Assessing the Viability of PPK Techniques for Accurate Mapping with UAS

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ABSTRACT:

Utilizing ground control points (GCPs) to georeference photogrammetry-based point cloud data is a common practice in unmanned aerial system (UAS) mapping. Direct georeferencing or integrated sensor orientation (ISO) can be used to obtain georeferenced point clouds from UAS without relying heavily on GCPs. However, the accuracy of the point cloud may be impacted by the accuracy of the trajectory solution obtained by GNSS. To improve point cloud accuracy, post-processing kinematic (PPK) solutions can be applied to the UAS trajectory, which may provide higher accuracy than low-accuracy trajectory solutions and minimize the reliance on GCPs. This study compares the accuracy and precision of two different point clouds generated using different methods. One point cloud was generated using traditional photogrammetric methods with low accuracy Global Navigation Satellite System (GNSS) observations from the UAS and GCPs that have an average accuracy of one to two centimeters, while the other was generated using PPK trajectory solution for the UAS's trajectory with two software: open-source Emlid Studio and the widely used Inertial Explorer. The use of PPK techniques in UAS mapping may have several potential benefits over traditional methods. By correcting the errors in the UAS's trajectory, a user may only need to depend on fewer ground control points, which can reduce the time and cost associated with fieldwork. This is particularly useful in areas that are difficult to access or have limited ground control point options, such as in urban or forested areas. To evaluate performance, a GNSS receiver is used to obtain measurements on checkpoints, which are used to assess the accuracies of the point clouds. In our experiments, the accuracy of the point clouds generated using PPK trajectory solution with high accuracy GCPs was found to be higher than those generated with low accuracy GNSS observations while aided with high accuracy ground control points. While the use of PPK with GCPs is generally expected to provide more accurate and reliable data than low-accuracy GNSS observations even after adjusting with GCPs, the number and distribution of GCPs can still significantly impact overall accuracy. Therefore, careful consideration of the number of GCPs and their placement is essential to achieve the desired level of efficiency and effectiveness in UAS mapping.

1. INTRODUCTION

The introduction of UAS has revolutionized mapping and surveying practices, providing high-resolution data quickly and cost-effectively. However, the accuracy of UAS mapping data can be impacted by various factors such as the quality of the imaging sensor and GNSS observations during flight, the accuracy of GCPs, and the data collection process. PPK solutions for the trajectory of the UAS can provide highly accurate sensor position/orientation and thus have the potential to improve the accuracy and reliability of UAS mapping data.

PPK is a differential technique that uses observations from two receivers, one on the UAS and a static base station to calculate the precise trajectory of a UAS after the flight has taken place. This technique is like Real-Time Kinematic (RTK) positioning, but instead of relying on a real-time correction signal, PPK processes the data after the flight is completed. By obtaining a more accurate UAS trajectory, users have a chance to create accurate point clouds with fewer GCPs, reducing the time and cost associated with fieldwork. This is particularly useful in areas that are difficult to access or have limited ground control point options, such as urban or forested areas.

(Tomaštík et al., 2019) conducted a study evaluating the use of PPK solutions with a UAS to acquire camera positions for mapping hazardous parts of forests. The accuracy of this approach was compared with two GCP configurations, one with 4 GCPs and the other with 9 GCPs. The study found that the most accurate point clouds were generated by having PPKcorrected trajectories of the UAS's position, with higher horizontal accuracy and no significant difference in vertical accuracy compared to the 9 GCP approach. This suggests that using PPK for sensor positioning may result in higher point cloud accuracy compared to using only GCPs in certain situations, as observed in this study.

While investigating the importance of high-accuracy trajectory data, it is equally important to consider the impact of GCP configurations on point cloud accuracy. For example, (Liu et al. 2022) evaluated the accuracy of a direct georeferencing method for a UAS and found that it achieved a horizontal accuracy of 1.46 to 1.64 times the GSD, and a vertical accuracy of 2.16 to 2.25 times the GSD, which is comparable to results of other studies. However, it's important to note that the accuracy of the point cloud depends on a variety of factors, including the quality of the imaging system and its sensor specifications, as well as the quality of the GNSS and IMU measurements. Therefore, the applicability of these findings to other UAS mapping scenarios may vary depending on the specific equipment used.

The study also found that increasing the number of GCPs can improve the accuracy of the direct georeferencing method up to a certain point, depending on the level of accuracy required and the density of the GCP network but the effect becomes less significant beyond a certain point. The study recommends using at least 6 to 8 GCPs per 10 hectares distributed throughout the area of interest to achieve accurate UAS mapping results, although the specific number and distribution of GCPs may vary depending on factors such as camera resolution, image overlap, and desired level of accuracy. The main takeaway from these studies is that, when using low-accuracy GNSS for georeferencing, it is important to experiment with different numbers and positions of GCPs to achieve the highest possible accuracy when relying solely on GCPs.

Increasing the number of GCPs can usually lead to more accurate results by helping to reduce errors and improve the quality of the georeferencing. However, there is a point of diminishing returns, where adding more GCPs may not lead to any significant improvement in accuracy. It is important to balance the number of GCPs with their accuracy and consistency to ensure the highest possible accuracy of the resulting dataset. (Martínez-Carricondo et al. 2022) used a PPK solution with their UAS and compared the results of corrected trajectories by using two different base stations. They flew at three different altitudes 50, 70, and 90 meters above ground level (AGL) to create data sets that covered an area of interest measuring 328 m by 235 m, which amounts to 7.70 ha. They used no GCPs for some data sets and five GCPs for other data sets, creating a total of 45 different data sets from the three different flights by combining all these parameters and comparing the entire project's accuracy. The study found that the influence of increasing the number of GCPs to increase accuracy is not evident as at a certain threshold it will no longer add more accuracy. The best results were obtained by averaging the two correction bases, as expected.

These publications suggest that both PPK providing air control and GCPs are essential for achieving high accuracy point clouds in UAS mapping projects. Finding the optimal balance between air and GCPs depends on the specific project requirements and constraints. Clearly, there is still a need to assess the accuracy of PPK-generated data and compare it to traditional mapping approaches with GCPs. This investigation compares the accuracy and precision of two different point clouds generated using different methods: one point cloud generated using traditional photogrammetric methods with low accuracy GNSS observations from the UAS and ground control points, and the other generated using PPK trajectory solutions for the UAS's trajectory, with or without GCPs. The second case may provide more accurate and reliable data, highlighting the importance of PPK techniques in improving the efficiency and effectiveness of UAS mapping.

2. METHODS

2.1 Equipment and Test Setup

2.1.1 UAS – Phantom 4

The UAS used in this study was a Phantom 4 RTK, equipped with a 20-megapixel camera with a mechanical shutter, allowing for acquiring high-quality aerial images. Although the Phantom 4 RTK has the capability to use RTK for realtime positioning, this experiment focused solely on the assessment of PPK's accuracy, and thus no RTK corrections were applied during data acquisition. All missions were flown with low accuracy GNSS positioning with one to three meters of accuracy for all trajectories, while the carrier phase data was logged. (Taddia, Y et al. 2020) describes how a Phantom 4 RTK can be used in a PPK setting, where the flight path is reconstructed using PPK solutions. Secondly, the APC position at the time of image capture is computed by interpolating between two PPK solutions. Finally, to determine the camera position and orientation during image capture, the camera's relative position and orientation with respect to the aircraft must be accounted for using boresighting, as the navigation solution is generally computed for the platform. While Inertial Measurement Unit (IMU) measurements can help estimate the relative position and orientation of the camera, additional data sources, such as GNSS measurements with PPK solutions, are needed for accurate results; typically, an GNSS/IMU integration by an Extended Kalman Filter. These steps enable the Phantom 4 RTK to accurately determine the position of the camera center for each image, which is crucial for generating accurate and precise point clouds. This is illustrated in Figure 1.

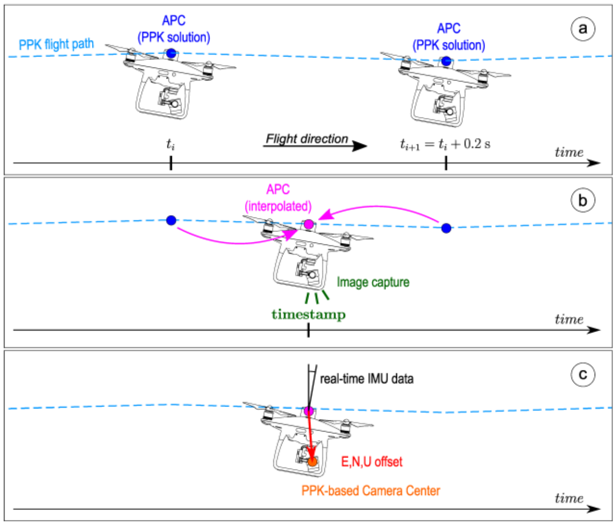

Figure 1: Phantom 4 RTK method to using a PPK solution (Taddia, Y et al. 2020).

2.1.2 Base and Rover – Emlid Reach RS2

TThe accuracy of PPK corrections is largely dependent on having a properly functioning base station that is recording data from a static location simultaneously with the UAS flight, see Figure 2. In this study, an Emlid Reach RS2 GNSS receiver was used as the base station. The RS2 can receive signals from multiple satellite constellations, including GPS, GLONASS, BeiDou, and Galileo, providing more signal sources for PPK processing, which can lead to increased accuracy and more importantly to higher reliability compared to using a receiver that only tracks one or two constellations. The Emlid Reach RS2 is a high-precision geodetic grade receiver that utilizes carrier phase measurements to achieve cm-level accuracy positioning performance (Famiglietti et al. 2021). The base station exported an observation file used to perform PPK corrections on any data collected at the same time within the same vicinity of the base station, see Figure 3.

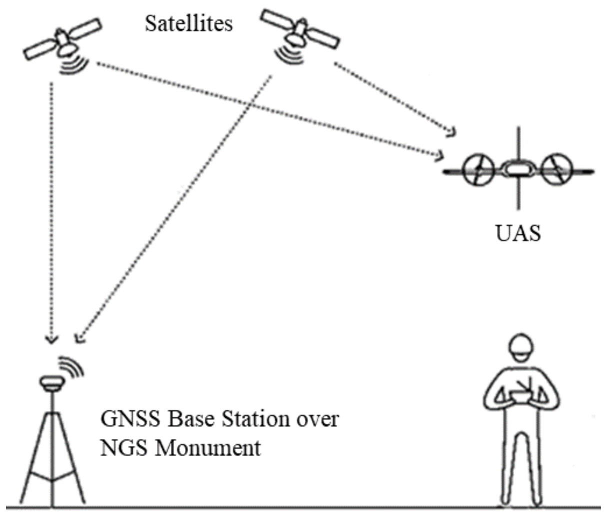

Figure 2: GNSS Base Station observing satellites simultaneously with the UAS mission. No communication is present during the mission between the UAS and the Base.

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Figure 3: The Reach RS2 Base Station over an NGS monument

A second GNSS receiver was used as a rover to collect single solution positions of 5 GCPs and checkpoints on the site. These points will be used in different configurations to test their effectiveness while helping improve point cloud accuracy.

2.1.3 National Geodetic Control Monument

For point cloud accuracy assessment with respect to using both air (PPK) and ground (GCP), there is no need to work in an accepted mapping frame, as the local coordinate system can be used. However, if absolute positioning accuracy is needed then the local frame must be connected to the national geodetic control system. This can be accomplished by either using a monumented NGS point or establishing the base station location by using NOAA NGS OPUS service, which provides survey-grade accuracy. Since there was a National Geodetic Control Monument with known coordinates from the National Geodetic Survey, it was used as a base station in our experiments. The PID of this monument is DI6132 set by the Michigan Department of Transportation. Table 1 shows the coordinates of DI6132 referenced from its NGS Data Sheet.

Table 1: Coordinates of NGS Monument DI6132
NGS Data Sheet: https://www.ngs.noaa.gov/cgi-bin/ds_mark.prl?PidBox=DI6132

PID	Latitude (DMS)	Longitude (DMS)	Ellip Ht (meters)
DI6132	42º 32' 19.5483" (N)	082º 57' 38.64086" (W)	150.846

The RAW observations from the base station and the UAS receiver were processed using Inertial Explorer and Emlid Studio for comparison to generate PPK solutions for the UAS trajectory, which were then used to help georeference the point cloud generated from the photogrammetric processing.

2.1.4 Study Area

The study area for this project is Harrington Park and Trail in Fraser, Michigan, located directly north of the NGS monument point. The data collected during the project is projected onto the NAD83 Michigan South Zone horizontal coordinate system and the NAVD88 vertical coordinate system, using the GEOID18 model. The site is approximately one hectare in size and was selected to ensure proximity to the base station for this experiment, minimizing any potential errors associated with having a base station too far away from the project site. Figure 4 shows an aerial perspective of the park.

Figure 4: Harrington Park and Trail, where the blue flight lines mark for the 50-meter altitude flight, the yellow for the 70-meter flight, and the red for the 90-meter.

2.2 Methodology

2.2.1 Mission Planning Parameters

The study involved three flights of the UAS at different altitudes of 50, 70, and 90 meters, respectively. This approach aimed to provide varying GSD for the site to evaluate how altitude and resolution could impact the accuracy of the point cloud.

The methodology involved several scenarios that were simulated using the data collected from the three UAS flights at different altitudes. The 50-meter flight has five flight lines, the 70-meter flight has four flight lines, and the 90-meter flight has only three flight lines. All these missions have about 80% overlap and sidelap. The first scenario involved applying PPK corrections to the UAS trajectories, but none of the GCPs were used for processing. In the second scenario, some of the GCPs were used with PPK corrections. The third scenario utilized all the GCPs, but no PPK corrections were applied during processing. The fourth scenario involved using PPK corrections along with all the GCPs.

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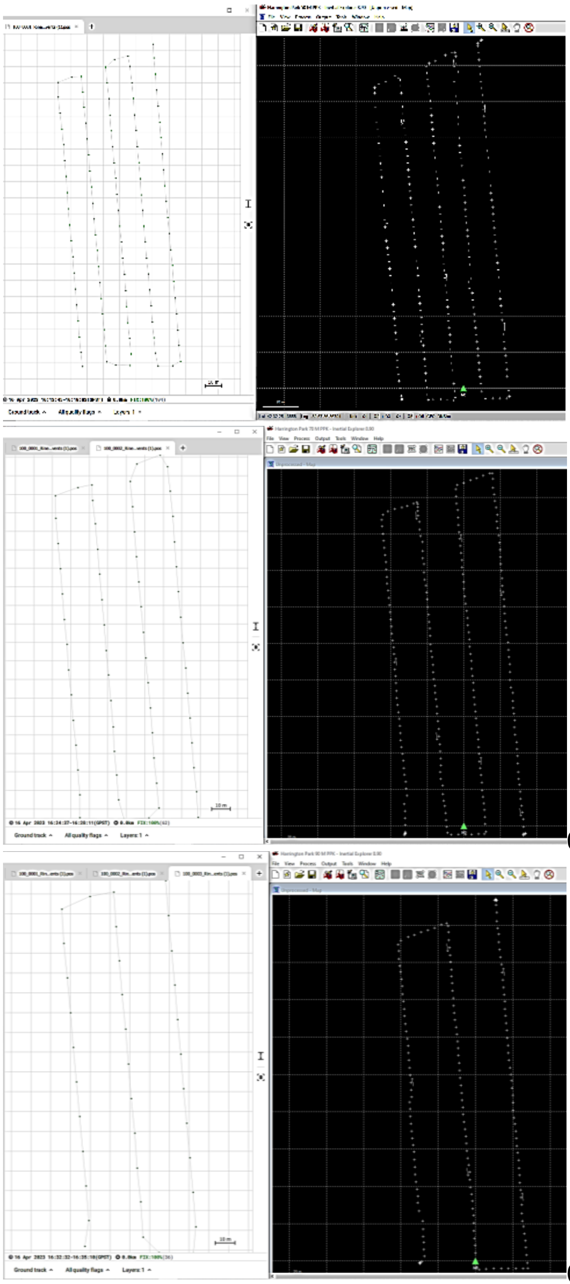
2.2.2 Simulated Scenarios

During the first simulated scenario, the Phantom 4 was flown at three different altitudes of 50, 70, and 90 meters above ground level to generate varying GSDs for the site. The collected data was then processed using Emlid Studio, and PPK corrections were applied to the trajectories of the UAS. To evaluate the accuracy and precision of the PPK UAS trajectory solution, a similar process was conducted using Internal Explorer. The results obtained from the two different PPK engines were then compared to determine if there were any significant differences between the two algorithms. Figure 5 shows the trajectories of the three flights on both Emlid Studio and Inertial Explorer.



(a)

(b)

(c)

Figure 5: Trajectory comparison between Emlid Studio "left" and Inertial Explorer "right": (a) 50-meter flight altitude, (b) 70-meter flight altitude, and (c) 90-meter flight altitude.

The numerical comparisons showed a close match between the two PPK solutions, and thus, the Emlid PPK trajectories were mostly used in the subsequent investigations.

Once the camera center estimates have been calculated, the imagery is then run through Pix4Dmapper for photogrammetric processing, generating a point cloud. All these simulated scenarios utilized Pix4Dmapper for processing at their respective altitudes.

In the second scenario, we utilized the data collected from the three flights and incorporated PPK corrections along with two ground control configurations (GCC): one with just the center point, and the other using the four outside points. Figure 6 shows the configuration of these GCP networks. The first case of this scenario utilized just the center GCP and set the exterior GCPs as checkpoints. This allowed us to evaluate the accuracy of the generated point clouds when using only one control point in the center of the study area, along with checkpoints for validation purposes (Cho et al, 2023). The second case of this scenario only used the exterior GCPs and set one internal point as a checkpoint. This allowed us to evaluate whether using only external control points would yield accurate and precise point clouds, or if it was necessary to include internal control point(s) as well.

(a) (b)

Figure 6: (a) GCPs used in the first iteration, (b) GCPs used in the second iteration.

The third scenario involved the GNSS single positioning solution, which provides a modest accuracy of the UAS trajectory; a commonly used method in the industry for aerial mapping. During this computation, all the GCPs were utilized. The purpose of this effort was to show the impact of GCPs on the accuracy of the final data set; basically, setting a baseline solution for this widely used case. To evaluate the performance, two interpolated and two extrapolated points found in the imagery were compared between the first scenario with only PPK corrections and this third scenario using the five GCPs. The ground features are shown in Figure 7.

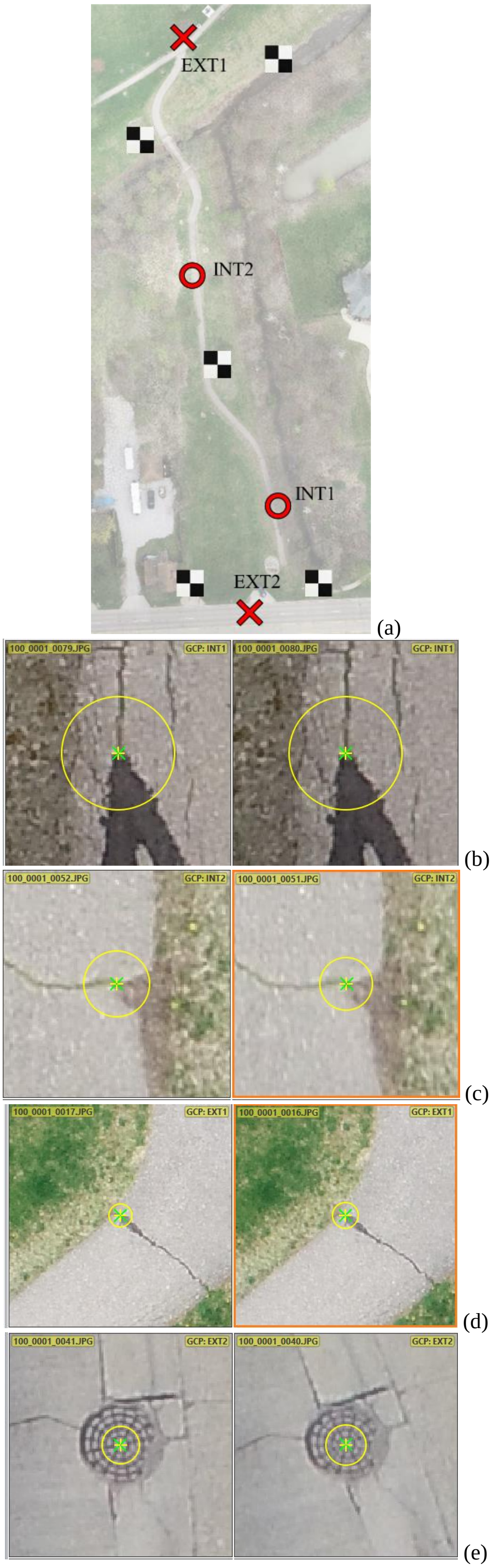


Figure 7: The locations of the interpolated (INT) and extrapolated (EXT) (a), ground features used as checked points: (b) INT1, (c) INT2, (d) EXT1, and (e) EXT2.

In the fourth and final scenario, both PPK corrections for the UAS trajectory and GCPs were used. This simulated scenario was designed to demonstrate the maximum level of control both in the air and on the ground to create the highest level of accuracy for the data.

By incorporating the PPK corrections for the UAS trajectory. By comparing the results of this scenario to the results of the other scenarios, we can determine which combination of altitude, PPK corrections, and GCPs provides the highest level of accuracy and precision for mapping with a UAS.

3. RESULTS

3.1 First Scenario – PPK corrections only

After running PPK processing to obtain from GNSS observations using both Emlid Studio and Inertial Explorer, Tables 2 and 3 show the differences between the coordinates of the GCPs used as checkpoints and the positions of the targets identified in the data using the PPK solution from Emlid Studio and Inertial Explorer, respectively.

The trajectory solutions indicated that the differences between the solutions created by the two software tools were very minimal; differences are in the range of a few millimeters in both horizontal and vertical positions, as shown in Figure 8. Therefore, for the remainder of the experiment, Emlid Studio solutions were used for data processing since they provided comparable accuracy to Inertial Explorer.

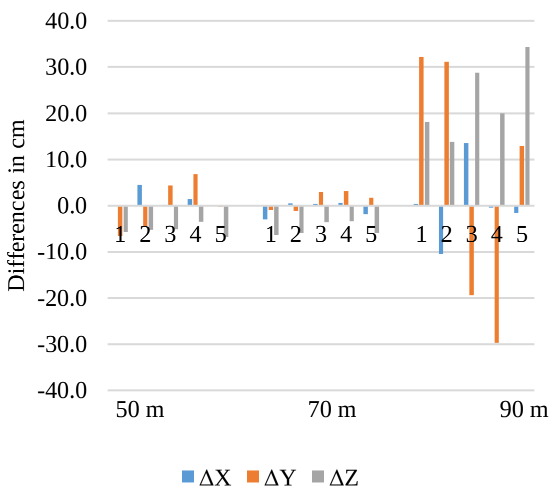
At the lowest altitude of 50 meters with a 20-megapixel camera, the GSD at nadir is 1.37 centimeters, which is the highest resolution that was achieved in this experiment. This imagery allows for more accurate measurements and analysis in comparison to imagery taken at higher altitudes with the same camera specification and environment. However, there are still small differences in coordinates of no greater than 7 centimeters in both the horizontal and the vertical directions. At 70 meters altitude, the GSD increases to 1.92 centimeters per pixel. Despite this decrease in resolution, the accuracy of the measurements remains decent, with only about 3 centimeters of difference in the horizontal and 7 centimeters in the vertical. Finally, at 90 meters altitude, the GSD reaches 2.47 centimeters per pixel, resulting in a noticeable decrease in accuracy, with errors increasing to 30 centimeters in both the horizontal and vertical directions, which are larger than expected based on the height differences in altitude. Obviously, tower altitude flights with higher GSDs result in more accurate imagery, while higher altitude flights with lower GSDs result in less accurate imagery.

3.2 Second Scenario – PPK corrections with different GCC

During the two iterations, both gave different results showing the importance of the spatial distribution of the GCPs. The first iteration only uses the center GCP in the solution with PPK corrections, and Table 5 shows the difference between the other four after only referencing center GCP with PPK.

Table 2: The differences using the PPK solution from Emlid Studio with the 50-, 70-, and 90-meter altitudes.

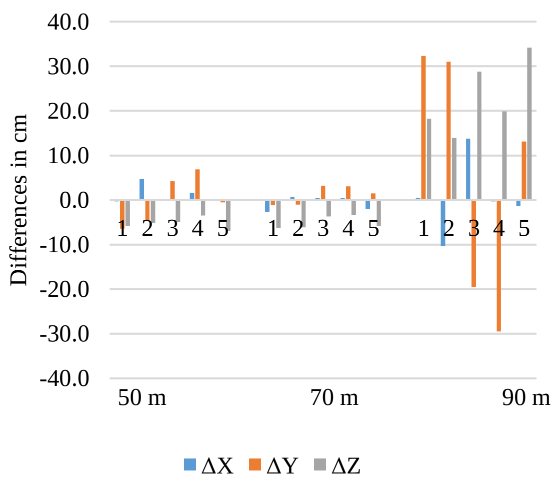
50 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
1	-0.1	-6.5	-5.7
2	4.5	-4.4	-5.2
3	0.2	4.4	-5.1
4	1.4	6.8	-3.5
5	0.0	-0.3	-6.8
70 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
1	-3.0	-1.0	-6.4
2	0.5	-1.1	-5.9
3	0.4	2.9	-3.6
4	0.6	3.1	-3.4
5	-1.9	1.7	-5.9
90 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
1	0.4	32.2	18.1
2	-10.5	31.1	13.8
3	13.5	-19.4	28.8
4	-0.4	-29.7	20.0
5	-1.6	12.9	34.3



Observing the 50-meter altitude flight, we see a significant improvement in points 1 and 2, which had a direct line of sight to GCP number 5 in the center of the project. However, points 3 and 4 still had some improvement with errors ranging between 3 to 5 centimeters but still more errors than those found on points 1 and 2. The 70-meter flight seems to show some improvement over the 50-meter flight, which is probably random; with all differences being under 3 centimeters and the elevation having only a 1-centimeter difference between the PPK solution and the coordinates of the points. Interestingly, the 90-meter flight also showed some improvement but points 3 and 4 still had errors ranging from 20 to 30 centimeters, while points 1 and 2 improved to only 15 centimeters of error. This indicates that controlling the exterior of the site could help in improving accuracy. This could be explained by the fact that only the data coming from the images when doing photogrammetry can calculate the positions of these points. The PPK corrections only apply to the GNSS position of the UAS, but the reconstruction processes aren't aided with PPK. Hence having exterior GCPs is critical for aiding the accuracy of the point cloud.

Table 3: The differences using the PPK solution from Inertial Explorer with the 50-, 70-, and 90-meter altitudes.

50 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
1	-0.3	-6.4	-5.8
2	4.7	-4.6	-5.1
3	0.1	4.2	-4.9
4	1.6	6.9	-3.5
5	-0.2	-0.5	-6.9
70 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
1	-2.7	-1.2	-6.3
2	0.7	-1.0	-6.1
3	0.4	3.2	-3.7
4	0.4	3.1	-3.4
5	-2.0	1.5	-5.8
90 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
1	0.5	32.3	18.2
2	-10.3	31.0	13.9
3	13.8	-19.5	28.8
4	-0.3	-29.5	19.9
5	-1.4	13.1	34.2



In the second iteration of this scenario, utilizing the four exterior GCPs provides us with differences for the center point. Table 6 shows the coordinate differences of point number 5, the only checkpoint in this iteration.

At the 50- and 70-meter altitudes, the horizontal accuracy of point number 5 was about 1 centimeter, and the vertical accuracy was at 2 centimeters. Even at the highest altitude of 90 meters, we still saw an improvement in horizontal accuracy to 3 centimeters and vertical accuracy to 10 centimeters. This suggests that it is important to carefully consider the altitude, GSD, and sufficient overlap when planning a drone mapping project to achieve the desired level of accuracy. These iterations demonstrated the importance of having ground control points in a certain configuration and how it can impact the accuracy of the generated point cloud when utilizing PPK corrections. It also provided insight into whether internal or external control points are necessary when generating point clouds using PPK.

Table 4: Direct differences between the 5 checkpoints using Emlid Studio and Inertial Explorer with the 50-, 70-, and 90-meter altitudes.

50 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
1	-0.2	0.1	-0.1
2	0.2	-0.2	0.1
3	-0.1	-0.2	0.2
4	0.2	0.1	0
5	-0.2	-0.2	-0.1
70 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
1	0.3	-0.2	0.1
2	0.2	0.1	-0.2
3	0	0.3	-0.1
4	-0.2	0	0
5	-0.1	-0.2	0.1
90 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
1	0.1	0.1	0.1
2	0.2	-0.1	0.1
3	0.3	-0.1	0
4	0.1	0.2	-0.1
5	0.2	0.2	-0.1

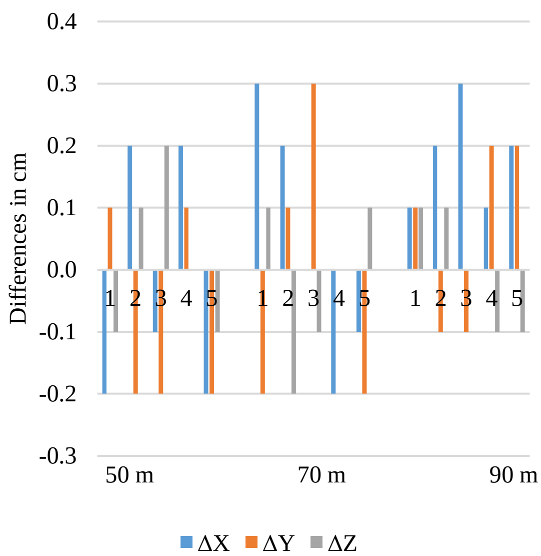


Table 5: The differences between using the PPK solution with the center GCP from Emlid Studio with the 50- 70-, and 90-meter altitudes.

50 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
1	0.3	-0.2	-2.9
2	1.7	1.5	-4.3
3	2.3	-3.5	-3.1
4	0.6	-3.4	-5.6
5	-	-	-
70 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
1	-1.1	-1.0	0.9
2	0.6	-0.8	1.4
3	2.7	0.0	-0.3
4	1.7	-1.4	0.5
5	-	-	-
90 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
1	1.2	15.1	-13.4
2	-7.0	13.9	-19.0
3	14.0	-25.0	-12.7
4	3.1	-33.2	-25.5
5	-	-	-

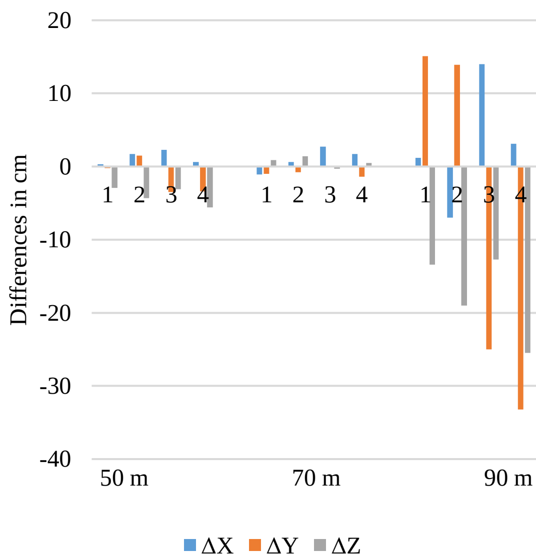
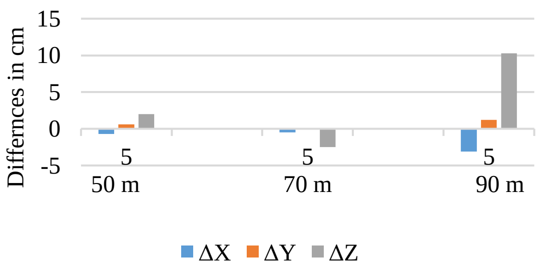


Table 6: The differences between using the PPK solution with the exterior GCPs from Emlid Studio with the 50-, 70-, and 90-meter altitudes. Points 1-4 all have a near-zero difference.

50 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
5	-0.7	0.6	2.0
70 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
5	-0.5	0.1	-2.5
90 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
5	-3.1	1.2	10.3



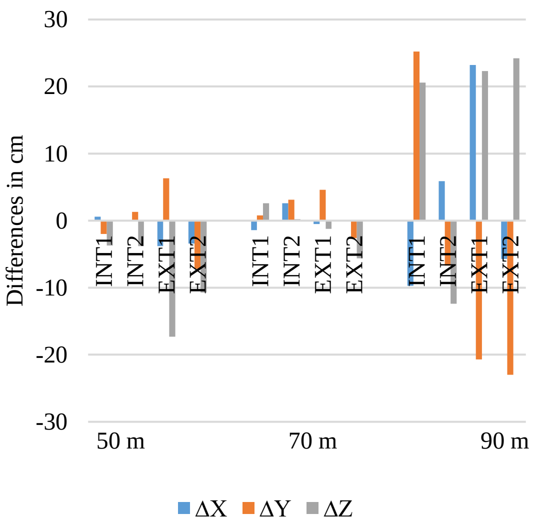
3.3 Third Scenario – No PPK corrections with all GCPs

Upon processing the three flights using just the GCPs, Table 7 shows the resulting differences between the 2 interpolation points and the two extrapolated points in comparison to the PPK-only solution.

As altitude increases, there is a noticeable decline in the quality, meaning the cm/pixel increases, and a corresponding increase in the differences in coordinates. At an altitude of 50 meters, interpolated points have an expected horizontal accuracy of about two centimeters and vertical accuracy of about four centimeters in relation to PPK corrections only, which meets surveying standards. However, extrapolated points from the control network exhibit larger differences, with a horizontal error of about 7 centimeters and vertical errors of up to 10-17 centimeters. Establishing a control network around the perimeter of the survey area is a standard practice in airborne mapping to maintain data accuracy. This ensures a robust network in areas with terrain variations and external factors that could impact the data. It is essential for creating reliable maps and models.

Table 7: Comparing the coordinates of the three flights using five GCP points in comparison to scenario 1 with PPK corrections only.

50 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
INT1	0.6	-2.0	-3.7
INT2	0.0	1.3	-3.8
EXT1	-3.8	6.3	-17.3
EXT2	-3.4	-7.2	-10.7
70 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
INT1	-1.4	0.8	2.6
INT2	2.6	3.1	0.2
EXT1	-0.5	4.6	-1.2
EXT2	-0.1	-2.6	-5.6
90 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
INT1	-9.7	25.2	20.6
INT2	5.9	-6.7	-12.4
EXT1	23.2	-20.7	22.3
EXT2	-5.7	-23.0	24.2



The results of the 70-meter flight showed that the differences between the extrapolated data and the actual data were slightly reduced, suggesting that there are benefits to increasing the altitude of the flight. One of the advantages of flying higher is that it allows for a larger area to be covered, which can lead to better overlap between images and more accurate results. However, it is important to note that densifying the flight lines can also achieve similar or better results at lower altitudes. Therefore, the choice of altitude should be based on careful consideration of factors such as the size and shape of the survey area, the required level of accuracy, and the available resources. However, errors in both interpolated and extrapolated areas persist. At 90 meters, the errors in both the interpolated and extrapolated areas exceed 20 centimeters, which raises significant concerns about accuracy. This pattern remains consistent throughout the experiment and with other scenarios, emphasizing the need for significantly more control at higher altitudes to maintain accuracy.

3.4 Fourth Scenario – All air and ground control

The final scenario shows the results of having both PPK corrections on UAS trajectories as well as influence from the GCPs. Table 8 shows the results of the differences between the same two interpolated and two extrapolated points between scenario one with just PPK corrections.

Table 8: Comparing the two interpolated and two extrapolated points' coordinates of the three flights using just PPK corrections in comparison to a PPK and 5 GCPs.

50 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
INT1	1.3	0.6	0.3
INT2	-0.7	1.3	0.0
EXT1	-5.3	3.1	-5.2
EXT2	-4.6	4.3	-6.8
70 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
INT1	1.2	0.1	0.0
INT2	-2.0	1.4	0.6
EXT1	-4.1	1.1	-6.3
EXT2	-3.3	-1.4	-5.7
90 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
INT1	3.7	-4.8	3.3
INT2	-6.5	2.9	4.0
EXT1	-8.6	10.6	-10.9
EXT2	-5.9	-12.0	-8.6

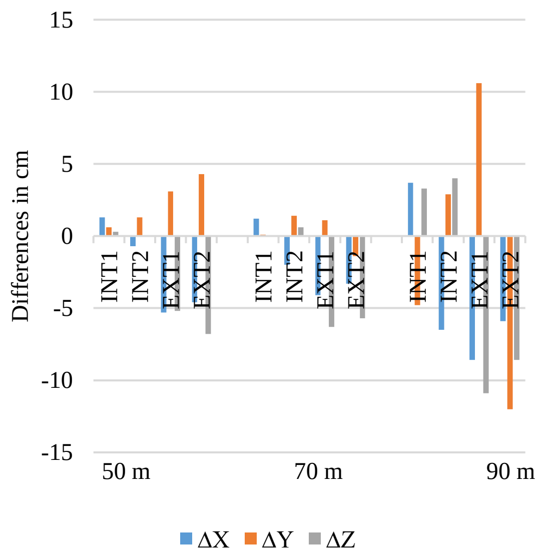
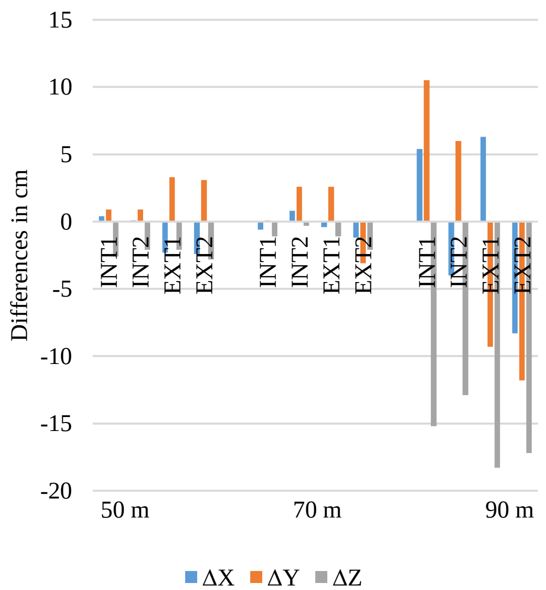


Table 9 shows the differences between the third simulated scenario using just the 5 GCPs and using a solution with both PPK and the 5 GCSs on the two interpolated and two extrapolated points.

Table 9: Comparing the two interpolated and two extrapolated points' coordinates of the three flights using just the solution with 5 GCPs in comparison to PPK and 5 GCPs.

50 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
INT1	0.4	0.9	-2.6
INT2	0.1	0.9	-2.1
EXT1	-2.3	3.3	-2.1
EXT2	-2.4	3.1	-2.8
70 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
INT1	-0.6	0.1	-1.1
INT2	0.8	2.6	-0.3
EXT1	-0.4	2.6	-1.1
EXT2	-1.2	-3.1	-2.1
90 meters	ΔX (cm)	ΔY (cm)	ΔZ (cm)
INT1	5.4	10.5	-15.2
INT2	-4.0	6.0	-12.9
EXT1	6.3	-9.3	-18.3
EXT2	-8.3	-11.8	-17.2



Upon analyzing the differences in coordinates between the various control types utilized in the experiment, it is evident that each has its strengths and weaknesses when it comes to improving the georeferencing of point cloud data. The results demonstrate that the lower altitude flights at 50-70 meters perform significantly better than flights at 90 meters, which consistently produced higher differences. PPK offers the advantage of higher accuracy outside of the control network, as all trajectories have corrected positions resulting in less variation in the extrapolated points compared to the GCP-only model. However, PPK struggles to maintain the correct elevation, as evidenced by the similar differences observed across all four points. This is where GCPs come into play, as the elevation differences across all the data sets drop significantly. Both control types play a critical role and serve different purposes in achieving the required accuracy of the project.

4. DISCUSSION AND CONCLUSION

The study aimed to compare the accuracy of using PPK corrections in UAS mapping while also incorporating GCPs into the solution and finding the strengths and weaknesses of both air and ground control. The study also aimed to generate varying GSDs using different altitudes for the UAS to find the optimal altitude to maintain efficiency without compromising accuracy. The trajectories of three flights at different altitudes (50, 70, and 90 meters) were compared using both Emlid Studio and Inertial Explorer, which showed very minimal differences between the two software. The differences in both horizontal and vertical positions were only a few millimeters, indicating agreement between the two software solutions.

It's clear to say that higher altitude flights compromise accuracy, as we demonstrated with the 90-meter flights. All the data shows the dependency that higher altitude flights have on both air and ground control to maintain accuracy in the project. Additionally, higher GSD values may diminish the resolution of the project and remove many important details. Altitudes of 50-70 meters show similar levels of accuracy regarding their GSD, but of course, the lower the GSD, the better the resolution of the imagery, and the more detail we can see. These findings are in line with what Liu claimed, suggesting lower altitude flights with lower GSD values to maintain the accuracy of the project when GCPs are limited.

Trajectory corrections with PPK are an excellent tool for any UAS mapping project. Using PPK on a UAS will provide acceptable accuracies in areas like along forest boundaries. This was demonstrated with the extrapolated points we compared differences to the outside of the GCP network. PPK did need help with elevation, as we saw a constant shift in the data sets with all the points in comparison to the GCP models.

Utilizing a reliable reference base helped alleviate errors in our initial starting point. This also ensures our corrections are referencing the correct geodetic position that our UAS and rover GNSS receiver are observing when collecting data. Had we similarly set a point using the rover GNSS receiver on network RTK, we would not be able to assess any errors with our corrections since our starting point has utilized the same method as our data collection. Having a reference point eliminates this problem.

To improve on this experiment, it would be wise to utilize network RTK and compare the results. Having another form of correction could be helpful in validating that our data is being measured correctly. It would also be wise to follow in Martínez-Carricondo's footsteps and have a second base station to compare two different PPK solutions from two locations. The corrections could also be run again on Inertial Explorer to see how every data set turns out. Having the initial test between Emlid Studio and Inertial Explorer was essential to test the consistency of Emlid Studio, but more testing could take place to ensure its reliability. One final improvement could be to test this experiment on a larger site and with more GCPs. While simulating the higher GSDs to test the accuracy of different regions of projects, having a project that is ten or even one hundred acres in size could really put these simulated scenarios to the test and see how the accuracies stack up.

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