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The Analysis of GCP Correction Toward GNSS-PPK for Land Registration Base-map in Muktisari Village, Cipaku District, Ciamis Regency

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Abstrak

Persyaratan utama program Pendaftaran Tanah Sistematis Lengkap (PTSL) adalah peta dasar registrasi tanah skala 1:1000 dengan akurasi *horizontal* (CE90) kelas 1 sebesar 0,3 meter. *Global Navigation Satellite System – Post Processing Kinematic* (GNSS-PPK) dianggap memberikan akurasi yang baik tanpa koreksi GCP, karena itu dapat mengurangi biaya dan waktu akuisisi data. GNSS-PPK tanpa koreksi GCP dianggap akurat di daerah dengan elevasi <500 meter. Penelitian ini bertujuan mengetahui pentingnya koreksi GCP pada proses *Post Processing Kinematic* (PPK). Akurasi foto udara menggunakan GNSS-PPK dengan dan tanpa koreksi GCP akan dianalisis di daerah dengan ketinggian 200 – 430 meter. Data yang diperlukan dalam studi ini adalah foto udara, koordinat dalam file RINEX, Digital Terrain Model (DTM), dan 8 titik GCP. Koordinat dihitung menggunakan metode PPK kemudian digunakan untuk koreksi foto. Foto-foto kemudian diproses dengan dan tanpa koreksi GCP. Pengolahan data tanpa koreksi GCP memiliki deviasi yang lebih besar dibandingkan dengan data yang diproses dengan koreksi GCP dan tidak memenuhi ketentuan CE90. Perhitungan korelasi menunjukkan bahwa akurasi memiliki korelasi negatif terhadap elevasi sebesar -0,041 tanpa GCP dan sebesar -0,76 dengan GCP. Studi ini membuktikan bahwa metode GNSS-PPK masih memerlukan GCP dan tidak terbukti bahwa deviasi pada data tanpa koreksi GCP memiliki korelasi berbanding lurus dengan elevasi.

Kata kunci: Fotogrametri, GNSS-PPK, Ground Control Point, Peta Dasar

Abstract

The Comprehensive Systematic Land Registration Program (PTSL) main requirement is land registration map in a scale of 1:1000 and horizontal accuracy (CE90) class 1 of 0,3 meters. Global Navigation Satellite System – Post Processing Kinematic (GNSS-PPK) provides good accuracy without Ground Control Point (GCP) correction, thus reducing cost and data acquisition time. GNSS-PPK without GCP correction is considered accurate in areas <500 meters elevation. This research aims to determine the GCP correction importance for photo accuracy in PPK process. This study analyzes aerial photo accuracy with and without GCP correction in areas with elevations from 200 to 430 meters. The data required are aerial photos, coordinates in RINEX files, Digital Terrain Model (DTM), and 8 GCP points. Coordinate files are calculated using the PPK method then used for photo correction. Photos are processed with and without GCP correction. Photo without GCP correction has a significant deviation than photo with GCP correction and does not meet the CE90 requirements. The accuracy has a negative correlation with an elevation of -0,041 without GCP and -0,76 with GCP. This study proves that GNSS-PPK method still requires GCP and it is not proven deviation in data without the GCP correction is directly proportional to elevation.

Keywords: GNSS-PPK, Ground Control Point, Basemap, Photogrammetry

1. Pendahuluan

UAV (Unmanned Aerial Vehicle) is broadly applied as a photogrammetric measurement tool. The aircraft is equipped with a global navigation satellite system (GNSS) receiver and some sensors allowing autonomous navigation along the flight path plan, and enabling the user to product accuracy estimation (Eker et al, 2021). UAVs can be designated by their taking-off/landing structure and type. In this study, we used a Vertical Taking-off and Landing (VTOL) UAV which is categorized as a vertical starting system UAV (Siebert et al., 2014). UAVs photogrammetry is based on high-resolution overlapped photos to generate digital elevation models (DEMs) and orthophotos using structure-from-motion (SfM). SfM is a method to generate three-dimensional model topography by overlapping 2D photos acquired from many areas and orientations (Eker et al, 2021). Mapping with UAVs has become one solution for mapping diverse terrain in Indonesia. This mapping technology has evolved from large, expensive manned aircraft platforms to very small and affordable UAVs. It is a reliable alternative for producing high-

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resolution digital aerial photo-based maps that can combine terrestrial mapping methods, are cost-efficient, and are easy to implement (Junarto et al., 2020).

The use of well-rectified maps facilitates the implementation of land boundary delineation (Junarto et al., 2020). Error in land registration can have long-term impacts, such as land disputes arising from discrepancies between digital data and on-site conditions. An error of just one meter can lead to issues in identifying land ownership. Remote sensing photos generated from satellites or aircraft are geometrically distorted due to platform movement. The aircraft movement is credited by local atmospheric disturbances. Therefore, a geometric correction is required. The geometric correction can be done by GNSS-tagged imagery or by utilizing ground control points (GCPs) (De Leeuw., 1988; Tomastik et al., 2019). UAV-based photogrammetry georeferencing is mostly executed using GCPs. GCPs are visible location points in the photos and the coordinates are known. GCPs georeferencing has proven to achieve high accuracy in high-resolution photos (James et al., 2017). The use of GCPs can provide reliable positioning. The GCPs are used to judge the correction function (Konecny, 1976). However, GCP number and spatial distribution can influence model accuracy, more GCP leads to a smaller residual (Zhang et al., 2019; De Leeuw., 1988). The GCPs selection must be accomplished precisely. The GCPs must be assigned evenly over the location of the photo (De Leeuw., 1988). GCPs are mostly measured using the real-time kinematic (RTK) method, tied to the nearby base station, or with Continuously Operating Reference Station (CORS) differential correction. These methods accuracy are 1-2 cm in horizontally and 2-3 cm vertically.

The previous research conducted by Junarto et al (2020) implemented GCP to create well-rectified maps facility for PTSL (land registration) program. Research conducted by Mian et al (2015) using a single GCP to generate an orthophoto. The accuracy achieved from the flight was 5 centimeters RMS horizontal for the ortho products, 3 centimeters RMS horizontal, and 11 centimeters RMS vertical for stereo products, using single GCP, image end-lap, and side-lap of 60% and 40% respectively, and one cross strip (Mian et al., 2015). Another previous research conducted by Eker et al (2021) estimated the UAV RTK/PPK accuracy procedure for mapping different surfaces, the RTK/PPK accuracy procedure without GCPs, and determined whether the GCPs application is still required for accuracy improvement. Based on this research, it was found that PPK-GNSS provides good accuracy in camera location and the GCPs application in the photo-alignment and optimization procedure did not have a significant impact on computed camera location error level. The PPK procedure gave the best result compared to other methods discussed in this study. Elevation has an essential effect on accuracy. The accuracy level decreases in the location of more than 500 m. Dinkov et al (2020) also used PPK for accurate georeferencing photos gained by UAVs. This study was conducted in urban conditions. The results were gained in centimeters accuracy without any GCPs at the scale of 1:1000 orthophoto and 1:5000 digital elevation.

Therefore research aims to analyze the influence of GCPs on a GNSS-PPK photogrammetry of an area with an altitude of less than 500 meters. This research is a further study from previous research conducted by Wijayanti et al (2023). The study is in Muktisari Village, Cipaku District, Ciamis Regency, West Java, Indonesia with an altitude of 200 – 430 meters. The research will analyze whether or not the GCP correction is essential for the GNSS-PPK method photogrammetry to fulfill the Indonesia land registration base map regulation using a statistical method that has never been researched before.

2. Method

A huge number of GCPs are mostly used in the conventional method. Unlike the conventional method, direct georeferencing is the airborne mapping sensor's direct measurement therefore each pixel can be georeferenced to the earth's surface without any ground information acquired on the field (Dinkov et al., 2020). It can be done by employing data collected by GNSS integrated with inertial sensor measurements attached to the mapping sensor (Eker et al., 2021). Mian et al (2015) proved that direct georeferencing allows the production of accurate map from UAV photos using a single GCP and with minimum overlap and side lap; it also shrinks time required. In RTK mode, the camera position is determined with the accuracy of centimeters in real-time during the flight. In PPK mode, as an alternative of RTK, all correction calculations are done post-flight (Eker et al, 2021). The GNSS observation datas are stored in a log file in RINEX (Receiver Independent Exchange) extension (Taddia et al., 2020). The idea of using RTK/PPK methods in UAV photogrammetry is to minimize the GCPs needed (Eker et al, 2021). Therefore, this method can conduct less field activity and georeferencing cost, time and resources saving due to GCPs needed. Direct georeferencing is suitable in which it is not possible to measure any GCP. This method eliminates the GCP needed by enabling high-resolution photos to be generated. The prime feebleness is the systematic errors and accuracy height, which can be solved by applying 1 to 3 GCPs (Dinkov et al, 2020).

The RMSE value can be used to establish an objective criterion to compare the relative accuracy between different photogrammetric projects (Carvajal-Ramirez, 2016). The root means square of planimetric information can be calculated using the formula (Dinkov et al., 2020; Carvajal-Ramirez, 2016):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \Delta x_1^2}{n}} \quad (1)$$

Where Δx is the gap between reference coordinates and the coordinates generated from the remote sensing data and n is the number of GCPs.

The aerial photography was acquired on December 14, 2022, with a mean altitude of ±244 meters over 9.46 km^2 using a Fixed-Wing Vertical Take-off Landing (VTOL) UAV model equipped with a Sony ILCE-6000 camera with a maximum resolution of 6000 x 4000 and effective pixel of 24 megapixels. Rotary-winged (familiar as multi-copter or VTOL – Vertical Take-off & Landing) UAVs tend to be developed for shorter flight times, lower altitude operation, and small surveys area (Eker et al, 2021). The VTOL was equipped with GNSS-PPK referred to as Continuously Operating Reference Station (CORS) at 7º15'48.7274" S and 108º21'51.6431" E in elevation of 339.3152 meters an antenna height of 0.09 m. The flight was done three times to cover 800 Ha (±25 minutes for each flight).

Figure 1. VTOL UAV

Indirect geo-referencing involves measuring visible reference targets placed on the ground in the area of interest before flight. If these targets are absent, fixed environment features like manhole covers or road markings can serve the same purpose. These reference points require surveying through methods like differential GPS or tachymetry. During data processing, manual identification of reference points in the software's model is necessary. Measured target coordinates are then aligned with the model, and a spatial transformation geo-references the entire model. A minimum of three reference points is required, though using more is recommended (Siebert et al., 2014). Eight GCPs are evenly distributed over the study area. The GCPs were further used to perform geometric correction.

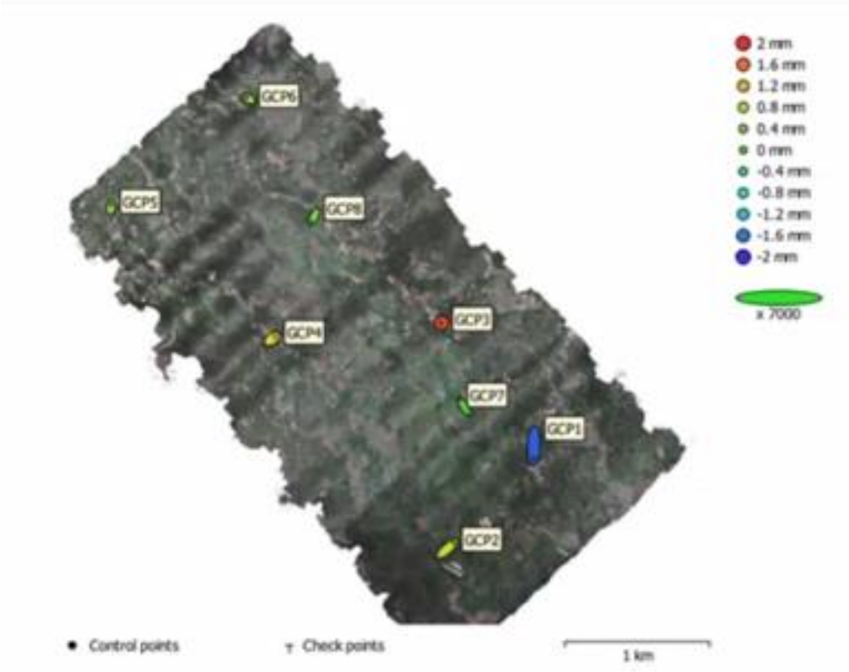

Figure 2. The GCPs Location

Table 1. GCPs Location

Name	Northing	Easting	Elevation (mdpl)
GCP1	9195501	209567	285.730
GCP2	9194913	209016	251.091
GCP4	9196341	207780	368.031
GCP5	9197253	206647	407.240
GCP6	9197996	207582	412.143
GCP8	9197136	208031	388.616
GCP3	9196437	208927	359.251
GCP7	9195907	209058	332.278

This research ignores the vertical accuracy due to Indonesia land registration base map regulation which is highly concerned with horizontal accuracy. The horizontal accuracy was calculated twice with and without the GCPs correction and then plotted in Table 2 to determine whether or not the product fulfills the Indonesia land registration base map regulation.

Table 2. Accuracy Assessment

No	Scale	Contour Interval (m)	RBI Map Accuracy					
			Class 1		Class 2		Class 3	
			Horizontal (CE90 in m)	Vertical (LE90 in m)	Horizontal (CE90 in m)	Vertical (LE90 in m)	Horizontal (CE90 in m)	Vertical (LE90 in m)
1	1:1.000.000	400	300	200	600	300	900	400
2	1:500.000	200	150	100	300	150	450	200
3	1:250.000	100	75	50	150	75	225	100
4	1:100.000	40	30	20	60	30	90	40
5	1:50.000	20	15	10	30	15	45	20
6	1:25.000	10	7,5	5	15	7,5	22,5	10
7	1:10.000	4	3	2	6	3	9	4
8	1:5.000	2	1,5	1	3	1,5	4,5	2
9	1:2.500	1	0,75	0,5	1,5	0,75	2,3	1
10	1:1.000	0,4	0,3	0,2	0,6	0,3	0,9	0,4

The coordinate generated from this data acquisition is in the form of a Receiver Independent Exchange Format (RINEX) file. The coordinate file was then computed using Emlid Studio software to generate the coordinates recorded from the GNSS. The coordinates are then attached to the photo file using Agisoft Metashape software then the photo mosaic can be aligned. The highest accuracy setting was used in this process. The process was done twice with and without GCP correction.

This research takes place in Muktisari Village, Cipaku District, Ciamis Regency, West Java, Indonesia. Based on the Indonesian Central Statistic Bureau (2020), Muktisari is the widest village in the Cipaku district of 9.28 km2. Muktisari village is located 250 meters above mean sea level and is mostly covered by vegetation. The Muktisari village is located at a latitude of -7.2617861 and a longitude of 108.3806875. The study area location can be seen in Figure 3.

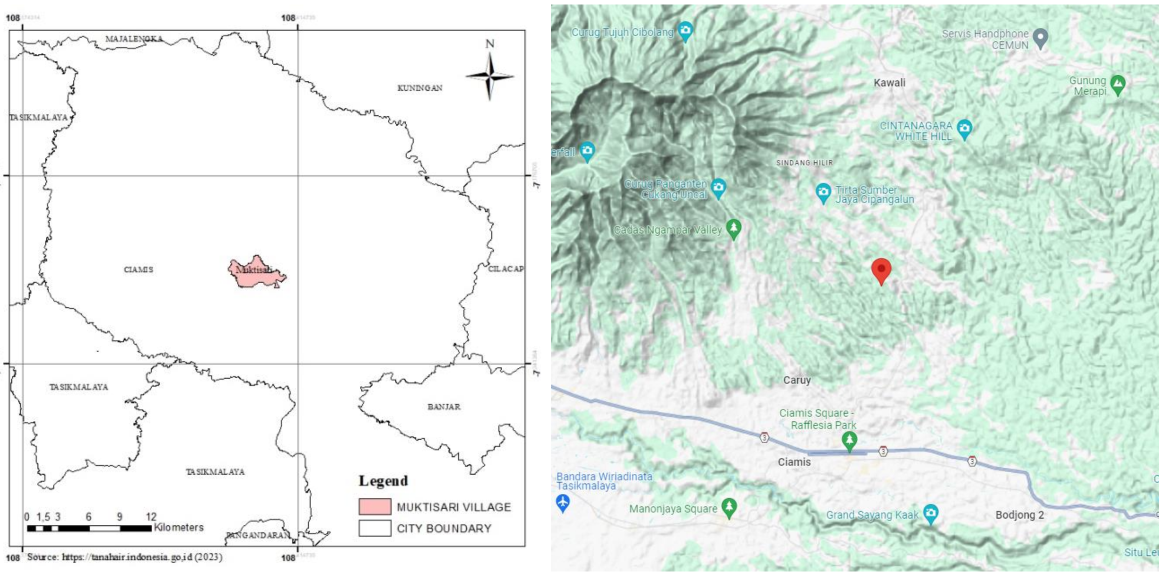

Figure 3. Study Location

Correlation analysis gauges variable relationship strength. Calculating the correlation coefficient is a common initial step in statistically analyzing environmental data to describe pairwise variable association. Scatterplots best visualize the two-variable relationship. The correlation coefficient is computed from symmetric coordinates, encapsulating all relevant information about the elements. Classical correlation analysis, ideally using log-transformed data, remains applicable for comparing two independent datasets (Reimann et al, 2017). Scatterplots offer a fundamental way to visually assess the correlation between two variables. In this approach, each axis signifies a variable, and plotted points mark an individual's observed value. Deviation from a straight line in the point cloud indicates correlation strength. To analyze multiple variables, a scatterplot matrix (SPLOM) generates a concise view, presenting all potential variable combinations (McKenna et al., 2016).

Pearson's correlation coefficient, a widely employed measure, gauges linear relationships between variables. Its broad application includes identifying disease-related genes and intricate sociological interactions. Visualizing pairwise correlations aims to inspire novel hypotheses for investigation. Pearson's correlation equals the cosine of the angle between mean-centered variables. The Pearson correlation formula is defined as

$$\hat{r}\,(x, y) = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\,\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (2)$$

The coefficient of determination, R^2 (or "R squared"), is a crucial metric signifying the model's ability to explain variation in the response variable using a set of predictors. It gauges the predictive capability of these predictors and aids in selecting the best set when the model size (number of predictors) remains constant. R^2 is widely employed to assess the goodness-of-fit of underlying models in practice (Zhang, 2017).

3. Result and Discussion

The error analysis is employed through target-to-actual comparison, with target coordinates determined by tachymeter measurements and actual coordinates derived from the photogrammetric surface model (Siebert et al., 2014). The input in this RMSE is the distance between the premark on the photo to the GCPs coordinate generated. Premark is the location on the field where the GCP measurement was located. The location will be marked with a contrast color, length of 10 pixels, and width of 3 pixels therefore the premark can be seen through the photos taken by the vehicle. The closer the distance between GCPs coordinates to the premark, the more accurate the orthophoto is, and vice versa.

Figure 4 and Figure 5 show the examples of pictures with and without GCP correction. Due to the page limitation, we only show the example of the GCP3 location which has the highest deviation.

Figure 4. Orthophoto without GCPs Correction

Figure 5. The Orthophoto with GCPs Correction

Based on Figure 4 and Figure 5 we can conclude that the orthophoto without GCPs correction is less accurate compared to the orthophoto with GCPs correction. The deviation between the premark and the GCP 3 coordinate is 19.25 meters for the orthophoto without GCPs correction and 0.06 meters for the orthophoto with the GCPs correction. This site is located at an altitude of 359.251 meters and shows the biggest deviation of all. The magnitude of this deviation is considered fatal especially the orthophoto output further will be used as a basemap in plotting land parcels. The error of more than 0.3 meters cannot be tolerated as it can lead to errors in the issuance of land ownership certificates which in the future can lead to community tension.

The deviation calculation of eight GCP locations can be seen in Table 3 below:

Table 3. Deviation Calculation

Name	Northing	Easting	Elevation	Without GCPs	With GCPs
GCP 1	9195501	209567	285.730	10.92	0.50
GCP 2	9194913	209016	251.091	12.80	0.44
GCP 4	9196341	207780	368.031	19.23	0.03
GCP 5	9197253	206647	407.240	13.45	0.09
GCP 6	9197996	207582	412.143	4.29	0.03
GCP 8	9197136	208031	388.616	12.37	0.16
GCP 3	9196437	208927	359.251	19.25	0.06
GCP 7	9195907	209058	332.278	13.61	0.15

Based on Table 3 the average deviation is 13.24 meters for orthophoto without the GCPs correction and 0.1825 meters for orthophoto with GCPs correction. The RMSE is 4.45 meters for orthophoto without GCPs correction and 0.17 meters for orthophoto with GCPs correction. The orthophoto without GCPs correction RMSE result indicates that the product cannot be used for the Indonesia land registration base map due to the regulation to create a map in the scale of 1:1000 and class 1 which has a maximum CE90 of 0.3 meters. Therefore, it is not proven that GNSS-PPK photogrammetry at an altitude of less than 500 meters is accurate without any GCPs correction. However, well distributed eight GCPs correction is enough to create a land registration basemap on the scale of 1:1000, and class 1 referred to Indonesia land registration basemap regulation.

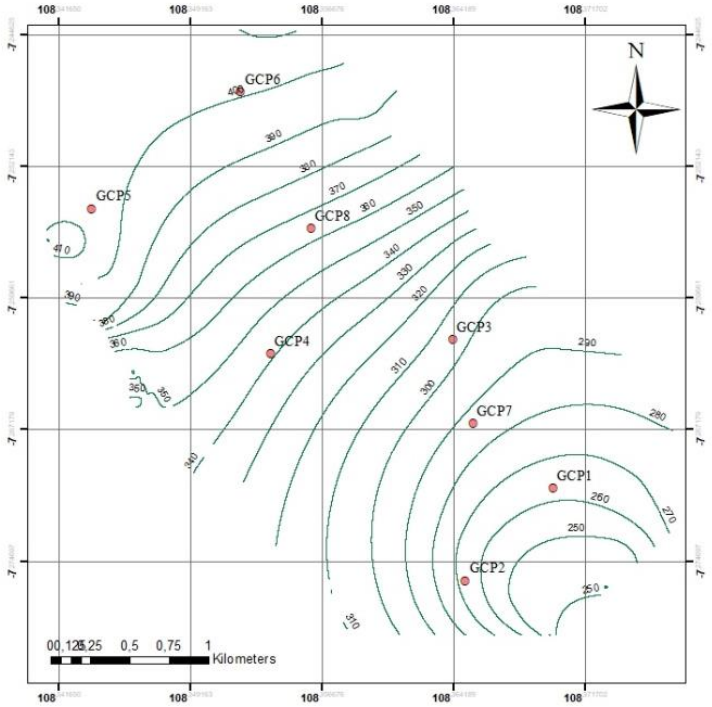

Figure 6. The GCPs Distribution to Elevation Model

The deviation error is suspected to be influenced by the elevation. Based on Eker et al (2021) elevation difference also has an essential effect on accuracy. The area with an elevation of more than 500 m comes out with worse accuracy. Pearson's correlation and coefficient determination (R^2) are calculated in this study to estimate how elevation influences the photogrammetry position. The hypothesis is higher elevation correlates to higher RMSE due to uneven surface. It was thought that uneven surfaces could not be estimated precisely by the photogrammetric method.

Based on Figure 6 we can see that the GCP's elevations are between about 250 to 420 meters. The coefficient of determination between the deviation was calculated using the scatterplot method and show the result below:

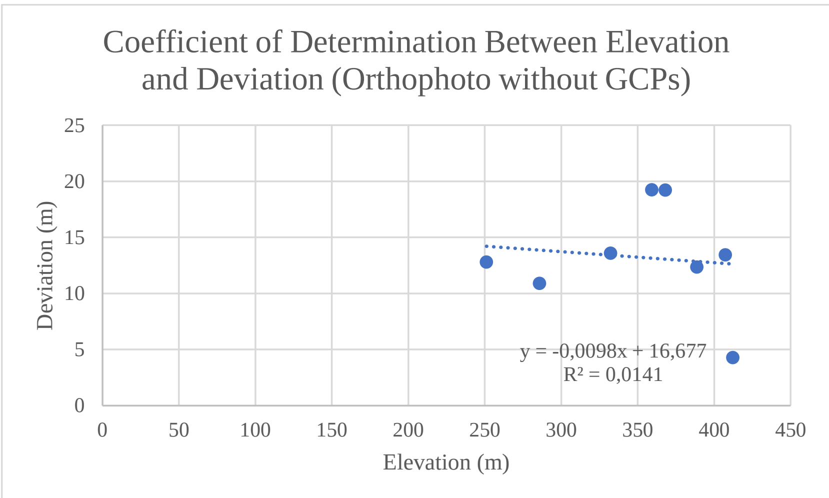

Figure 7. R^2 Elevation to Orthophoto without GCPs Deviation Graph

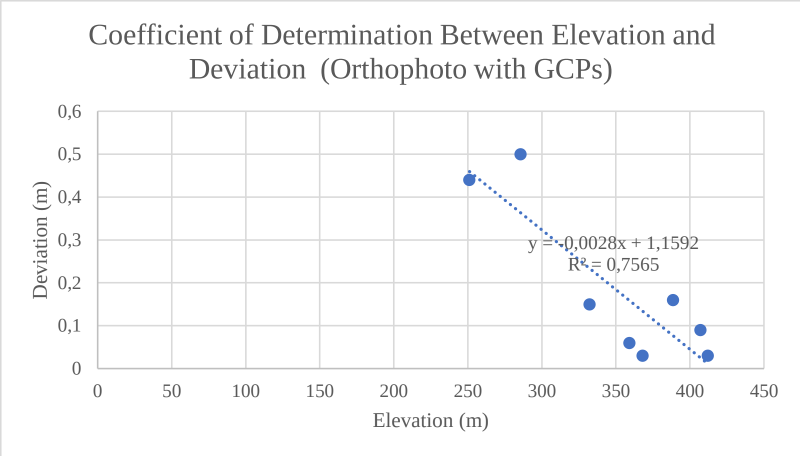

Figure 8. R^2 Elevation to Orthophoto with GCPs Deviation Graph

Based on Figure 7 we can see that the R2 of elevation to deviation is 0.014 (very weak) for orthophoto without GCPs and based on Figure 8 we can see the R2 of elevation to deviation is 0.7565 (very strong) for orthophoto with GCPs. Both data show a negative correlation between elevation to deviation. It means that the higher elevation led to less deviation and vice versa. Pearson's correlation result is -0,11873 for orthophoto without GCPs and -0,8697 for orthophoto with GCPs.

R^2 and Pearson's correlation result show a negative correlation which means higher elevation doesn't correlate to higher RMSE. It needs further study how higher elevation can create lower error compared to lower elevation. The orthophoto with GCPs shows a better correlation to elevation compared to the orthophoto without GCPs correlation. Indirectly this shows that orthophoto with GCPs correction has better performance compared to orthophoto without GCPs correction. Research conducted by Nagendran et al (2018) also concluded that the photo with GCP can tie up nicely when overlaid with the orthophoto of both conditions (with and without GCPs) in a Google Earth file (KMZ). Therefore, GCP is necessary to produce photogrammetric output that has a good accuracy in height variation (Nagendran et al., 2018).

Conclusion

Data processing without GCP correction showed an RMSE of 4.45 m and a mean deviation of 13.24 meters while the data processing with eight GCP corrections showed an RMSE of 0.17 m and a mean deviation of 0.18 meters. The R^2 of horizontal deviation to elevation orthophoto without GCPs showed a negative correlation of 1.41% (very small) and a Pearson correlation of -0,11873. While orthophoto with GCPs correction has R^2 of 75.65% (strong) and Pearson's correlation of -0,8697. Therefore, this study proved that the GNSS-PPK method installed on the UAV for aerial photographs still requires GCPs. The results obtained from the analysis of R^2 and Pearson's correlation indicate a negative correlation, suggesting that there's no direct relationship between higher elevation and higher Root Mean Square Error (RMSE). This unexpected finding prompts the need for a more in-depth investigation into how higher elevations could potentially lead to lower errors compared to lower elevations. Furthermore, when comparing the correlation between elevation and orthophotos with Ground Control Points (GCPs) and those without GCPs, a significant difference emerges. The orthophotos with GCPs exhibit a stronger correlation with elevation, indicating a more accurate representation of the terrain. This indirectly implies that orthophotos corrected with GCPs perform better than those without such correction. In essence, these findings highlight the importance of incorporating GCPs in orthophoto correction processes, as they contribute to better alignment with actual terrain elevation. Further exploration into the mechanism behind the unexpected correlation between elevation and RMSE at different elevations is necessary to fully understand and leverage this phenomenon for improved accuracy in elevation mapping and related applications.

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Reference

Carvajal-Ramirez, Fernando., Aguera-Vega, Francisco., Martinez-Carricondo, Patricio J (2016) Effect of image orientation and ground control points distribution on unmanned aerial vehicle photogrammetry project on a road cut slope. *J. Appl. Remote Sens.* 10(3), 034004

De Leeuw, A.j., Veugen, L.M.M., Van Stokkom, H.T.C (1988) Geometric correction remotely-sensed imagery using ground control points and orthogonal polynomial, International Journal of Remote Sensing, 9:10-11, 1751-1759

Dinkov, Davis., Kitev, Atanas (2020) Advantages and applicability of GNSS post-processing kinematic (PPK) method for direct georeferencing of UAV images. *Proceeding Vol. 1, 8th International Conference on Cartography and GIS*

Eker, Remzi., Alkan, Ece., Aydin, Abdurrahim (2021) A comparative analysis of UAV-RTK and UAV-PPK methods in mapping different surface types. *Eur J Forest Eng, 7(1): 12-25*

James, M.R., Robson, S. and Smith, M.W (2017) 3-D uncertainty-based topographic change detection with structure-from-motion photogrammetry: precision maps for ground control and directly georeferenced surveys. *Earth Surf. Process. Landforms*, 42(12), 1769-1788

Junarto, R. and D. Djurjani (2020). "Pemanfaatan Teknologi Unmanned Aerial Vehicle (UAV) untuk Pemetaan Kadaster." BHUMI: Jurnal Agraria dan Pertanahan 6(1).

Kecamatan Cipaku dalam Angka (2020) *Badan Pusat Statistik Kabupaten Ciamis (*Indonesian Central Statistic Bureu) https://tanahair.indonesia.go.id (access: January 2023)

Konecny, G (1976) Mathematische Modelle und Varfahren zur geometrischen Auswertung von Zeilenabtaster-Aufnahmen. *Bildmessung und Luftbildwesen*, 44, 188-197.

McKenna, S., et al. (2016). "s-CorrPlot: An Interactive Scatterplot for Exploring Correlation." Journal of Computational and Graphical Statistics 25(2): 445-463.

Mian, O., Lutes, J., Lipa, G., Hutton, J.J., Gavelle, E., Borghini, S (2015) Direct georeferencing on small unmanned aerial platforms for improved reliability and accuracy of mapping without the need for ground control points. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science, Volume* XL-1/W4

Nagendran, S. K., et al. (2018). "Accuracy assessment on low altitude UAV-borne photogrammetry outputs influenced by ground control point at different altitude." IOP Conference Series: Earth and Environmental Science 169.

Reimann, C., et al. (2017). "A new method for correlation analysis of compositional (environmental) data - a worked example." Sci Total Environ 607-608: 965-971.

Siebert, S. and J. Teizer (2014). "Mobile 3D mapping for surveying earthwork projects using an Unmanned Aerial Vehicle (UAV) system." Automation in Construction 41: 1-14.

Taddia Y, Stecchi F, Pellegrinelli A (2020) Coastal mapping using DJI Phantom 4 RTK in post-processing kinematic mode. Drones 4: 9

Tomastik, J., Mokros, M., Surovy, P., Grznarova, A., Merganic, J (2019) UAV RTK/PPK method-An optimal solution for mapping inaccessible forested areas? *Remote Sensing,* 11: 721

Wijayanti, R. F., et al. (2023). "Utilizing Post Processing Kinematic (Ppk) Unmanned Aerial Vehicle (Uav) to Accelerate Detailed Land Mapping." Jurnal Geosaintek 9(3).

Zhang, D. (2017). "A Coefficient of Determination for Generelized Linear Models." The American Statistican 71:4: 310-316.

Zhang, H., Aldana-Jague, E., Clapuyt, F., Wilken, F., Vanacker, V., Van Oost, K., (2019) Evaluating the potential of post-processing kinematic (PPK) georeferencing for UAV-based structure-from-motion (SfM) photogrammetry and surface change detection. Earth Surf Dyn, 7: 807-827.