Comparative Accuracy of GNSS, NTRIP, and Base Station UAV Surveys

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SUMMARY

Achieving accurate positioning data when UAV (Unmanned Aerial Vehicle) surveying can be challenging. While surveyors often plan carefully by controlling variables such as GSD (Ground Sampling Distance) and image overlap to achieve high quality outputs. The accuracy of the data also heavily depends on the baseline precision of the onboard GNSS (Global Navigation Satellite System) receiver. Typically, onboard GNSS can achieve in the range of 2-10m accuracy depending on survey conditions but when corrected with an RTK (Real Time Kinematic) connection, this can be reduced to centimetres. As the surveying industry increasingly adopts autonomous methods, this study aims to compare RTK corrected and standard GNSS with the sub-millimetre accuracy of traditional total stations, determining the suitability of UAVs for high-precision survey applications.

Data was collected using a DJI Mavic 3 Enterprise RTK at three UK sites with varying environmental challenges, such as limited satellite visibility and coastal weather. At each site, three flights were conducted using different positioning methods: standard onboard GNSS, a DJI D-RTK2 base station, and an NTRIP server providing RTK correction signals. The UAV was flown at an altitude to achieve a GSD of <10mm with the camera maintained at nadir. A fourth control site was also surveyed with a total station. Nine Ground Control Points (GCPs) were placed at varying elevations and measured for comparative analysis then coordinates from the UAV surveys were extracted and analysed against the control data to assess positional accuracy for distances between points.

Three methods for analysis were applied to assess positional accuracy across each dataset. First, raw EXIF data was extracted and exported to a CSV file to identify positional deviations among the positioning methods. Photogrammetry software then generated a 3D dense point cloud, which was analysed in specialised software to measure post-processed deviations along the X, Y, and Z axes. Finally, GCP's were extracted from the point cloud to compare inter-point distances with measurements calculated from total station data, providing an independent benchmark for accuracy assessment.

Results showed that all three positioning methods achieved point-to-point accuracies within 25mm. The on-site base station provided the most consistent accuracy, achieving <15mm, while the NTRIP connection demonstrated occasional accuracies below 10mm but with a mean error of <20mm, indicating variability in accuracy.

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1. INTRODUCTION

UAV (Unmanned Aerial Vehicle) use in surveying has grown significantly in recent years, partly attributed to the advancement of onboard remote sensors and GNSS (Global Navigation Satellite Systems) improvements within UAV systems. While standard GNSS can typically provide accuracies between 2-10m, applications such as topographical surveys and construction monitoring often require sub-centimetre accuracy to be considered valid. Increasingly UAV systems can integrate base station RTK (Real Time Kinematic) correction or NTRIP (Network Transport of RTCM via Internet Protocol) server connection, to enhance positional accuracy for such use cases.

Despite the extensive research conducted into conventional GNSS systems, the comparative accuracy of NTRIP and RTK base corrections when conducting UAV surveys remains insufficiently explored. As the UAV survey sector grows demanding higher precision and higher accuracies, identifying the capabilities and limitations of these systems has become paramount to its success. By providing data on their performance, surveyors and researchers alike will be able to make informed decisions and better tailor equipment to their needs.

Through various field experiments at rural, urban, and coastal sites, this study aims to evaluate the accuracy and precision of each standalone system and identify environmental factors to be considered in the future. Data was collected using a DJI Mavic 3 Enterprise and analysed in the pre and post processed phases. Further testing at a control site used GCPs (Ground Control Points) to determine positional precision and accuracy, when compared to a total station.

This research provides a detailed analysis of GNSS, NTRIP, and RTK base corrected positioning methods in the context of UAV-based surveying, offering practical insights into their accuracy and applicability under different conditions. Furthermore, the study will explore average positional errors when measuring between points for applications such as volumetrics, construction monitoring and topographical mapping. The paper is organized as follows: Section 2 describes the methodology, including site selection and data collection procedures, section 3 details how the data was presented, section 4 details the analysis of the results and finally section 5 concludes with implications for practice, limitations, and recommendations for future research.

2. METHODOLOGY

To maintain consistency, a DJI Mavic 3 Enterprise with an optional module that receives the corrections either by the onsite D-RTK2 base station or an NTRIP server via the internet was used. Both systems and standard GNSS were tested at each site excluding the first trip to the Pennines, where a base station was not available. Each system used the same flight plan to produce 3 identical surveys where positional accuracy can be compared.

2.1 Site Selection

Survey sites were carefully chosen to include a range of environmental conditions, such as low satellite visibility and varying altitudes, to evaluate their impact on GNSS performance. Additionally, all sites were required to comply with the CAA's open A2 category regulations. The following list summarises the selected sites and their key characteristics.

- Higher Shelf Stones, Pennines, Derbyshire (Low satellite coverage, rural site, low phone signal, high altitude).
- Chimney Bank, Rosedale Abbey, North Yorkshire (Rural site, abandoned structure, varying terrain, high altitude).
- Staithes Harbour Wall, Staithes, North Yorkshire (Coastal site, large structure, low altitude, low satellite visibility).
- University of Derby Kedleston Road Sports Field, Derby, Derbyshire (Urban site, flat terrain, high satellite visibility, control site)

The University of Derby Kedleston Road sports field was selected for the GCP comparison as multiple variables could be controlled. The pitch was constructed to be relatively flat (within construction tolerances), reducing elevation deviations when setting the targets on a 3x3 grid at 9m centres.

2.2 Flight Planning

Before conducting any surveys, each site was planned to ensure compliance with the CAA's open A2 category requirements. According to the requirements, a horizontal distance of 50m from uninvolved persons must be maintained during the flight. To ensure this distance, safety measures, including spotters and secure coned off areas to ensure were implemented throughout. The document also states a minimum distance of 150 meters from uninvolved buildings and roads should be maintained, which effected the urban sites of this study.

Due to the UAV's maximum safe operating wind speed of 12m/s and lack of an IP weather rating, a week was allocated to each site to improve the likelihood of favourable weather conditions to maximise chance of obtaining suitable data. Prior to arriving at each site, a UAV assist report from Altitude Angel was completed to identify any potential hazards, and to inform other pilots of flight times and locations. A flight log was then produced to store the flight data gathered by the UAV during each survey.

2.3 Data Collection

For each site the same photogrammetry parameters were utilised, such as an 80% horizontal and vertical image overlap to increase the number of common features during the photogrammetry process. GSD (Ground Sampling Distance) was also considered to maximise point density, however system limitations resulted in a maximum GSD of 4mm using a 12m AGL (Above Ground Level) altitude. Utilisation of these parameters for all sites resulted in a significant range in quantity of images (100-900 per site), creating a significant variance in processing time and computer power requirements.

Within the control survey for the sports field, all measurements from the total station were taken from an arbitrary location to calculate distances between points. The grid was divided into three elevations defined by manufactured box dimensions: ground level (0mm), 300mm and 700mm. Each target was then set out using intersections between pitch lines 9m apart. When the total station was levelled and set up, 3 sets of face left/right readings were taken for each target using a Leica mini prism on a bespoke 3D printed tripod as shown in figure 1.

Figure 1: 3D Printed Mini Prism Tripod

2.4 Post-Processing

The photogrammetry processing software used for this study was Pix4D Matic due to the simple user interface and reputation in the industry. This software offered the option to input other data into the photogrammetry processes, such as control point coordinates, however for this study this was excluded to analyse the positioning systems alone. The workflow produced a dense point cloud (figure 2), an Orthomosaic (figure 3) and a quality report detailing the number of image matches, altitude deviations and camera parameters. The dense point cloud is the primary output, used for cloud-to-cloud analysis and extraction of GCP coordinates from the Sports Field.

Figure 2: Chimney Bank dense point cloud

The photogrammetry process interpolates information from the data, resulting in an estimation of point coordinates based on the mean values for X, Y, and Z. To identify where this differs from the raw images EXIF data was extracted from Pix4D Discovery to a text file and imported into an Excel document for each site. As each survey used the same flight plan, each coordinate set should have a corresponding set in the other two surveys that is comparable to identify deviations in the raw data.

Figure 3: Chimney Bank orthomosaic

3. DATA PRESENTATION

The data for this study was presented in three different ways from raw to post-processed data. Firstly, extracted EXIF data was refined to investigate the UAV's positional accuracy. Secondly, point cloud was analysed in Leica Cyclone 3DR, to identify deviations before and after the photogrammetry process. Lastly, deviations in GCP coordinates of final models were utilised to compare the precision of the UAV with the total station.

3.1 Exif Data

The EXIF data extracted from each image set was exported as latitude, longitude (decimal degrees) and altitude (metres) referencing the WGS 84 coordinate system. To convert the latitude and longitude into a suitable comparable format, an Excel macro was programmed, which used the UTM offset, UTM scale, and Earth diameter to produce easting and northing coordinates as shown in table 1. Due to breaks in the flight plan caused by onsite interruptions, duplicated image data needed to be removed prior to any analysis.

Table 1 EXIF Data Example

Image ID	Lattitude	Longitude	Altitude	Easting	Northing
DJI_20240302145943_0001_V.JPG	52.93810219	-1.496242556	191.523	6290685.363	299833784.660
DJI_20240302145949_0002_V.JPG	52.93802911	-1.496091833	191.564	6290677.230	299833801.403
DJI_20240302145955_0003_V.JPG	52.93794464	-1.495918556	191.577	6290667.831	299833820.652
DJI_20240302150000_0004_V.JPG	52.93786092	-1.495746028	191.579	6290658.515	299833839.818
DJI_20240302150006_0005_V.JPG	52.93777989	-1.495579306	191.528	6290649.498	299833858.339

Additional sheets were created to then compare the differences between each positioning system, for example GNSS and NTRIP. Positional deviations were calculated for each image and graphed to identify any patterns or anomalies across the sites. Additionally, 3 tables were created to calculate mean averages and upper/lower boundaries. Averages were taken as absolute values to avoid negative/positive deviations cancelling each other out. As the UAV's height should have been constant throughout the flight, mean averages and ranges were calculated to identify how precise each system estimates altitude. 1σ STD were taken on all calculations to further identify and remove anomalies from the data.

3.2 Point Cloud Comparison

Cloud Compare was originally selected to refine and analyse the post-processed point cloud, as it is open source, however due to the large data sets, this was not feasible. Leica Cyclone 3DR was subsequently selected and allowed all 3-point clouds from a site to be refined and analysed in one file. Prior to analysis the point cloud was cleaned of noise and cropped to the area of interest, followed by a surface analysis producing a heat map of each survey. This displayed altitude estimations comparable to the EXIF data allowing for identification of changes between processed and raw data.

The primary focus of this analysis is the cloud-cloud comparison function, which measures distances between identical points and produces a normal distribution graph of the deviations. To refine the display of the graph, upper and lower boundaries were reduced to 95% of the data to remove miscalculations. To maintain consistency with the EXIF data, the analysis was run in the X, Y, and Z planes producing 3 different heat maps for each survey pair as shown in figure 4. Each heat map produced for the site was compiled into a detailed report in the inbuilt editor and exported for further analysis.

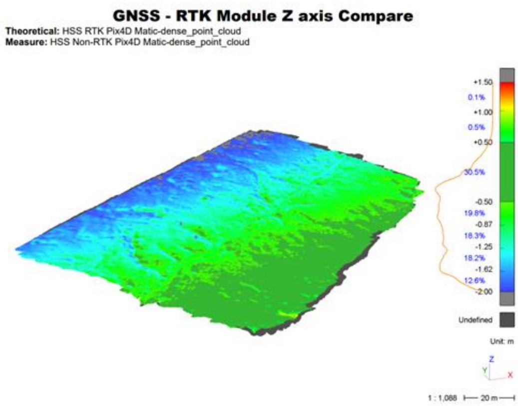

Figure 4:Cloud – Cloud Analysis

3.3 Ground Control Point Comparative

Measurements recorded by the total station were formatted as Vertical and horizontal angles and vertical distance in the DMS (degrees, minutes, and seconds) and metres formats respectively. Each angle was converted to decimal degrees and a mean average was taken of all face left and right observations. The total station was then assigned the arbitrary coordinates (100, 200, 10) and X, Y, and Z values were calculated for each of the targets and subsequent distances were calculated between each of the points ready for comparison.

To calculate the distances between the UAV's targets, the point cloud produced in Pix4D was converted to a 3D mesh during the point cloud analysis phase. Using the label function in the software, coordinates were extracted from the center of each target in the model visible in figure

5. The coordinates were then entered into the Excel document to their respective names and distances between points were calculated.

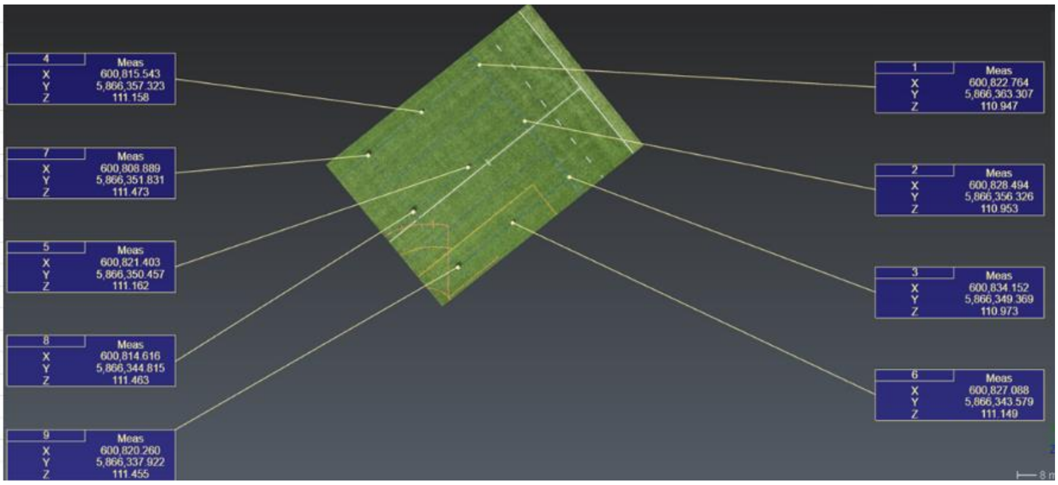

Figure 5: GCP Coordinate Extraction

Distances between each GCP were categorized based on direction defined by the UAV's flight plan and distance calculated from the theoretical 9x9m grid. Using the total station data as the baseline, each positioning system was compared to determine deviations across each measurement. Mean and 1σ STD averages were taken for each parameter followed by each systems full data set. Each step was separated into different tables and were used to identify any significant fluctuations or consistencies between each of the surveys.

4. ANALYSIS OF RESULTS

This analysis aims to identify the accuracy of each positioning system and what factors may impact the results. The image EXIF data has been compared at each site to determine deviations between the raw positioning data and identify environmental factors affecting the data. The point clouds have then been analysed to compare raw and processed data and assess the interpolation of the photogrammetry software. Finally, the GCP coordinates have been compared to a total station to indicate the positional accuracy of each system between two points.

4.1 Exif Data

As the same flight plan was used for each site, altitude should have remained consistent and comparable between each survey. In table 2, the range of altitude measurements were calculated. Both the NTRIP and RTK Base station remained in the range of <250mm whilst GNSS varied depending on the site conditions. Higher Shelf Stones produced the first anomaly found in the data, where the GNSS and NTRIP data sets estimated in a range of approximately 4.8m. When compared to the second visit, the data implies that the NTRIP connection was inconsistent causing the UAV to resort back to standard GNSS, likely caused by the poor phone signal in the area.

Table 2 EXIF Altitude Ranges

Location	GNSS Altitude Range (m)	NTRIP Altitude Range (m)	RTK Altitude Range (m)
Higher Shelf Stones (Nov)	4.834	4.855	N/A
Higher Shelf Stones (April)	3.795	0.233	0.232
Chimney Bank	2.382	0.113	0.203
Staithes Harbour Wall	1.810	0.166	0.200
Sports Field	0.269	0.068	0.187
Mean Average	3.205	0.145	0.205

Staithes Harbor Wall produced another anomaly, where GNSS significantly underestimated altitude compared to the two RTK systems. Unlike Higher Shelf Stones, the area had sufficient satellite coverage, but cliffs bordered all edges of the site excluding the East limiting view of the visible hemisphere. This obstruction will have reduced the number of visible satellites and as the data indicates, impacted standard GNSS positional accuracy.

Table 3 shows that the University Sports Field produced the smallest deviations and 1σ STD compared to the other sites, achieving <500mm and <200mm respectively. The site was much smaller than the others and the UAV was flown at a lower altitude likely contributing to the closer data range. The April visit to Higher Shelf Stones and Chimney Bank shows similar deviations across each metric and were surveyed under similar conditions suggesting a better representation of each system's precision. However, the Sports Field does show the only large altitude discrepancy between NTRIP and the RTK, where NTRIP estimated closer to standard GNSS. Since this is the only urban site, the data would suggest possible interference with the NTRIP connection, limiting correction data.

Tabel 3 Positional deviation analysis

GNSS - NTRIP						
Location	Mean X Deviation	X 1σ STD	Mean Y Deviation	Y 1σ STD	Mean Z Deviation	Z 1σ STD
Higher Shelf Stones (Nov)	1.332	0.976	0.997	0.837	1.830	1.364
Higher Shelf Stones (April)	0.500	0.300	0.384	0.299	0.951	0.575
Chimney Bank	0.997	0.554	0.398	0.379	0.933	0.333
Staithes Harbour Wall	0.544	0.520	1.221	1.019	5.163	0.434
Sports Field	0.223	0.094	0.379	0.158	0.060	0.041
Mean Average	0.719	0.489	0.676	0.538	1.788	0.549
GNSS - RTK Base						
Location	Mean X Deviation	X 1σ STD	Mean Y Deviation	Y 1σ STD	Mean Z Deviation	Z 1σ STD
Higher Shelf Stones (Nov)	N/A	N/A	N/A	N/A	N/A	N/A
Higher Shelf Stones (April)	0.848	0.774	0.715	0.677	0.952	0.360
Chimney Bank	0.774	0.774	0.396	0.677	0.879	0.360
Staithes Harbour Wall	0.326	0.329	0.792	0.589	5.075	0.427
Sports Field	0.298	0.185	0.355	0.267	1.336	0.092
Mean Average	0.562	0.515	0.564	0.552	2.060	0.310
NTRIP - RTK Base						
Location	Mean X Deviation	X 1σ STD	Mean Y Deviation	Y 1σ STD	Mean Z Deviation	Z 1σ STD
Higher Shelf Stones (Nov)	N/A	N/A	N/A	N/A	N/A	N/A
Higher Shelf Stones (April)	0.799	0.474	0.593	0.368	0.048	0.033
Chimney Bank	0.501	0.316	0.176	0.146	0.063	0.027
Staithes Harbour Wall	0.350	0.237	1.029	0.757	0.092	0.046
Sports Field	0.184	0.133	0.610	0.263	1.346	0.040
Mean Average	0.459	0.290	0.602	0.383	0.387	0.036

For each system, each image comparison was graphed chronologically in the X, Y, and Z planes. Across the study, a correlation between a shift in positive/negative in the X and Y and the flight path of the UAV was identified. Each two images viewed at the data spike occurred when the UAV changed direction. An example can be seen in figure 6 from Chimney Bank where both X and Y drastically shift every 25 images coordinating with the UAVs turn. As this is consistent across all sites, it is likely that the phenomenon occurs due to inconsistent turns from the UAV and possible weather conditions at sites where this is exaggerated.

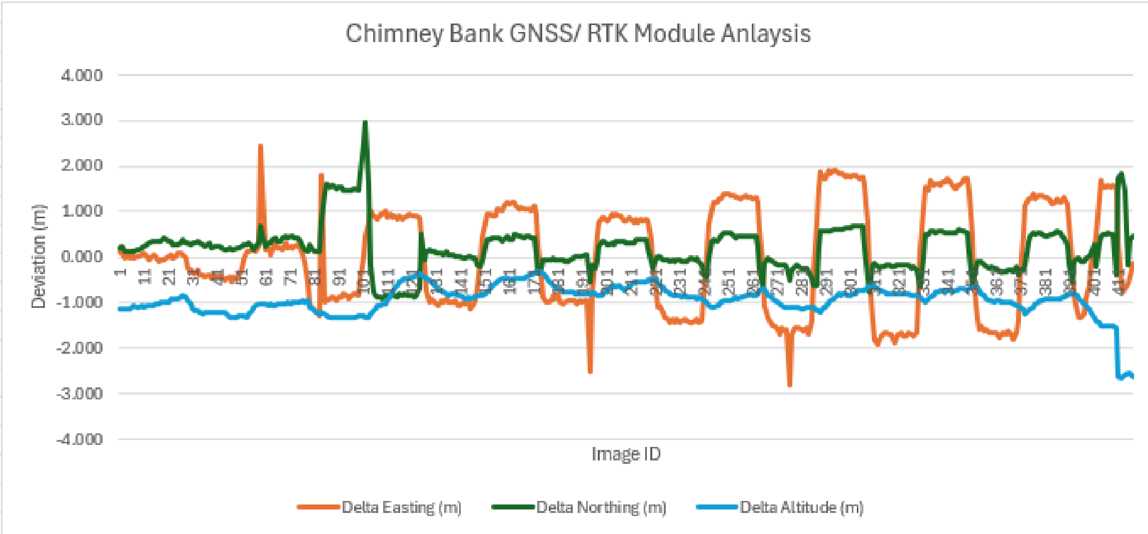

Figure 6: Chimney Bank GNSS/RTK deviation chart

4.2 Point Cloud Comparison

Compared to the EXIF data X and Y deviations, the point cloud analysis reports detail lower distances between points than calculated between two images, such as Higher Shelf Stones GNSS/NTRIP mean average deviations for X and Y were 500mm and 384mm respectively. The cloud comparison however, reported 90% of distances between points were within ±100mm where errors were evenly distributed across the positive and negative axis. Although Pix4D does shift internal camera positions, the photogrammetry reports detail minimal X/Y movement further suggesting that the deviations found in the raw data stem from the inconsistent turning circle of the UAV.

The distances calculated in the Z axis are also significantly reduced when compared to the raw data. Using Chimney Bank as an example, the mean average Z EXIF deviation between GNSS and NTRIP was 933mm but in the Leica Cyclone report 70% of the distances are within ±50mm. The photogrammetry reports for elevation detail greater movement in the internal camera positions causing this shift in position. Furthermore, the analysis report in figure 7 shows most large deviations occur when there are changes in elevation or terrain. This could suggest that due to the Nadir position of the camera inclines are difficult for the software to interpret.

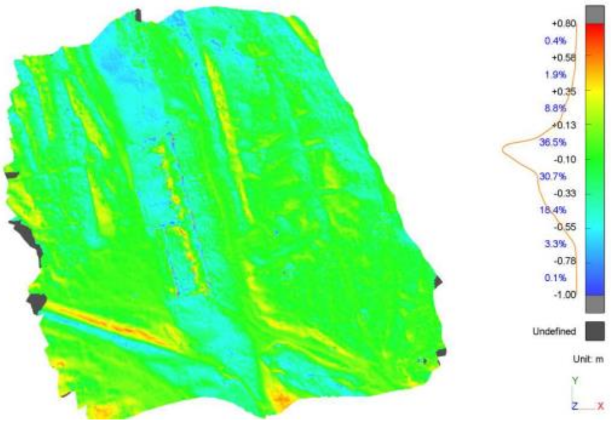

Figure 7: Chimney Bank GNSS/NTRIP point cloud analysis

Both Staithes and the first survey of Higher Shelf Stones sites encountered issues during the processing of the point cloud analysis. Surface elevation and Z comparison were successfully produced detailing the level difference of each model, but the X and Y analysis failed to identify >90% of the distances between common points. The reports indicate that models horizontally separated >1m apart cannot analysed due to overlapping similar points unless there is a key feature to reference such as the harbor wall edge. In the Z analysis, they were also the only 2 sites, which didn't produce deviations within ±100mm ranging as high as 3.5m. This difference between the raw and processed data is consistent across sites indicating Pix4D can move internal cameras estimations up to 1m depending on the range of the data.

4.3 Ground Control Point Comparative

The Topcon Monitoring Station chosen for this study is a 0.5" accurate machine capable of achieving <1mm accuracy between two points. To produce accurate baseline data, each GCP was measured 6 times recording the Horizontal/Vertical angles and the vertical distance from the total station. Ranges were calculated for the observations, achieving <1mm for distances and an average of 7" for angular measurements. Due to the incline on the pitch, the measured elevation differences between rows were approximately 100-200mm less than anticipated, where the second and third row were 210mm and 520mm AGL respectively.

GCP coordinate extraction had minor limitations, due to the detail of the processed point cloud. Three metal targets were used and as shown in figure 8, sunlight reflected of the surface making it difficult to identify the crosshair. Centre lines were drawn in the model for each poor target and coordinates were extracted from the intersection. Despite addressing this issue, the largest X/Y error of 29mm occurred in this row therefore an alternative should be used to mitigate this in the future.

Figure 8: Refelected GCP

GNSS, NTRIP, and RTK base systems produced maximum errors of 45mm, 25mm and 23mm respectively. Both RTK and NTRIP errors were produced from the reflective targets in the X/Y plane suggesting they were anomalies however GNSS were found in Z implying this is a system positional error. Below in table 4 are the mean averages and standard deviations taken in each direction and theoretical grid distance. After analysing each target individually, errors >35mm occur when distances have been measured from target A1 compounding to 45mm at 25m suggesting the altitude of the target was processed incorrectly.

Tabel 4 UAV GCP positional errors

GNSS - TS						RTK Module - TS						RTK Base Station - TS					
Direction	Distance	Variable	VD	HD	SD	Direction	Distance	Variable	VD	HD	SD	Direction	Distance	Variable	VD	HD	SD
Vertical	9	Mean Averag	0.011	0.011	0.011	Vertical	9	Mean Average	0.005	0.009	0.009	Vertical	9	Mean Average	0.007	0.003	0.003
		1σ STD (68%)	0.015	0.006	0.006			1σ STD (68%)	0.005	0.005	0.005			1σ STD (68%)	0.005	0.002	0.003
	18	Mean Averag	0.020	0.012	0.013		18	Mean Average	0.006	0.017	0.017		18	Mean Average	0.015	0.005	0.006
		1σ STD (68%)	0.016	0.010	0.011			1σ STD (68%)	0.001	0.006	0.006			1σ STD (68%)	0.005	0.001	0.001
	Combined	Mean Averag	0.014	0.011	0.011		Combined	Mean Average	0.005	0.011	0.011		Combined	Mean Average	0.010	0.004	0.004
		1σ STD (68%)	0.016	0.008	0.008			1σ STD (68%)	0.004	0.006	0.006			1σ STD (68%)	0.006	0.002	0.002
Horizontal	9	Mean Averag	0.003	0.009	0.009	Horizontal	9	Mean Average	0.003	0.008	0.008	Horizontal	9	Mean Average	0.004	0.009	0.009
		1σ STD (68%)	0.003	0.009	0.009			1σ STD (68%)	0.004	0.005	0.005			1σ STD (68%)	0.004	0.007	0.007
	18	Mean Averag	0.007	0.011	0.011		18	Mean Average	0.007	0.012	0.012		18	Mean Average	0.006	0.012	0.012
		1σ STD (68%)	0.004	0.008	0.008			1σ STD (68%)	0.007	0.006	0.006			1σ STD (68%)	0.002	0.004	0.004
	Combined	Mean Averag	0.004	0.010	0.010		Combined	Mean Average	0.005	0.009	0.009		Combined	Mean Average	0.005	0.010	0.010
		1σ STD (68%)	0.004	0.009	0.009			1σ STD (68%)	0.005	0.006	0.006			1σ STD (68%)	0.003	0.006	0.006
Diaganol	12.72	Mean Averag	0.009	0.014	0.014	Diaganol	12.72	Mean Average	0.005	0.010	0.010	Diaganol	12.72	Mean Average	0.009	0.007	0.007
		1σ STD (68%)	0.012	0.008	0.008			1σ STD (68%)	0.004	0.003	0.003			1σ STD (68%)	0.005	0.003	0.003
	25.46	Mean Averag	0.023	0.008	0.009		25.46	Mean Average	0.010	0.021	0.021		25.46	Mean Average	0.013	0.011	0.011
		1σ STD (68%)	0.022	0.002	0.001			1σ STD (68%)	0.002	0.004	0.004			1σ STD (68%)	0.002	0.004	0.004
	Combined	Mean Averag	0.012	0.013	0.013		Combined	Mean Average	0.006	0.012	0.012		Combined	Mean Average	0.010	0.008	0.008
		1σ STD (68%)	0.016	0.008	0.008			1σ STD (68%)	0.005	0.006	0.006			1σ STD (68%)	0.005	0.004	0.004
Combined	Varies	Mean Averag	0.010	0.011	0.011	Combined	Varies	Mean Average	0.005	0.011	0.011	Combined	Varies	Mean Average	0.008	0.007	0.007
		1σ STD (68%)	0.014	0.008	0.008			1σ STD (68%)	0.005	0.006	0.006			1σ STD (68%)	0.005	0.005	0.005
		1σ STD LB	-0.003	0.003	0.003			1σ STD LB	0.001	0.005	0.005			1σ STD LB	0.003	0.002	0.002
		1σ STD UB	0.024	0.019	0.020			1σ STD UB	0.010	0.017	0.017			1σ STD LB	0.013	0.012	0.012

In table 4, there is a clear correlation between the distance between points and the accuracy of the measurement. Mean averages typically have minor differences but when comparing the 1σ STD between 9m and 18m, values often double resulting in a greater range. To achieve a low GSD for mm accurate comparisons, the UAV was flown at a low altitude restricting the number of targets in an image to two. This requires further interpolation for greater distances in the processing phase, increasing the margin of error. Errors are also reduced in the horizontal direction, which the UAV flew parallel to, suggesting better image overlap across points in this direction.

All three positioning systems can produce a mean average of ±15mm between two points when compared to a total station however after considering 1σ STD and Upper/Lower bounds, the RTK base system is the most accurate. The onsite base station successfully achieved a mean average of <10mm and <5mm 1σ STD resulting in an accuracy of <15mm across a minimum of 68% of the measurements. Due to poor Z positioning, GNSS is capable of <25mm, which is reduced to <20mm in X and Y. Although NTRIP is occasionally more precise, such as the vertical 9m mean average of ±3mm, the lack of consistency indicates an intermittent connection with the server. This would further suggest that with a strong connection, an NTRIP connection could have greater precision due to the base station's extended positional refinement.

5. CONCLUSIONS

This study aimed to provide an in-depth analysis of GNSS, NTRIP, and RTK base station positional accuracy across various environments. The results demonstrate that while all three systems can achieve a mean average of ±15mm precision between two points, the RTK base further reduces this to ±10mm with an upper bound of ±15mm, outperforming both other systems in precision and reliability. The NTRIP server did produce the smallest isolated mean error of ±3mm at the shortest distance but the lack of consistency heavily impacts the performance especially in challenging environments. Regardless of the location, the study further demonstrates that the use of a an RTK system will significantly improve the accuracy of the survey where altitude estimation ranges reduce from an average >3m to <250mm, reducing errors in the photogrammetry process.

Despite providing valuable data, limitations were identified in the study that should be addressed for future research. The absence of a traditionally surveyed data set creates potential uncertainty as there is no baseline data for validation. As expressed in the analysis, the quality of the onboard camera restricted GSD and affected the detail of the models. Furthermore, the limited time available for the RTK base to refine its position could have impacted the accuracy of the correction data.

To address the limitations and build upon the findings of this study, future research should include an additional site with a geodetic control network. The area can then be topographically surveyed or ideally LiDAR scanned to provide a baseline data set. GCP targets should also be evenly distributed around the site to further analyse distances between points. Using a UAV with a larger sensor could also reduce the GSD of the surveys and improve the detail of the models. Additionally, including PPK (Post Processed Kinematic) could further identify factors effecting the connection between the base and rover.

Overall, this research paper demonstrates the growing potential of RTK technology when conducting high precision aerial surveys. By identifying factors effecting performance, limitations and overall accuracies of each system, researchers and surveyors have an improved understanding when tailoring their equipment to specific tasks.

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