International Journal of Geosciences, 2025, 16(12), 958-973
https://www.scirp.org/journal/ijg
ISSN Online: 2156-8367
ISSN Print: 2156-8359

Three-Dimensional Analysis of the Photogrammetric Methods PPK, DRTK2 and DRTK + GCP

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How to cite this paper: Ndour, M.M.M., Sylla, P.M., Seck, C. and Diouf, A.D. (2025) Three-Dimensional Analysis of the Photogrammetric Methods PPK, DRTK2 and DRTK + GCP. *International Journal of Geosciences*, **16**, 958-973.
https://doi.org/10.4236/ijg.2025.1612047

Received: November 17, 2025
Accepted: December 28, 2025
Published: December 31, 2025

Abstract

The development of drones has given new impetus to modern photogrammetry. These unmanned aerial vehicles (UAVs) have become highly valued for 3D modeling. They allow cartographers, surveyors, and others to more easily collect the data necessary for a perfect three-dimensional reconstruction of objects on the Earth's surface. The advent of real-time kinematic positioning (RTK) systems and their use by drones allows for time savings, a reduction in ground control points (GCPs), a reduction in cost and facilitates data acquisition while maintaining good accuracy. The objective of this study is to perform a three-dimensional comparative analysis of three modern photogrammetric positioning approaches: DRTK2, DRTK2 combined with GCPs, and short-baseline PPK obtaining corrections from a GNSS base station. Data was acquired using a DJI Phantom 4 RTK. These different approaches were used in both relatively flat and rugged terrain to help users choose the most appropriate one for a given project. The evaluation focused on their accuracy in relation to the topography and their ease of implementation. The methodology was initially based on establishing an altimetric reference system through direct leveling from a reference point linked to the 1953 General Levelling Survey of West Africa (NGAO53) and a planimetric reference system using the Senegal West African Navigation (SWAN) network of permanent stations. Subsequently, the data obtained by each positioning method were processed using Pix4D Mapper software and compared with the reference data. The results obtained reveal that the **DRTK2 + GCP combination** (RMSE xyz = 0.062 m) ensures more consistent accuracy, particularly in rugged terrain where acquisition conditions are more complex. **PPK** (RMSE xyz = 0.046 m) provides better results in a non-rugged area, with simpler implementation. These results offer a better understanding of the advantages and limitations of these three GNSS positioning techniques applied to drone photogrammetry.

Keywords

3D Photogrammetry, GCP, GNSS, DRTK2, PPK, Direct Leveling

1. Introduction

The emergence of drones (UAVs—Unmanned Aerial Vehicles) has enabled a new form of topographic data acquisition that is fast, flexible, and inexpensive. These unmanned aircraft make it possible to fly over hard-to-reach areas and obtain high-resolution images, which, once processed using photogrammetry, give rise to essential geospatial products: orthophotos, digital elevation models (DEMs/DSMs), point clouds, etc. This density of information is directly linked to specific scientific and professional objectives [1] [2], particularly in the study of urban areas, road developments, hydraulic structures or sanitation projects, etc.

However, while drones offer easy access to data, the choice of positioning method for georeferencing images remains crucial for achieving good accuracy. Georeferencing photogrammetric models is traditionally done indirectly, by establishing ground control points (GCPs) over the study area. This operation is often demanding in terms of time, labor, and cost. However, direct georeferencing of these models is constantly evolving thanks to technologies embedded in drones [3]. The DRTK method provides real-time correction from a fixed base station (such as the DRTK2 station) and is appealing due to its simplicity in the field. In contrast, the PPK method, which performs corrections after acquisition, offers greater robustness against signal loss or in noisy environments. The accuracy achieved then depends on multiple factors: terrain type, satellite coverage, quality of the reference bases, etc. [4] [5]. The resulting research question is: which method is best suited according to the constraints of the terrain (rugged or relatively flat relief) and the cartographic objectives (2D or 3D).

The objective of this study is to compare the performance of GNSS positioning combined with a drone in PPK, DRTK2 and DRTK2 + GCP mode on two sites chosen for their different morphological characteristics.

2. Methodology

2.1. Presentation of the Study Area

Senegal, located in the far west of Africa, covers an area of approximately 196,722 km^2 and opens onto the Atlantic Ocean to the west. The country's terrain is generally flat, with low elevations ranging from 0 to 581 m at Mount Assirik, giving the territory a gently rolling character. The hydrographic network is dominated by the Senegal, Gambia, and Casamance rivers, which contribute to shaping the landscapes and agricultural activities [6] [7].

Covering an area of 6601 km², the Thiès region is located in the west of the country, between Dakar and Diourbel. It occupies a strategic position in the Niayes region, known for its sandy soils and horticultural activities. Its gently rolling terrain, characterized by low plateaus and depressions that promote water retention, makes it an important agricultural area. [8] Demographically, Thiès has approximately 2 million inhabitants, representing nearly 12% of the national population, with a regional density exceeding 350 inhabitants/km² and a high concentration in urban areas such as Thiès-ville and Mbour, reflecting a rapid urbanization dynamic linked to its proximity to Dakar [7]. The city of Thiès is seeing the realization of major infrastructure and development projects, notably the airport, the toll highway, and the new city [9].

Both sites are located in the department of Thiès. The site with rugged terrain is located in the commune of Keur Mousseu specifically in the plateaus of Thiès and is located between longitudes 16˚59'27.60" W and 16˚59'14.28" W; and latitudes 14˚46'55.92" N and 14˚46'57.00" N. As for the site with non-rugged terrain, located in the commune of Thiès Sud, it is part of the Mbour 4 zone and can be located between longitudes 16˚57'56.52" W and 16˚57'44.64" W and latitudes 14˚46'28.92" N and 14˚46'28.56" N. Each of the two zones covers an area of 11 hectares (**Figure 1**).

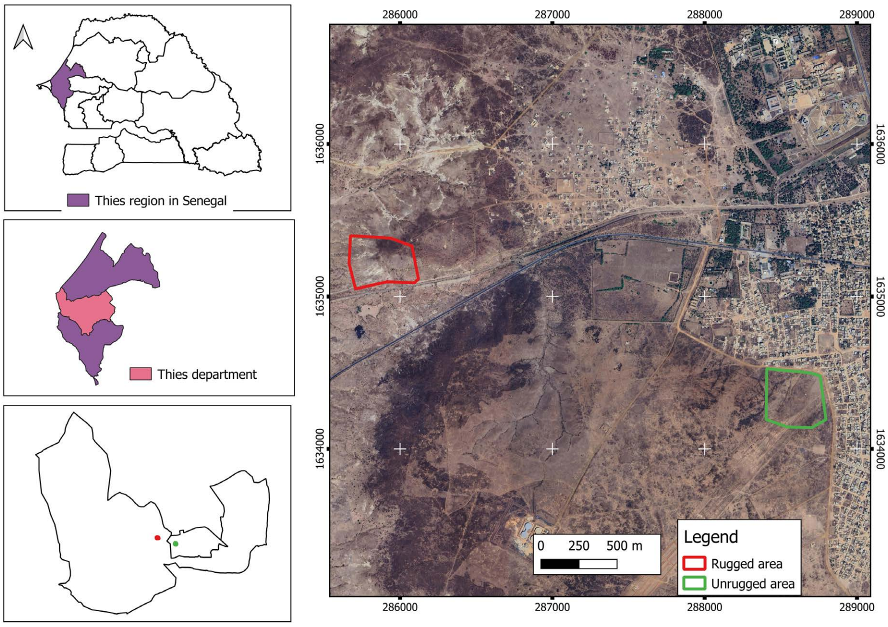
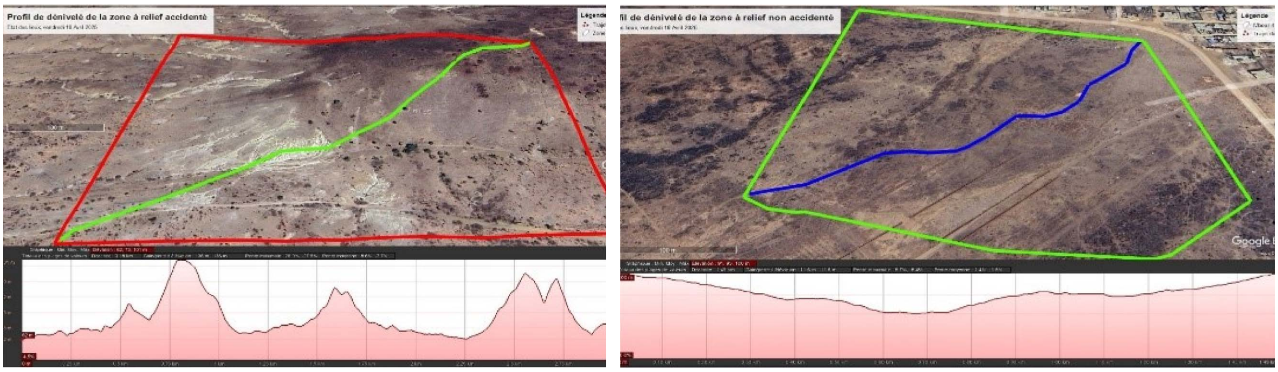


Figure 1. Geographical location of the study areas.

2.2. Data Acquisition

For a comparative topographic study, it is important to have high-quality data throughout the process. First, the choice of the two study areas was crucial to ensure varied terrain morphologies. Therefore, a preliminary reconnaissance was carried out using Google Earth (see **Figure 2(a)** and **Figure 2(b)**).



(a) (b)

Figure 2. (a) Profile of the rugged area and (b) profile of the unrugged area.

Analysis of Figure 2(a) shows that the altitudes vary from 62 m to 101 m, a difference of 39 m in elevation, reflecting a significant topographic variation characteristic of rugged terrain in the Senegalese context. Figure 2(b), on the other hand, shows a more moderate variation in altitudes, between 91 m and 100 m, a difference of 9 m in elevation, indicating relatively flat terrain, corresponding to a non-rugged landscape (see Figure 3(a) and Figure 3(b)).

(a) (b)

Figure 3. Representation of the study areas: (a) Rugged area and (b) non-rugged area. (Source: Authors)

The data acquisition phase was subdivided into three stages: direct precision leveling, GNSS surveying, and drone photogrammetry. Each stage was rigorously applied to ensure the accuracy of the data used in the comparative analysis of positioning methods. These different acquisition stages guided the choice of equipment; thus, a Sprinter 250 electronic level, a CHCNAV i73 dual-frequency GNSS receiver, and a DJI Phantom 4 RTK drone were used.

2.2.1. Direct Precision Leveling

Levelling, and altimetry in general, consists mainly of determining the height of points above a reference surface, measuring the difference in altitude between points, carrying out and verifying the slope gradient in certain municipal works and so on [10].

The leveling phase began by reviewing existing documentation to locate the closest reference point to the sites, linked to the NGAO 1953 network. Point TH18, located inside the church in the Mbour 3 district, proved to be the closest to our sites among the 23 points in the urban network of the city of Thiès. A double-station traversing technique was chosen from this reference point to compensate for systematic errors and ensure high altitude accuracy.

2.2.2. GNSS Surveys

GNSS surveys are measurement operations that use satellite signals to accurately determine geographic positions on the Earth's surface. The speed, accuracy, and cost of GNSS surveys have made them indispensable in topography, geodesy, cartography, etc. [11] [12].

To ensure good GNSS reception, careful mission planning is essential to identify the optimal time period with the best satellite geometry distribution and favorable atmospheric conditions. The Trimble GNSS online planning software was used, and May 7, 2025, was selected for observations between 00:00 and 11:40 due to low signal interference and observed GDOP variations remaining below 1.8 (see **Figure 4**). Therefore, in each area, a control point (B1, B2) was established by static positioning from the permanent stations of SWAN 3 and SWAN 4.

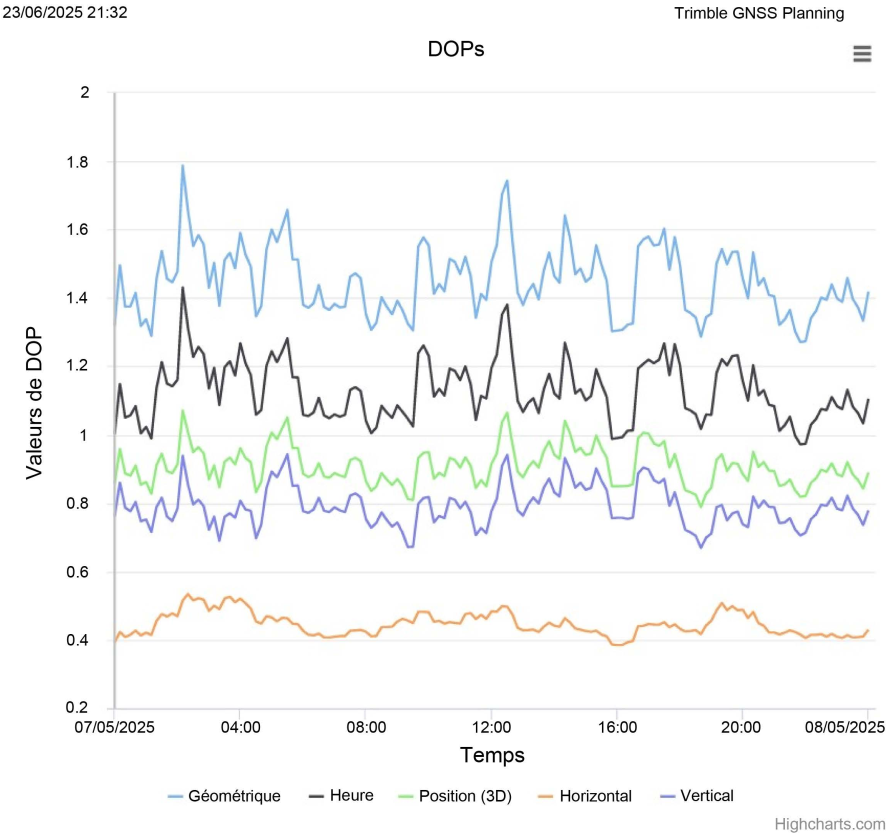
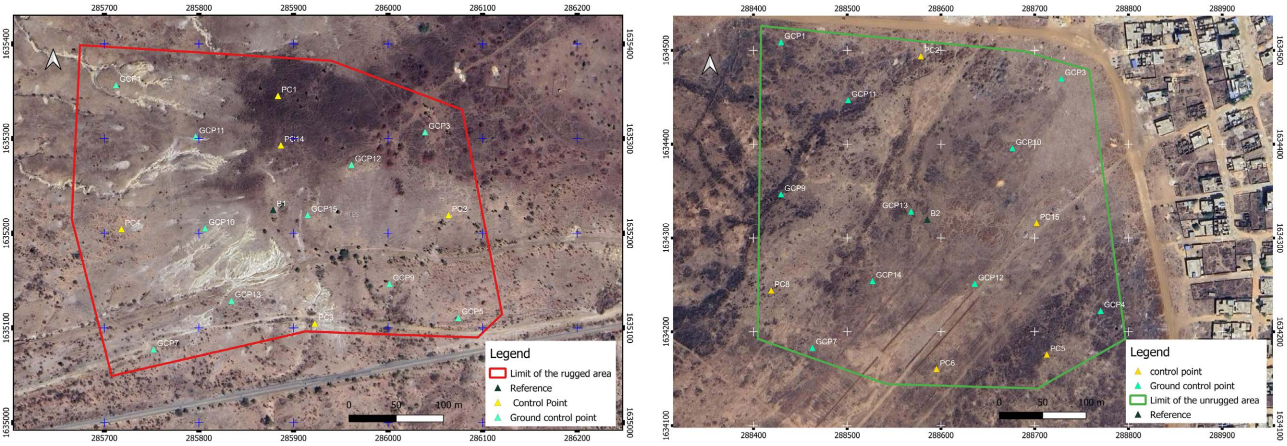


Figure 4. GDOP value for the date of Wednesday, May 7, 2025 (Trimble GNSS Planning (n.d.), 2025) [13].

Following these new reference points, GCPs and control points were established using the RTK method. These will be used for the geometric calibration of the drone data and for evaluating positioning discrepancies.

2.2.3. Acquisition of Photogrammetric Data

Data acquisition by drone is very reliable, but it is important to follow a rigorous process. The number of GCPs and their homogeneous distribution in the study area are of paramount importance [14]. Particularly in the context of our study, whose objective is to evaluate the three-dimensional accuracy of the data obtained by DRTK2 + GCP, DRTK2 simple and PPK modes with different reliefs (see **Figure 5**).



(a) (b)

Figure 5. Distribution of GCPs in the two sites: (a) accidental zone and (b) non-accidental zone.

For data acquisition in DRTK mode, the DRTK2 GNSS station is positioned at one of the reference points (B1 or B2). In PPK mode, the RTK function is first deactivated, and a base station (i73+) is positioned at one of the reference points to obtain RINEX observation data. The survey is then initiated in static mode for a duration of thirty (30) minutes. The maximum distance between the flight path and the reference station is 250 m. **Table 1** below summarizes the flight parameters and the number of images obtained per mode.

Table 1. Flight parameters and number of images.

Side overlap	70%			
Longitudinal overlap	80%			
Flight altitude	60 meters			
Spatial resolution	2.17 cm/pixel			
Number of images	Rugged area		Non-rugged area	
	DRTK	PPK	DRTK	PPK
	538	547	531	511

Following this data acquisition phase, we moved on to processing the different types of data and analyzing the results.

3. Processing and Analysis of Results

The acquired data were subjected to a series of processing steps aimed at producing precise georeferenced photogrammetric deliverables, enabling comparative analysis of different positioning methods.

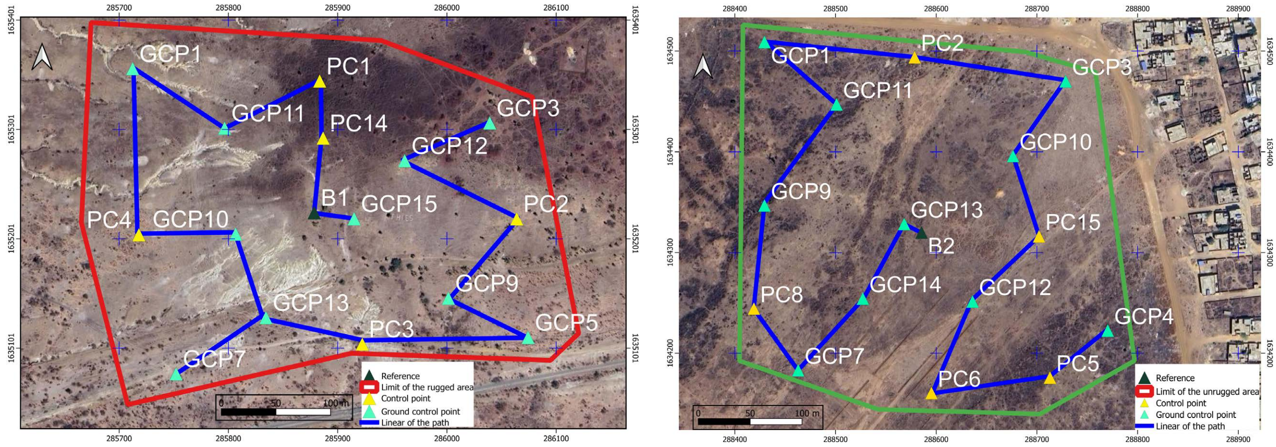
3.1. Precision Direct Leveling

The leveling work was carried out in two stages. First, an initial leveling of the reference points for each zone was performed, starting from point TH18. The traverse was conducted via point B2 to reach point B1, for a total distance of 10.2 km round trip. Then, all ground control points (GCPs) and control points (CPs) were leveled based on the reference points (**Figure 6** below). The data were processed to calculate the raw elevations and the closure. For calculating the tolerance, the standard in force in Senegal is the decree of January 21, 1980 [15], which is based on the following equation:

$$T = 4\sqrt{9L + L^2} \text{ if } n > 16 \tag{1}$$

with: L = Length of the route; N = number of elevation changes and $n = N/L$ number of elevation changes per kilometer.

The tolerance finally obtained after calculation is $T = 56$ mm with a closure of $f = 4.1$ mm. Since the closure is less than the tolerance, the raw elevations are compensated. **Figure 6(a)** and **Figure 6(b)** show the leveling linear mapping in each study area, respectively. These points provide a reliable altimetric reference for evaluating photogrammetric deliverables. Prior to establishing the altimetric reference system, the base points for planimetry were observed using GNSS measurements.



(a) (b)

Figure 6. Distribution of GCPs and PCs: (a) leveling line in the rugged area and (b) leveling line in the non-rugged area.

3.2. GNSS Measurements

GNSS measurements began with observations of reference points B1 and B2. Each observation lasted 120 minutes. The RINEX observation files for points B1, B2, SWAN3, and SWAN4 were checked, saved, and processed using Leica Infinity software. A minimum constraint adjustment of the network was performed to directly link the calculation to the local system (RRS04). Statistical validation, using an F-test at the 95% confidence level, confirmed the reliability of the results, and the obtained values remained below the critical threshold. The post-processing results provided the coordinates of points B1 and B2 in the following **Table 2**:

Table 2. Coordinates of reference points.

REFERENCES				
Points	Is (m)	North (m)	Altitudes (m)	Ellipsoidal heights (m)
B1	285878,572	1635224,864	82,835	113,318
B2	288585,450	1634319,737	96,592	127,036

The photogrammetric control points and the GCPs were then surveyed in RTK mode for the determination of their planimetric and altimetric coordinates (**Figure 6**).

3.3. Photogrammetric Data

Image processing was performed using PIX4D software. For PPK mode, REDtoolbox software was used to correct the initial GPS positions using RINEX data from a reference station. Following this processing, dense point clouds, DEMs, and orthophotos were obtained for each acquisition mode.

The following **Figure 7** summarizes the entire data acquisition methodology, from the different processing stages to the results.

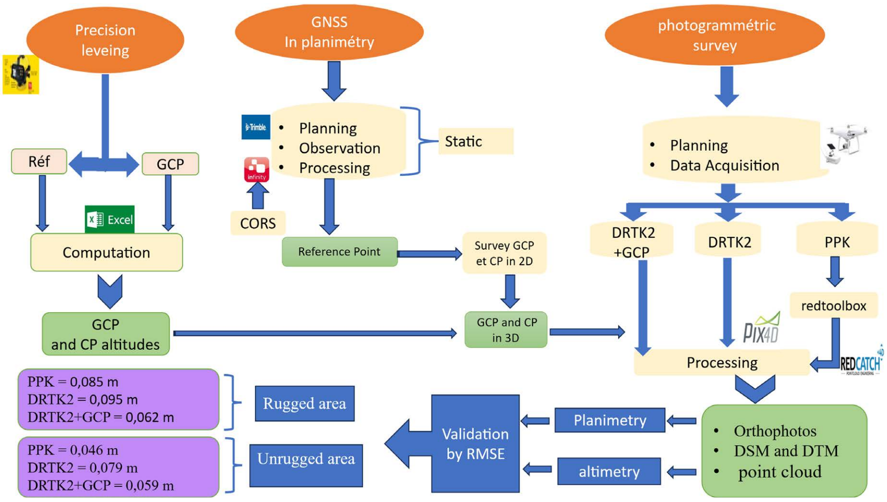


Figure 7. Summary of the methodology.

Once the various results were obtained, we proceeded to the evaluation by first measuring the positional discrepancy between the previously calculated control points and their georeferencing counterparts. Next, another evaluation was performed solely on the elevations, using the altimetric reference points and their orthophoto equivalents. Finally, the overall discrepancy was evaluated by combining the planimetry and altimetry of the different reference points and control points. To do this, the following Equations (2), (3) and (4) were used to calculate the RMSE. This equation was chosen because it allows for external evaluation between the previously established reference frame and the various models obtained.

$$\text{RMSExy} = \sqrt{\frac{1}{n}\left(\sum_{i=1}^{n}(\text{Xignss} - \text{Xiorth})^2 + (\text{Yignss} - \text{Yiorth})^2\right)} \tag{2}$$

$$\text{RMSEz} = \sqrt{\frac{1}{n}\left(\sum_{i=1}^{n}(\text{Ziniv} - \text{Ziorth})^2\right)} \tag{3}$$

$$\text{RMSExyz} = \sqrt{\frac{1}{n}\left(\sum_{i=1}^{n}(Xignss - Xiorth)^2 + (Yignss - Yiorth)^2 + (Ziniv - Ziorth)^2\right)} \tag{4}$$

with, *N*: number of checkpoints; Xgnss and Ygnss: coordinates surveyed with GNSS; Xorth and Yorth: coordinates taken with orthophoto; Zniv: leveled altitudes and Zorth: orthophoto altitudes

The results obtained in the rugged terrain by each positioning method are shown in **Figure 8**. Analysis of these results reveals significant variations between the DRTK2 + GCP, PPK, and DRTK2 methods. In planimetry (x, y), the DRTK2 + GCP method exhibits the best performance with an average error of approximately 0.025 m, significantly lower than that of PPK (0.065 m) and DRTK2 alone (0.070 m). This performance (DRTK2 + GCP) could be explained by the contribution of ground control points, which correct distortions related to the complex terrain morphology and the satellite masking common in this type of area.

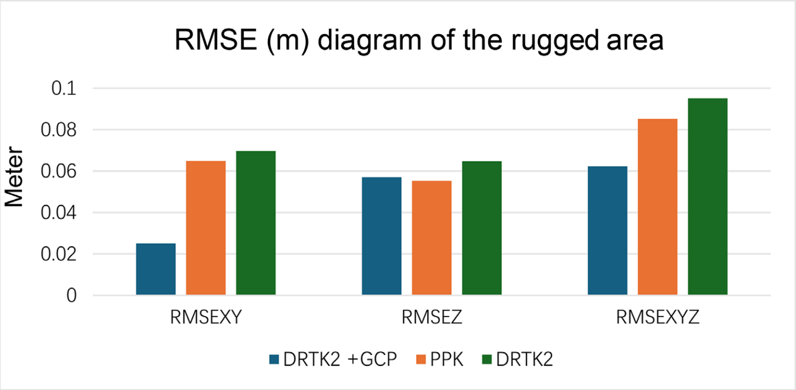


Figure 8. RMSE of the rugged area.

The RMSE analysis, which considers only altimetry (RMSEz), shows that the values are relatively close: 0.057 m for DRTK2 + GCP, 0.055 m for PPK, and 0.066 m for DRTK2. We can conclude that the vertical component remains sensitive to terrain effects and reception errors, even though PPK and DRTK2 + GCP maintain a slight advantage. However, the three-dimensional analysis ($RMSE_{XYZ}$) shows that the variation becomes more significant with DRTK2 + GCP, with an RMSE of 0.063 m compared to 0.085 m for the PPK method and 0.095 m for DRTK2. From these results, we can confirm that, within the framework of our study, the combined use of DRTK2 + GCP constitutes the most accurate solution in rugged terrain because it effectively compensates for disturbances related to the terrain and variations in satellite visibility.

A similar study with the same parameters was carried out in the non-accident area and the results obtained are represented by **Figure 9**.

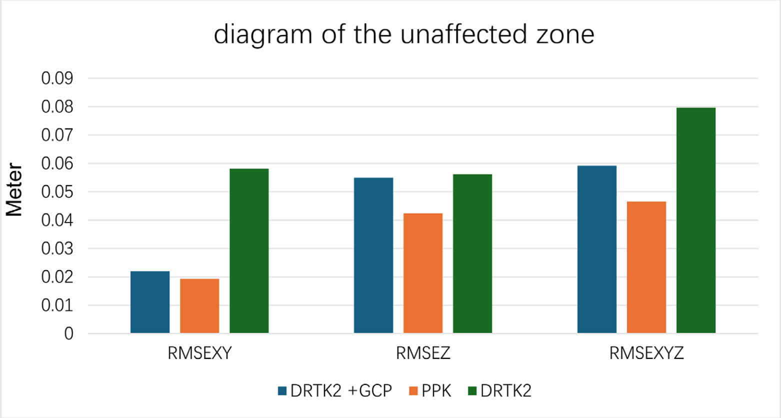


Figure 9. RMSE of the non-accident zone.

The results from the uncomplicated area highlight a different behavior. The PPK mode achieves better accuracy at all levels, benefiting from excellent satellite visibility and a more stable trajectory. Planimetric analysis ($RMSE_{XY}$) reveals that the PPK mode records an average error of 0.019 m, compared to 0.022 m for the DRTK2 + GCP mode and 0.058 m for DRTK2. As for the altimetric evaluation (RMSEZ), it reveals that PPK maintains its advantage with an RMSE of 0.042 m, while DRTK2 + GCP and DRTK2 show 0.055 m and 0.056 m respectively. Finally, the global 3D evaluation ($RMSE_{XYZ}$) gives PPK as the best performing mode with an RMSE of 0.046 m, followed by the DRTK2 + GCP mode with 0.059 m and the DRTK2 mode with 0.079 m. The advantage of PPK mode over others could be explained by its ability to apply post-processing corrections optimally when the satellite geometry is favorable, which is the case on flat, fairly open terrain.

From the various results obtained from observations within this study, we can conclude that the choice of method depends heavily on the environmental conditions of the study area. In rugged terrain, the DRTK2 + GCP mode proved more suitable by reducing uncertainties due to the topography and the probability of satellite signal loss. Conversely, the PPK mode performed better in flat terrain thanks to the highly effective post-processing in an environment free of obstacles. DRTK2 alone remains the least effective in both cases, highlighting the importance of integrating GCPs, as in conventional photogrammetry, or opting for differential processing.

4. Discussion

The results obtained in this study highlight the crucial influence of terrain morphology on the performance of GNSS positioning techniques used in drone mapping. In the flat Mbour 4 area, the data show that PPK generally offers better accuracy with the addition of post-processing.

Furthermore, in rugged terrain, the PPK method is penalised by a deterioration in GNSS signal quality due to occultations, satellite lock loss, and variations in the signal-to-noise ratio. These conditions promote cycle jumps in RINEX files and make ambiguity resolution less reliable, even after post-processing. These limitations explain the lower accuracy of PPK in this type of environment, unlike the DRTK2 + GCP method, which benefits from more stable geometric anchoring thanks to ground control points.

In planimetry in the non-rugged zone, analysis of the results of Oniga *et al.* [16] with the DJI Phantom 4 Pro v2 near Lasi (Romania) and Eker *et al.* [4] with the DJI Phantom 4 RTK in western Türkiye, respectively on agricultural land and homogeneous surfaces (road and bare soil) without the use of GCP, yielded RMSE values between 0.02 m and 0.033 m with the PPK method. We observe that our result with the same method under similar conditions, with an RMSE of 0.019 m, is satisfactory and consistent with these results. However, the DRTK2 method gives an RMSE of 0.058 m, 0.012 m less precise than the study by Eker *et al.*, who used the RTK-CORS method with an RMSE of 0.0334 m. This slight difference could be explained by the contribution of the CORS station. As for the DRTK2 + GCP method, it presents an RMSE of 0.022 m, which is within the range of measurements reported by Volvo *et al.* [18] who studied the RTK mode associated with GCPs on the Grande plage of the southwest of the Ile d'Oléron in France (mission 1: 0.016 m; mission 2: 0.023 m) with respective deviations of 0.006 m and 0.001 m.

Using the PPK altimetry method, we obtained an RMSE of 0.042 m compared to 0.048 m reported by Eker *et al.* [4], a favorable difference of 0.006 m. The DRTK2 method shows an RMSE of 0.056 m, 0.038 m more precise than that of Eker *et al.* [4] (0.0943 m). Similarly, the DRTK2 + GCP method gives an RMSE of 0.055 m, 0.039 m more precise than that of Eker *et al.* [4], with values of 0.0943 m and 0.029 m, and 0.005 m more precise than the work of Volvo *et al.* [18] (Mission 1: 0.026 m and Mission 2: 0.045 m).

Zhang *et al.* [17] carried out several flight missions with two different camera-drone systems: a micro-drone equipped with a wide-angle action camera (FOV) and a professional drone equipped with a single-lens digital SLR camera. They reported on homogeneous agricultural areas in the Belgian loess belt (Belgium), an RMSE of 0.03 m in PPK, performance very close to that obtained in our study with a three-dimensional error of 0.046 m, or a difference of 0.016 m. This agreement confirms that PPK fully benefits from the favorable conditions offered by open terrain. Similarly, Miron *et al.* [19], with the DJI Phantom 4 Pro v2 a flat urban context in Iasi (Romania), analyzed the georeferencing of PPK without GCP using a local base station at a flight altitude of 60 m and obtained an accuracy of 0.037 m. Comparing these results with ours under the same conditions, the observed differences remain 0.009 m lower. The findings of Taddia *et al.* [20] with an identical drone provide further insight in a coastal context in the northern Adriatic Sea, Italy. Their use of nadir imagery enabled them to achieve a three-dimensional accuracy between 0.034 m and 0.075 m. The RMSE values recorded in this study corroborate ours (0.046 m in 3D), thus confirming the consistency of the observed performance. However, the DRTK 2 method yields an RMSE of 0.079 m, which is more accurate than the study by Eker *et al.* [4] (0.1001 m), with a difference of 0.021 m. Finally, the DRTK 2 + GCP method has a precision of 0.059 m, less precise compared to the work of Volvo *et al.* [18] (mission 1 of 0.03 m and mission 2 of 0.055 m) with deviations of 0.029 m and 0.005 m.

In planimetry, in the rugged area, the DRTK2 + GCP method exhibits the best performance with an RMSE of approximately 0.025 m, thus confirming good horizontal accuracy. This improvement results from the integration of ground control points (GCPs), which effectively correct deformations in the photogrammetric model and ensure precise registration of the point cloud. These results are consistent with those of Monjardin-Armenta *et al.* [3] using the DJI P4, who obtained 0.0507 m in DRTK + GCP mode in Culiacán, Mexico. Although our study shows twice the accuracy, both works clearly demonstrate the decisive influence of GCPs in improving planimetric accuracy. In comparison, the DRTK2 method without GCPs achieves 0.070 m, which remains satisfactory but slightly lower than the literature references, particularly those of Monjardin-Armenta *et al.* (0.052 m), Zeybek *et al.* [21] with the DJI Phantom 4 RTK (0.038 m in the Merkez district, Türkiye) and Kim *et al.* [5] (0.03 m in Gyeongsangnam-do, South Korea). The PPK method, on the other hand, provides an RMSE of 0.065 m, reflecting good overall performance, with deviations of 0.03 and 0.04 m respectively from the results of Zeybek *et al.* [21] and Kovanič *et al.* [22] using an identical drone (0.031 m in eastern Slovakia), reflecting the influence of GNSS signal quality and local conditions.

In altimetry, still within the rugged terrain, the DRTK2 + GCP method also stands out, with an RMSE of 0.057 m, reflecting good vertical accuracy thanks to the use of GCPs. However, this accuracy remains slightly lower than those reported by Monjardin-Armenta *et al.* [3] (0.0201 m) and Zeybek *et al.* [21] (0.039 m), with discrepancies ranging from 0.018 to 0.037 m, which can be attributed to flight configuration, GNSS signal quality, and topographic complexity. The DRTK2 method without GCP shows 0.066 m, a decent performance but lower than the literature (Monjardin-Armenta *et al.* [3]: 0.0209 m; Zeybek *et al.* [21]: 0.039 m), which highlights the dependence of accuracy on environmental conditions and the shooting geometry. Finally, the PPK without GCP provides an RMSE of 0.055 m, reflecting an overall satisfactory performance, with deviations of 0.002 to 0.057

m compared to the studies cited previously (Zeybek *et al.* [21]: 0.059 m and Kovanič *et al.* [22]: 0.112 m) confirming its robustness for vertical restitution even in the absence of control points.

In 3D, the DRTK2 + GCP method maintains the best accuracy, with an RMSE of 0.063 m, close to that of Monjardin-Armenta *et al.* [3] (0.0546 m). The 8.4 mm difference confirms the reliability of our measurements and the importance of GCP for three-dimensional accuracy. The DRTK2 method without GCP achieves 0.095 m, a performance lower than the values reported in the literature (Monjardin-Armenta *et al.* [3]: 0.0561 m; Zeybek *et al.* [21]: 0.0545 m). PPK, on the other hand, offers an RMSE of 0.085 m, reflecting generally satisfactory accuracy, with deviations of 1.8 to 5.1 cm compared to reference studies, confirming its reliability for three-dimensional reconstruction even without GCP.

Overall, these results show that GCP integration remains essential for achieving optimal accuracy, while PPK provides a robust and practical alternative when GCPs are unavailable. These findings can be explained by more complex topographic and environmental conditions, which influence GNSS signal stability, image geometry, and variations in terrain elevation.

5. Conclusions

The objective of this study, to evaluate the planimetric and altimetric accuracy of modern photogrammetry using the DRTK2, DRTK2 + GCP, and PPK methods, was largely achieved. The results obtained demonstrate that in relatively non-rugged areas, all three methods showed acceptable accuracy, with only the PPK method remaining the most precise. Conversely, the DRTK2 + GCP method performed better in rugged terrain.

It is important to note that this study revealed on the one hand the importance of the use of GCPs and their proper distribution and on the other hand that in implementation PPK is the easiest to apply, followed by simple DRTK2, while the DRTK2 + GCP method was the most complex (with the choice of the number of GCPs and the optimization of their distribution).

The originality of our work lies in the fact that it combines two types of terrain with different morphologies, with rigorously standardized flights (same altitude, same configurations in DRTK and PPK). GCPs leveled directly on an altimetric network and surveyed themselves in RTK, as well as an optimization of the point distribution according to Villanueva and Blanco, 2019 [23]. This comprehensive methodology allowed us to experimentally validate the contexts in which each method excels.

However, our results call for caution, because although our study confirms the superiority of DRTK2 + GCP in terms of accuracy in rugged terrain, it also highlights the performance of PPK in such areas. Both DRTK2 and PPK remain limited in rugged terrain, and we did not explore factors such as point cloud density, systematic oblique image acquisition, or the direct effect of varying altitudes. In the future, it would be interesting to investigate the impact of the number of GCPs used with PPK, as well as performance in the presence of dense vegetation, which affects the reflectance and accuracy of photogrammetric point clouds.

Our study thus makes a significant contribution by highlighting the importance of adapting positioning methods to the context, in order to optimize the quality of cartographic products from modern photogrammetry.

In the rugged terrain, the DRTK2 + GCPs method is the most reliable, offering the best accuracy for both 2D (orthophotos) and 3D (DEM and point clouds) products. However, in the non-rugged area, the results show that the PPK method is the most effective for all cartographic products, whether 2D or 3D. These findings therefore help to guide the choice of method depending on the type of terrain and the cartographic objectives.

Based on the results obtained, several recommendations can be made. The choice of positioning method must be adapted to the topographic context and the project constraints. In flat areas, the PPK method appears to be the most appropriate, as it offers satisfactory accuracy, reduced cost, and simpler implementation. Conversely, in hilly areas, the DRTK2 + GCP method is preferable to ensure better three-dimensional accuracy, despite its higher cost and complexity. It is also important to emphasize the importance of an optimal distribution of GCPs, which largely determines the quality of the photogrammetric results. A homogeneous and well-considered placement of control points not only improves survey accuracy but also reduces uncertainties related to the terrain.

Further research would be valuable, incorporating other techniques such as Precise Point Positioning (PPP) or CORS networks, to reduce reliance on GCPs while maintaining high accuracy. Similarly, extending this type of study to diverse environments (dense urban areas, forest environments, and large areas) would allow for a better assessment of the quality and transferability of the tested methods.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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