitive aspect in generating cartographic products, and the use of GCPs in elevation improves altimetric accuracy.

Keywords: UAV; GCP; PEC-PCD

Resumo

O uso de Veículos Aéreos Não Tripulados (VANTs) como ferramenta para aquisição de imagens tem sido aplicado em diversas áreas, algumas dessas aplicações requerem produtos cartográficos com alta acurácia. Com isso, surge a necessidade de planejamento para a aquisição das imagens e para a distribuição de pontos de controle em solo (GCP), os quais serão utilizados na correção geométricas destas, visando conferir às cenas o nível de acurácia exigido. Este trabalho investiga se a quantidade de pontos de controle tal como sua distribuição em diferentes planos de altitude em terreno elevado interfere na acurácia dos produtos cartográficos gerados. Foram utilizadas imagens RGB registradas por uma câmera com resolução de 20 MP embarcada em um VANT multirotor. As imagens foram capturadas com uma sobreposição de 80% (longitudinal e lateral) e GSD estimado em 0,017 m. A área sobrevoada de 5,5 ha contou com 31 alvos levantados com GNSS RTK, sendo 21 definidos como pontos de checagem (CP) e 12 como pontos de controle em solo (GCP), os quais foram utilizados no processamento de imagens para geração dos ortomosaicos. Avaliamos a acurácia dos produtos com base na PEC-PCD. Os resultados evidenciaram que ao utilizar somente 2 GCPs os erros altimétricos são altos, sendo a única configuração que não se enquadrou na PEC-PCD escala 1:1.000 classe A. Com 5 GCPs obtivemos o melhor RMSE em altimetria (0,026 m). Com 6 GCPs obtivemos o melhor RMSE em planimetria (0,046 m). A altimetria se mostra a parte mais sensível na geração de produtos cartográficos e a utilização de GCPs em elevação melhora a acurácia altimétrica.

Palavras-chave: VANT; GCP; PEC-PCD

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1 Introduction

Unmanned aerial vehicles (UAVs) have become popular in recent decades because of their relatively low cost in data acquisition compared to aerial surveys performed with a metric camera, or even by high spatial resolution satellites. There has been considerable advancement in technology in this sector, both in terms of hardware, such as more robust multirotor, fixed and mixed wing UAVs, lighter and higher resolution cameras, and in the software set, such as flight plan applications and photogrammetric programs using computer vision, enabling the generation of high spatial resolution products at a lower cost.

The images captured by sensors embedded in UAVs are being used for studies in various areas, such as plant count and detection of planting lines (Osco et al. 2021), estimation of pasture biomass (Batistoti et al. 2019), analysis of glacier dynamics (Lewińska et al. 2021), 3D mapping of open pit mines (Le Van et al. 2020), quantification of soil erosion (Meinen & Robinson 2020), among others. The 3D position of the camera at the time of photo capture is an important factor for georeferencing the products generated with UAV. With the absolute position and orientation of the camera, accurate products can be obtained without the need for ground control points (GCPs) (Le Van et al. 2020). However, most UAVs are equipped with low accuracy Global Navigation Satellite System (GNSS) receivers (Han et al. 2020). There are studies with high-accuracy embedded GNSS that recommend using at least one GCP to achieve centimetric accuracy (Le Van et al. 2020; Padró et al. 2019; Revuelto, López-Moreno & Alonso-González 2021).

There are several flight planning factors that influence the quality of products generated with UAV images. Garcia and Oliveira (2021) performed an experiment evaluating some of these factors, concluding that the flight height (21, 31 and 40 m) did not show any difference in the quality of the products generated. Regarding the image overlap, if it falls below 80% in the lateral direction and 60% in the longitudinal direction, the orthomosaic may exhibit noise and lower quality details. The adjustments of the camera parameters and the amount of GCPs affected the generated products accuracy, performing manually the previous adjustment of the camera parameters it is possible to use only 5 GCPs, while letting the software calculate the parameters is needed than 8 GCPs.

The issue of the quantity and distribution of GCPs has been addressed by several works. Le Van et al. (2020) researched open pit mine mapping with DJI Phantom 4 RTK using 0, 1 and 2 GCPs and reported a Root Mean Squared Error (RMSE) variation in the altimetric component of 0.844 m, 0.043 m and 0.031 m, respectively. Calou et al. (2021) verified the quality of the orthomosaics using 3, 5 and 8 GCPs, obtaining RMSE values for the altitude of 0.033 m, 0.026 m and 0.0044 m, respectively. Yu et al. (2020) evaluated, in a small (7 ha), medium (39 ha) and large (342 ha) area, the GPCs variation of 3, 6, 9, 12, 15 and 18, and recommended for altimetry the use of at least 12 GCPs for small, 12 GCPs for medium areas, and more than 18 GCPs for large areas, with the RMSE for the altitude of these recommendations being 0.045 m, 0.038 m and 0.067 m.

The aforementioned works reveal that altitude is the most sensitive variable to the amount of GCPs. However, there are few studies evaluating the mixture of control points in elevation and in the plane, and this is the gap that we intend to fill in this study. That said, the objective of this work is to investigate whether the quantity and spatial arrangement of control points located on flat and elevated terrain interfere with the accuracy of cartographic products generated from images collected by sensors embedded in UAVs. The cartographic products generated are orthomosaic and the Digital Surface Model (DSM).

2 Methodology and Data

2.1 Area of study

A set of 468 images, with resolution of 4864 x 3648 pixels, from a region of approximately 5.5 ha of the University stadium Pedro Pedrossian de Campo Grande, Mato Grosso do Sul, Brazil was used to fulfill the objective of this work (Figure 1). The images have a Ground Sample Distance (GSD) of 0.0172 m. The study area was selected due to the ease of access and the possibility of using GCPs with different heights, that is, points located in the stadium stands.

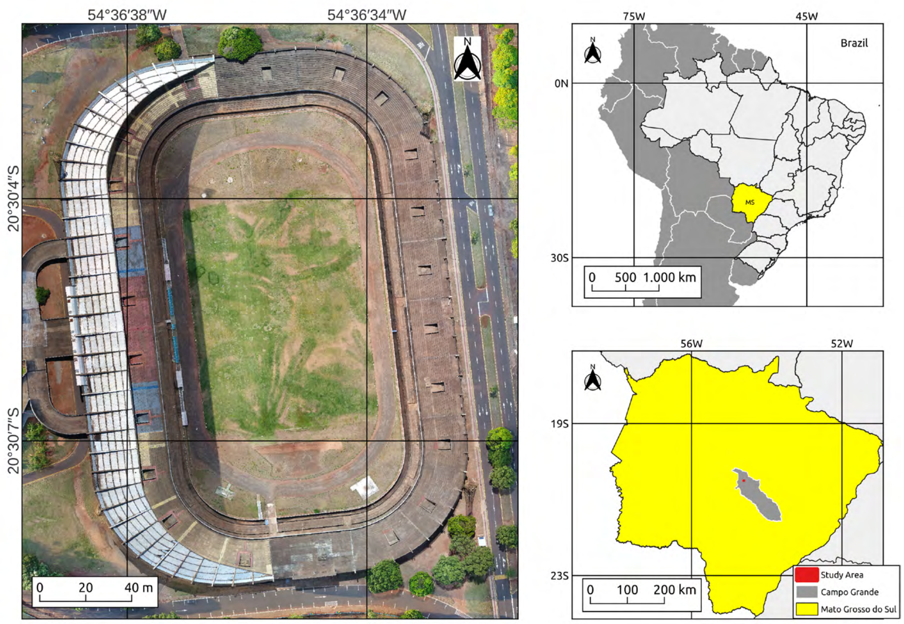

Figure 1 Location of study area, Pedro Pedrossian University Stadium, Campo Grande/MS, Brazil.

2.2 Data Acquisition

Thirty-one targets were distributed in the study area (Figure 2A): twenty-one were used for checkpoints, and ten were applied as ground control points in different arrangements, from which the three-dimensional coordinates were collected, using a Trimble RTK GNSS R8s receiver (Figure 2B). The 3D accuracy of this type of survey is approximately 30 mm, with the horizontal RTK survey in the order of 8 mm + 0.1 ppm, and vertical 15 mm + 1 ppm (Trimble 2013). With the targets still on the ground, the area was overflighted with a DJI Phantom 4 – Advanced UAV, which has a 20 MP on-board camera. With the help of the flight plan application Pix4Dcapture, the overflight area, the lateral and longitudinal overlaps of 80%, and the flight height of 70 m were determined, with the camera positioned towards the nadir.

2.3 Quantity of Control Points

With the collected points, the ones to be used as GCPs were selected. For this purpose, the premise was to have well-distributed points in the study area, as Zanetti, Gripp Junior and Dos Santos (2017) found that clustered control points result in less accurate cartographic products. The quantity of distributed points was evaluated, ranging from 2 to 6 GCPs, as shown in Figure 3.

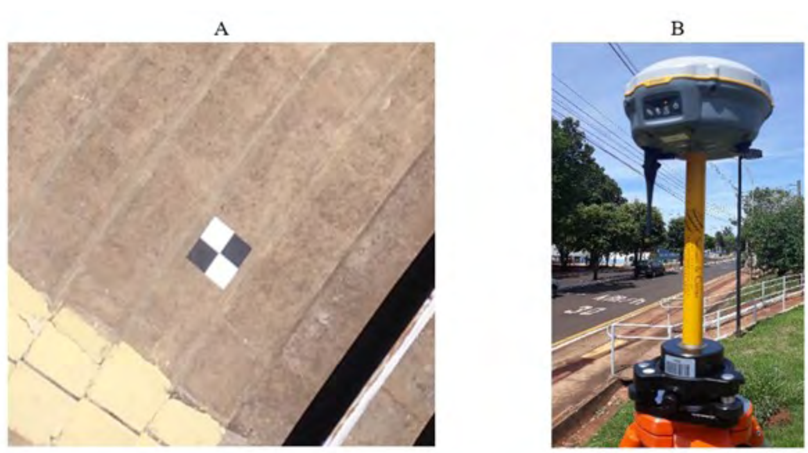

Figure 2 Equipment used to obtain three-dimensional coordinates: A Targets used to materialize control (GCP) and check (CP) points; B Trimble GNSS RTK R8s.

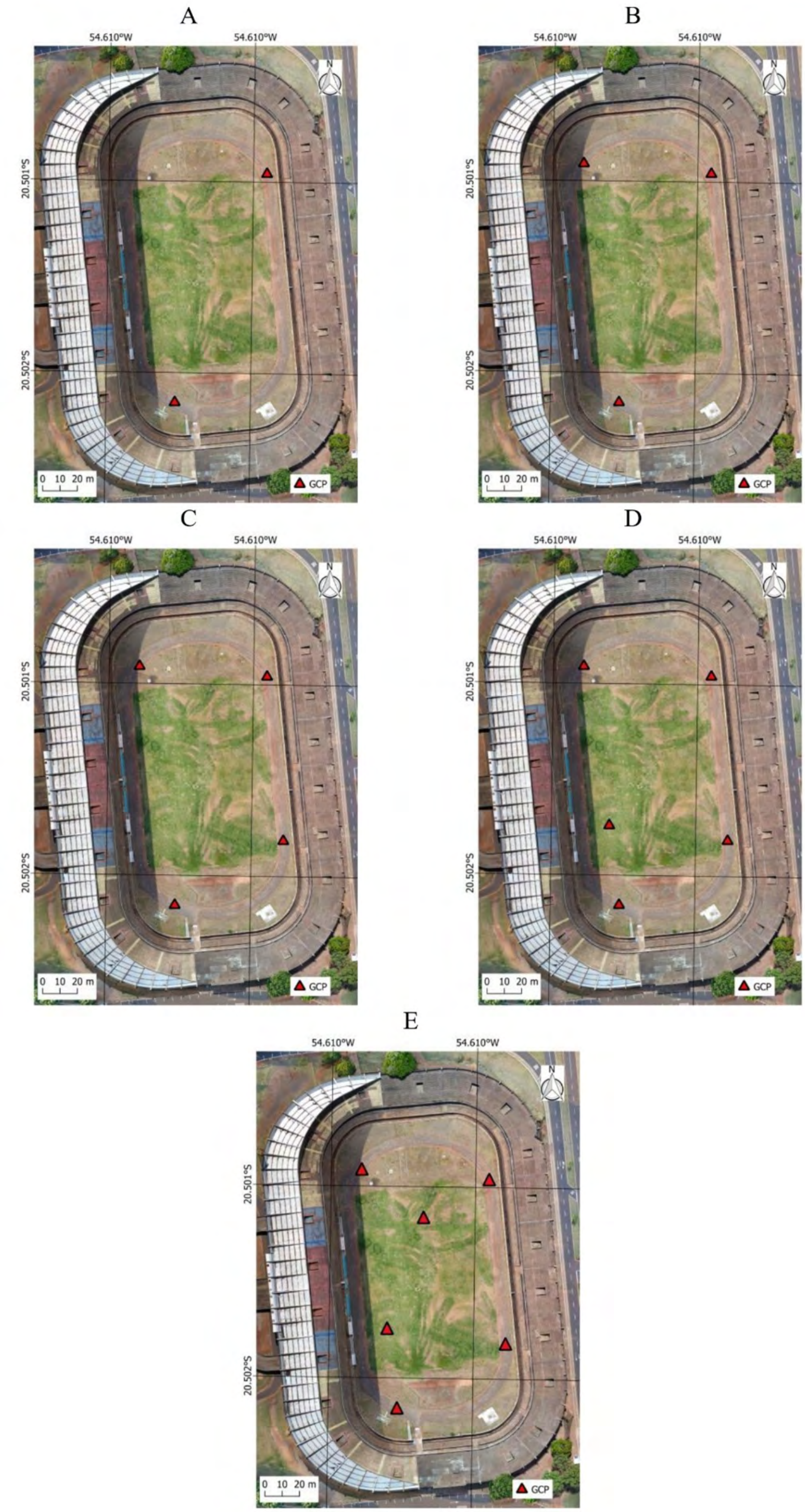

Figure 3 Configurations considered regarding the distribution of control points on the ground, with 2, 3, 4, 5, and 6 GCPs.

2.4 Control Points at Different Elevations

To investigate whether the significant difference in elevation between points, for example, points on the ground (soccer field of the stadium) and points at higher elevations (in the stadium stands), interferes with the geometric quality of the generated orthomosaic, a comparison of the 3D accuracy of the orthomosaic was conducted using different GCPs located in flat areas and at higher elevations (Figure 4). It's worth noting that the GCPs in flat areas were placed directly on the ground, while the GCPs at higher elevations were a mixture of GCPs located in both flat areas and elevated sections (bleachers). The distribution can be seen in Figure 5. The leave-one-out methodology was used, where one GCP is removed and the processing is performed, repeating this process until all GCPs have been excluded. Since 6 GCPs were used, the images were processed 6 times for the GCPs in flat areas and 6 times for the GCPs with some at higher elevations, with one GCP being left out in each processing. This methodology ensures that there are no gross errors in the reference data (GCPs), which increases the reliability of the final result.

2.5 Generation of Cartographic Products

The processing in Pix4Dmapper (v.4.1.25) for the generation of cartographic products (DSM and Orthomosaic) followed the flowchart outlined in Figure 6A. The coordinate system used in the project was WGS 84 / UTM zone 21S (egm96). In Figure 6B, the process of indicating which pixel in the image corresponds to which control point can be observed. This marking is done manually, and all control points, both GCPs and CPs, should be marked. Processing options: Pix4D allows for changing some parameters for processing. For this experiment, we kept the default values for all processing steps. It separates the processing into three stages: Initial processing (basically matching the images, i.e., finding common points between the images), point cloud and mesh (based on the homologous points found in the previous stage, it densifies the point cloud, i.e., generates coordinates for each point in the image), and DSM and Orthoimage (In this stage, the DSM and orthoimage are generated from the data generated in the previous stage).

2.6 Validation of Digital Cartographic Products.

To validate the experiments, 21 CP were used, although these points were not used in the processing (Figure 7). After processing the images in the Pix4Dmapper application (v.4.1.25), we exported the orthophoto and digital surface model on the QGIS application (QGIS Development Team 2019), where we collected the coordinates where the orthophoto indicates the target. Then, we collected the altitude of the same point in the DSM. With these three-dimensional coordinates from the orthophoto and DSM, we compared them with the coordinates collected in the field using RTK. The planimetric and altimetric discrepancies were calculated according to Equation 1 and Equation 2. Using the discrepancies, we calculated the RMSE (Equation 3), mean, and standard deviation (SD).

(1)

$$\Delta S = \sqrt{(X_i - XRTK_i)^2 + (Y_i - YRTK_i)^2}$$

(2)

$$\Delta H = Z_i - ZRTK_i$$

(3)

$$RMSE = \sqrt{\frac{\sum Discrepancy^2}{n}}$$

Where represents the planimetric discrepancies, represents the altimetric discrepancies, are the UTM coordinates (Easting and Northing) obtained from the orthophoto, represents the altitudes obtained from the DSM, are the UTM coordinates (Easting, Northing, and altitude) obtained from the RTK GNSS survey, is the number of CP evaluated.

The digital products were classified according to the Cartographic Accuracy Standard for Digital Cartographic Products (PEC-PCD) (DSG 2016). The orthophoto was classified according to the PEC-PCD for planimetry, and the DSM was classified according to the PEC-PCD for altimetry. These classifications categorize the digital products into different scales (1:1,000, 1:2,000, 1:5,000) and classes (A, B, C, and D). Since the generated products have high spatial resolution, they were evaluated to determine if they fit into the 1:1,000 scale, Class A, as specified in Table 1.

For a cartographic product to be classified as Class A at a scale of 1:1,000, for example, it must have an RMSE lower than the Standard Error (EP) of 0.17 m, and 90% of the errors (discrepancies between the reference coordinates and those represented in the cartographic products) must be less than 0.28 m for planimetry and 0.27 m for altimetry.

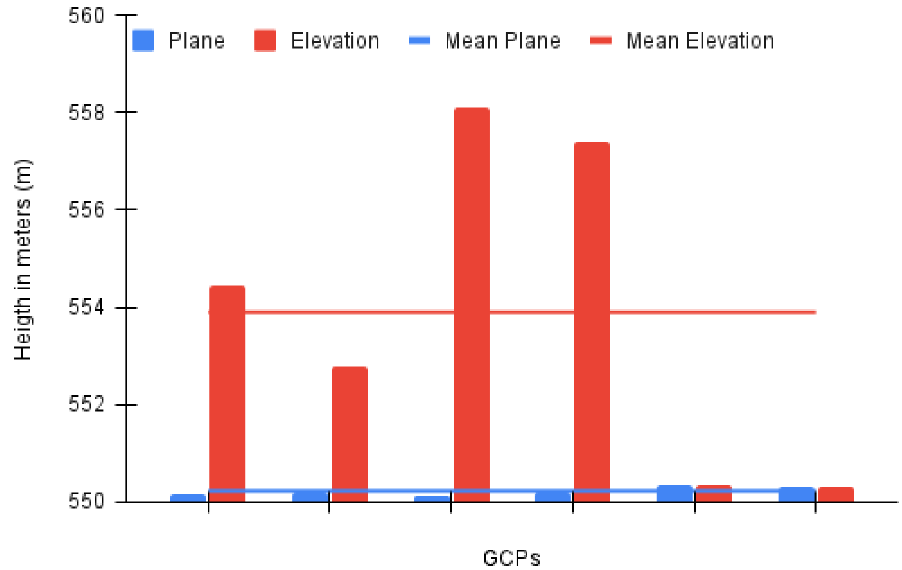

Figure 4 Difference in elevation between GCPs on the ground (blue) and at higher elevations (red).

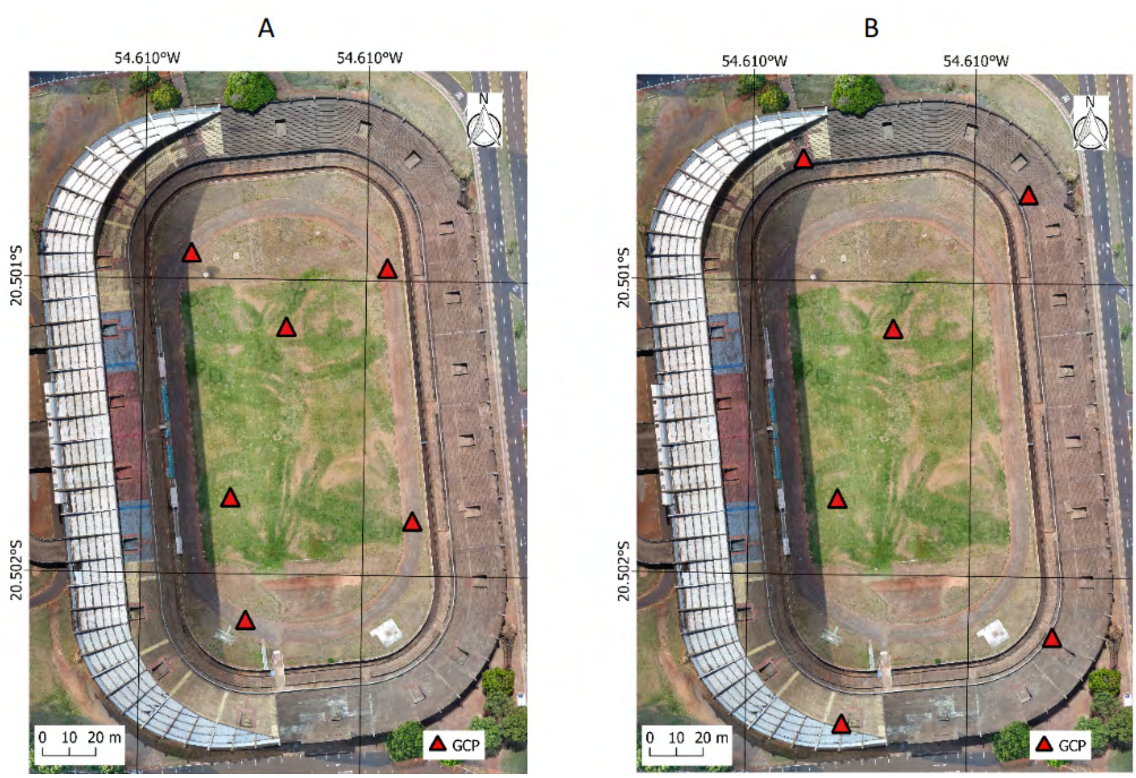

Figure 5 Distribution of control points: A: In flat terrain; B: With points at higher elevations.

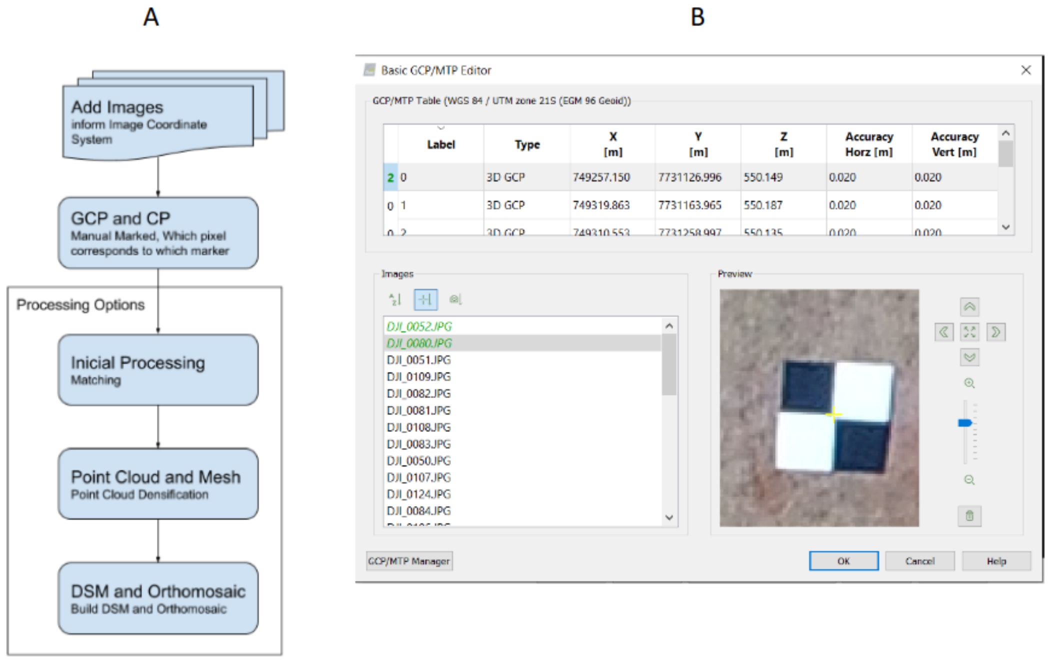

Figure 6 Pix4D Processing: A. Process Flowchart; B. Manual process of marking control points (GCP and CP). Window that is used to indicate which pixel in the image corresponds to the GCP.

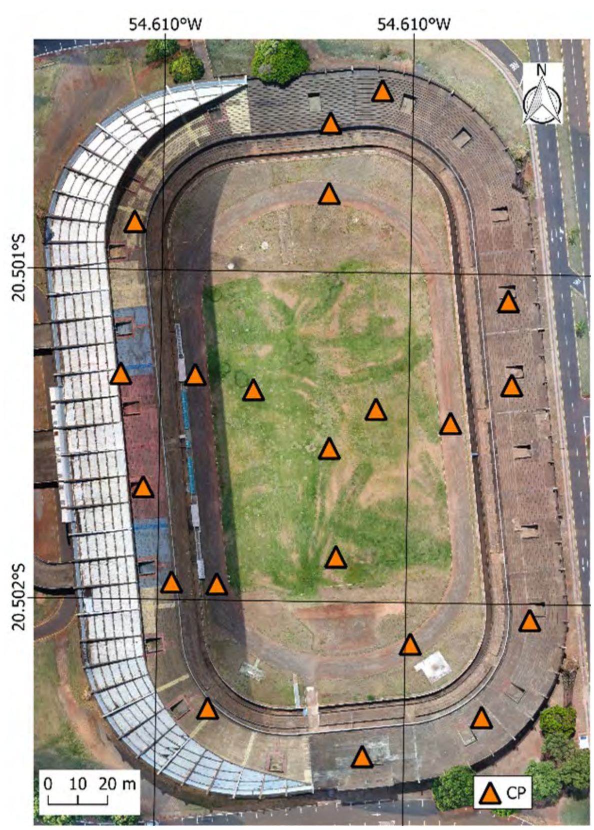

Figure 7 Distribution of checkpoints (CP).

Table 1 Tolerances for assessing the planimetric and altimetric accuracy of PEC-PCD for Class A.

PEC-PCD Classe A	Planimetry		Altimetry	
	PEC (m)	EP (m)	PEC (m)	EP (m)
1:1,000	0.28	0.17	0.27	0.17
1:2,000	0.56	0.34	0.27	0.17
1:5,000	1.40	0.85	0.54	0.34

Source: Adapted from (DSG 2016).

3 Results

3.1 Number of GCPs

The data dispersion can be seen in Figure 8. It was observed that the planimetry with two GCPs had the highest dispersion, while the altimetry values were even more contrasting. Due to this, the data for two GCPs were removed from Figure 8 to allow for better observation of the differences for other numbers of GCPs. With 3 and 4 GCPs, similar results were obtained in terms of dispersion for both planimetry and altimetry. The dispersion decreased with 5 and 6 GCPs, and outlines began to appear in the altimetry results.

Figure 9 presents the statistical data for planimetry concerning the number of GCPs. The minimum discrepancy values should tend to zero since planimetry measures distances. For the processing with 2 and 5 GCPs, the minimum values deviated from zero at 0.017 m and 0.014 m, respectively, while the others had similar values ranging from 0.004 m to 0.009 m. Regarding the maximum discrepancy, 2 GCPs had a higher value of 0.319 m, while the others ranged from 0.101 m to 0.08 m.

As for RMSE, it decreased as the number of GCPs increased. A similar pattern was observed for the standard deviation (SD). Both metrics measure the dispersion of the data, with RMSE representing accuracy and SD representing precision. Lower values are better for both metrics. With 6 GCPs, RMSE and SD were 0.046 m and 0.016 m, respectively, while with 5 GCPs, they were 0.049 m and 0.016 m, respectively.

The orthophoto classification according to the PEC-PCD for planimetry (Table 2) shows that for all numbers of GCPs, the classification was at a 1:1,000 scale, Class A. It is worth noting that with 2 GCPs, only 91% of the control points had discrepancies smaller than 0.28 m.

Figure 10 presents the statistical data for altimetry based on the number of GCPs. The minimum altimetric discrepancy values were similar for tests with 3 to 6 GCPs, ranging from -0.071 m to -0.053 m. When using only 2 GCPs, the minimum value was -3.3 m. The same trend is observed for the maximum values, where the 2 GCPs case had a difference of 2.61 m compared to the others, which ranged from 0.057 m to 0.067 m. Regarding the RMSE (Root Mean Square Error) and DP (Standard Deviation), there is a pattern of decreasing values as the number of GCPs increases. However, the results stabilize after 5 GCPs. Figure 9 shows that with 5 GCPs, the RMSE and DP values were 0.026 m and 0.02 m, respectively, while with 6 GCPs, the values were 0.030 m and 0.023 m, respectively.

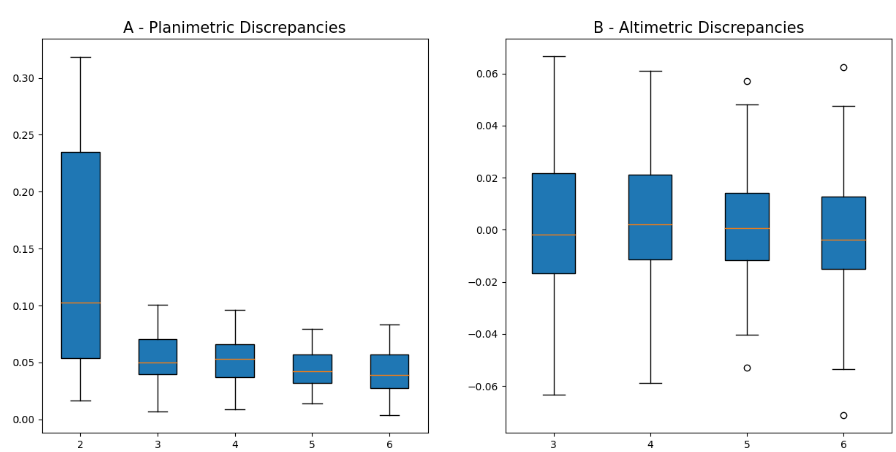

Figure 8 Boxplots of the evaluation of the number of control points in A planimetry and B altimetry.

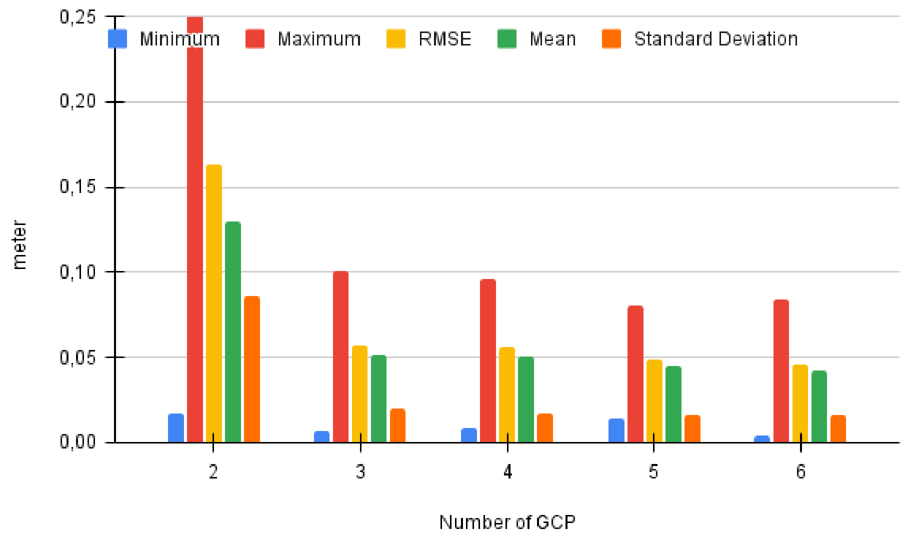

Figure 9 Data analysis of planimetric discrepancies in meters for different numbers of control points.

Table 2 Verification of data according to the tolerances of PEC-PCD for planimetry at a 1:1,000 scale, Class A.

PEC-PCD	(m)	2	3	4	5	6
EP	**0.17**	0.163	0.057	0.056	0.049	0.046
PEC	**0.28**	91%	100%	100%	100%	100%

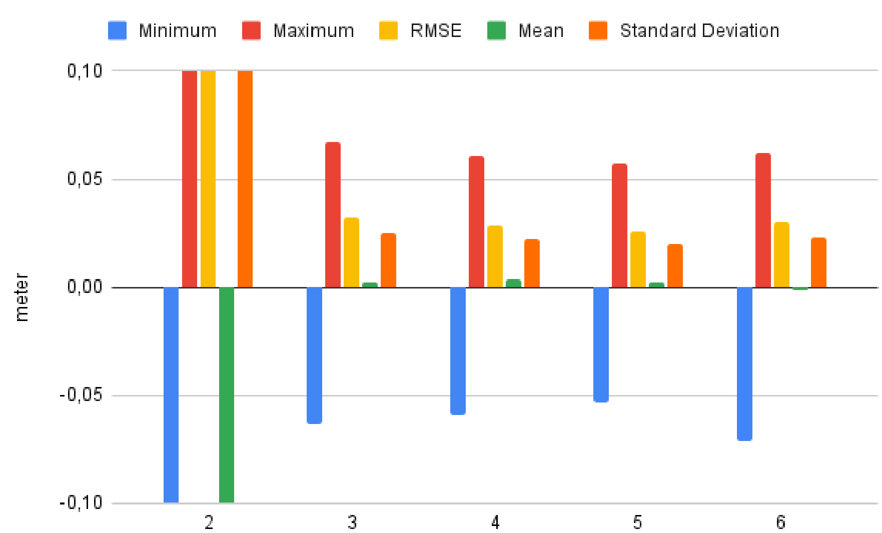

Figure 10 Data analysis of altimetric discrepancies in meters for different quantities of ground control points (GCPs). The y-axis of the graph is limited to +/- 0.1 m to avoid distortions caused by values obtained with only 2 GCPs (that obtained values in meters of: -3.3 minimum, 2.6 maximum, RMSE 1.77, mean -0.48, and standard deviation of 1.46), which would make it impossible to compare with the other GCP quantities used.

The classification of altimetry according to the PEC-PCD (Brazilian Cartographic Accuracy Standard) is presented in Table 3. It is noteworthy that only with 2 GCPs, it was not possible to achieve classification in the 1:1,000 scale class A. This is observed both in terms of the RMSE (Root Mean Square Error) validation against the standard error, which is greater than 1.77 m compared to 0.17 m, and in terms of 90% of the evaluations being below the PEC (Positional Error of the Cartographic Database) of 0.27 m, where only 9% met this requirement.

3.2 GCPs in Elevation

The results are shown in Figure 11, which displays the boxplot graph for each processing, evaluating the discrepancy in planimetry. It can be observed that the distribution of discrepancies ranged from 0.01 m to 0.10 m, with an outline of 0.13 m for the data with planar GCPs.

As for the planimetric PEC-PCD at a 1:1,000 scale, in all processings, both criteria were met, with values lower than the threshold values (Table 4).

For the evaluation in altimetry (Figure 12), there are some differences. The distribution of altitude discrepancies was smaller and had fewer outliers in the dataset with GCPs in elevation, indicating a subtle improvement when using these points. Regarding the PEC-PCD for altimetry at the 1:1,000 scale, both criteria were met in all processing, with values lower than the specified thresholds (Table 5).

In general, there was no difference in using GCPs in elevation for planimetry, as the dispersion of discrepancies was similar. For altimetry data, there were slight changes, with a small reduction in data dispersion and RMSE values. It is important to highlight that the best result in terms of arrangement was obtained with 5 GCPs, which represents an improvement compared to the results of this study. All processes were classified as class A in the PEC-PCD for both planimetry and altimetry at the 1:1,000 scale.

Table 3 Verification of data regarding tolerances of altimetry according to the PEC-PCD in the 1:1,000 scale class A.

PEC-PCD	(m)	2	3	4	5	6
EP	**0.17**	1.77	0.032	0.029	0.026	0.030
PEC	**0.27**	9%	100%	100%	100%	100%

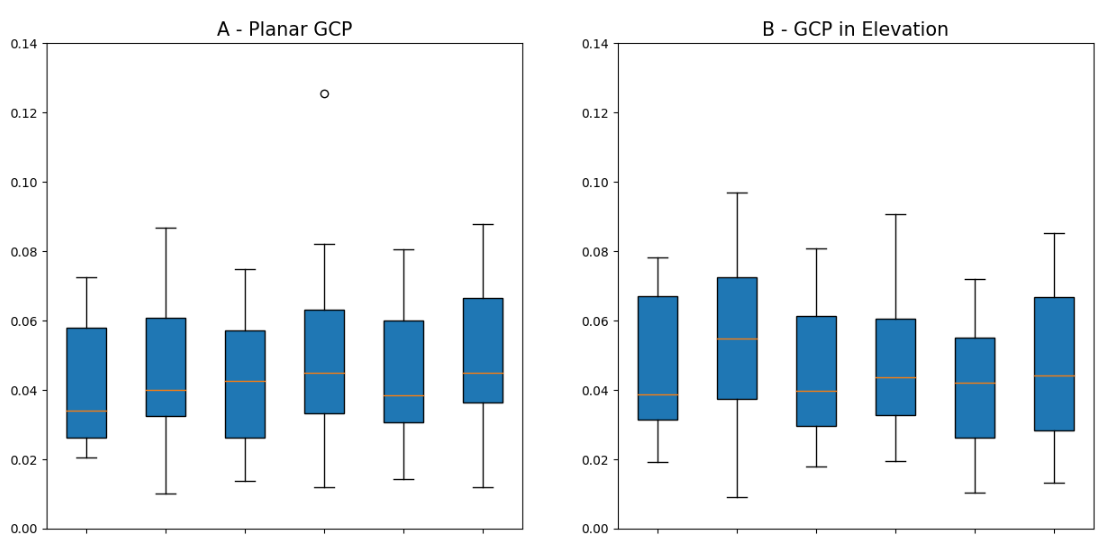

Figure 11 Boxplot of the leave-one-out experiment for each of the 6 processings with A planar GCPs and B GCPs in elevation, for planimetry.

Table 4 Verification of planar and elevation processings regarding the tolerances of the planimetric PEC-PCD at a 1:1,000 scale, class A.

	PEC-PCD	(m)	1	2	3	4	5	6
Plane	**EP**	**0.17**	0.044	0.048	0.045	0.056	0.047	0.053
	PEC	**0.28**	100%	100%	100%	100%	100%	100%
Elevation	**EP**	**0.17**	0.048	0.058	0.048	0.049	0.045	0.050
	PEC	**0.28**	100%	100%	100%	100%	100%	100%

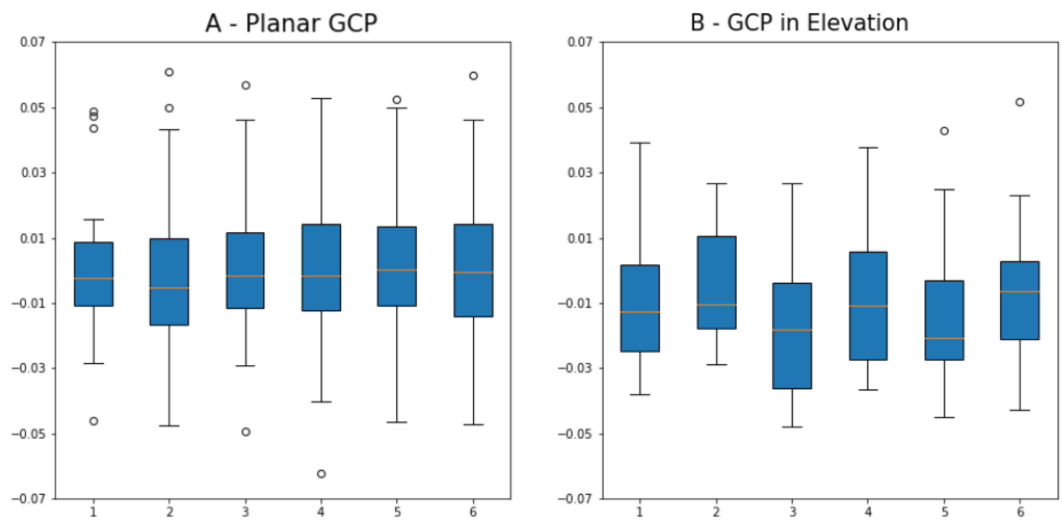

Figure 12 Boxplot of the leave-one-out experiment for each of the 6 processings with A GCPs in the planar and B elevation datasets for altimetry.

Table 5 Verification of the planar and elevation processings regarding the tolerances of the PEC-PCD for altimetry at the 1:1,000 scale, class A.

	PEC-PCD	(m)	1	2	3	4	5	6
Plane	**EP**	**0.17**	0.027	0.028	0.029	0.030	0.027	0.029
	PEC	**0.27**	100%	100%	100%	100%	100%	100%
Elevation	**EP**	**0.17**	0.023	0.021	0.028	0.023	0.028	0.024
	PEC	**0.27**	100%	100%	100%	100%	100%	100%

4 Discussion

The objective of this work is to investigate whether the quantity and spatial arrangement of control points located on flat and elevated terrain interfere with the accuracy of cartographic products generated from images collected by sensors embedded in UAVs. The surveyed area of 5.5 ha overflown area had 31 targets surveyed with GNSS RTK, 21 CP and 12 GCP.

Regarding the methodology employed in this study, its suitability is evident, as it aligns with approaches used in various scientific works. For instance, Ferrer-González et al. (2020) employed a similar methodology when assessing corridor mapping, testing the distribution of 3 to 18 Ground Control Points (GCPs) in four distinct ways. This study involved the collection of 47 points (comprising GCPs and Control Points - CP) using GNSS equipment in a 40-hectare area.

Hastaoglu et al. (2023) investigated the difference in height and geometry of GCPs in a larger area of 160 hectares. In this case, 122 CPs and 46 GCPs were surveyed, utilizing GNSS RTK technology. Liu et al. (2022)

addressed the impact of GCP configuration in a 50-hectare area, collecting 16 points (including GCPs and CP) for planimetric evaluation and 120 CPs for vertical assessment, all obtained through GNSS RTK.

It is evident that these studies employed both GCPs and CPs acquired through GNSS equipment. The variation in the quantity of GCPs and CPs used is noteworthy and directly linked to the size of the study areas, demonstrating an adaptation of the methodology to the specific scale of each research.

However, regarding the quantity of GCPs, it is observed that 2 GCPs present different results compared to the others, with a significant discrepancy in altimetry, as also observed by Siqueira et al. (2020), who found RMSE values of 0.3 m for planimetry and 1.7 m for altimetry with 2 GCPs. With 3 and 4 GCPs, the results were good for both altimetry and planimetry. For this quantity of GCPs, Siqueira et al. (2020) reported RMSE values of 0.13 m and 0.19 m for planimetry and altimetry, respectively. Yu et al. (2020) obtained RMSE values of 0.05 m and 0.11 m for a small area (7 ha), but these results with RMSE up to 0.20 m for altimetry can only be considered for small areas (in this experiment, 5.5 ha). Yu et al. (2020) reported RMSE values of 0.12 m and 1.148 m for planimetry and altimetry, respectively, for a medium-sized area (39 ha), and 0.91 m and 4.1 m for planimetry and altimetry, respectively, for a large area (342 ha) with 3 GCPs. With 5 and 6 GCPs, similar results were obtained for planimetry, but for altimetry, 6 GCPs showed slightly worse results, indicating that the accuracy had already been achieved. As presented by Siqueira et al. (2020), above 6 GCPs, the variation tends to be small, and using 6 and 8 GCPs did not increase accuracy.

Regarding the planimetric PEC-PCD (Cartographic Accuracy Standard), a class A classification was obtained for the 1:1,000 scale for the GCP distributions, which is consistent with the findings of Barbosa et al. (2021), who also classified UAV-derived orthophotos as class A in the 1:1,000 scale. However, Siqueira et al. (2020) classified the orthophoto with 2 GCPs as class A in the 1:5,000 scale. One possible explanation for this difference is the area size; they used a larger area of 51 ha compared to this experiment. In larger areas, the use of a greater number of control points becomes necessary to georeference the orthophoto. It should be noted that only 91% of the control points had values smaller than the threshold, so 2 GCPs approached the limit values.

For the altimetric PEC-PCD, except for 2 GCPs, all data points meet the class A criteria for the 1:1,000 scale. The results from Siqueira et al. (2020) were similar, with significant discrepancies observed with 2 GCPs, not meeting the criteria for the 1:1,000 scale, except with 4 GCPs, where the scale was 1:5,000 class A. However, the criterion for classification in the 1:1,000 scale, with 90% of the data having discrepancies below 0.27 m, was met.

In general, there was no difference in using GCPs in elevation for planimetry, as the dispersion of discrepancies was similar. For altimetry data, there were slight changes, with a small reduction in data dispersion and RMSE values. It is important to highlight that the best result in terms of arrangement was obtained with 5 GCPs, which represents an improvement compared to the results of this study. All processes were classified as class A in the PEC-PCD for both planimetry and altimetry at the 1:1,000 scale.

Ferrer-González et al. (2020) noted that the influence of GCPs distribution is more evident for altimetric accuracy. Liu et al. (2022) observed that, for the same area, the quantity of GCPs needed to stabilize accuracy differs between planimetry and altimetry, requiring more GCPs for altimetry. It is worth noting that the authors also found that altimetry is more sensitive, corroborating with the findings of the present study.

5 Conclusion

The necessary quantity of GCPs and the use of GCPs in elevation to improve accuracy in UAV surveys were evaluated. It was concluded that using only 2 GCPs results in low accuracy for the orthophoto and generated MDS in image processing. As the number of GCPs increases, accuracy improves, but only up to a certain limit. Beyond a certain quantity of GCPs, accuracy stabilizes (5 GCPs). In the case study, it was found that elevation is the most sensitive variable, and the quantity and arrangement of GCPs significantly influence elevation accuracy. The use of GCPs for elevation improves elevation precision.

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Mauricio de Souza: conceptualization; formal analysis; methodology; validation; writing-original draft; writing – review and editing; visualization. **Henrique Lopes Siqueira:** methodology; validation. **Marcio Santos Araujo:** methodology; validation. **Lucas Yuri Dutra de Oliveira:** methodology; validation; writing – original draft. **Wesley Nunes Gonçalves:** writing – original draft; supervision. **Ana Paula Marques Ramos:** writing – original draft; supervision. **José Marcato Junior:** writing – original draft; conceptualization; supervision.

Conflict of interest

The authors declare no conflict of interest.

Data availability statement

Scripts and code are available on request.

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