

THE IMPORTANCE OF GROUND CONTROL POINTS IN A PHOTOGRAMMETRIC WORKFLOW

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ABSTRACT:

This study investigates the optimal distribution and pattern of ground control points (GCPs) in aerial photogrammetric projects. Aerial triangulation (AT), also known as bundle adjustment, is the fundamental step in refining 3D reconstruction models and camera positions, thereby minimizing reprojection errors. The study utilizes data from a national project in Romania, employing high-resolution aerial images acquisition using photogrammetric sensors. The project has rigorous requirements of ground control points (GCP) placement and field measurements using GNSS and geometric leveling techniques. The study employs various scenarios, manipulating the number and distribution of GCPs, to assess their influence on planimetric and altimetric accuracy. Results indicate that the configuration and number of GCPs significantly affect the accuracy of photogrammetric products, such as dense image point clouds, digital surface models, and orthophotos. Moreover, the study underscores the importance of precise GCP determination methods, especially in regions lacking a precise gravimetric geoid model. In scenarios with inadequate GCP coverage the outcomes have inferior quality, emphasizing the critical role of GCPs in ensuring the quality of photogrammetric products. Overall, the research gives a clear view on the best placement patterns of GCPs and their influence on AT process evaluation performed in check points (CHKs).

1. INTRODUCTION

Aerial photogrammetry is used to obtain a 3D data set for a large area using a set of overlapping images and includes precise methods for measuring and extracting geometric information from these images (Kyle 2013).

In photogrammetry, determining image orientation or pose parameters is crucial for creating a 3D representation of a scene. This task involves establishing the rotation and translation information of images relative to a 3D coordinate system. This process is commonly known as Structure-from-Motion (SfM) in computer vision and Simultaneous Localization and Mapping (SLAM) in robotics (Eltner A. 2020). The outcome of this task includes not only the orientation of images but also the 3D coordinates of tie points, resulting in a sparse 3D point cloud. This point cloud forms the basis for further analysis and reconstruction of the scene in 3D (Wang X. 2019)

The most important process in the photogrammetric workflow is aerial triangulation (AT) also called bundle adjustment. Bundle adjustment is a fundamental technique used to refine simultaneously the parameters of a 3D reconstruction model and the relative positions of the camera. It optimizes the parameters by minimizing the reprojection error, which is the difference between the observed image points and the corresponding points projected from the 3D model (Photogrammetry News | All about Photogrammetric Mapping, Software, News). The Ground Sampling Distance (GSD) or ground resolution is a parameter defined as the size of a pixel projected on the surface of the scene (Girod L. 2018).

Bundle adjustment involves solving a highly nonlinear optimization problem, typically using iterative methods (Rupnika E. 2013). By performing bundle adjustment, surveyors can improve the accuracy of their 3D reconstructions, leading to more precise measurements and better visualization of the scene. This process is usually done in 3 steps:

1. **Generating tie points.** Tie points (TP) are points identified in different images, who correspond to the same location. The main objective is to estimate how the images are related to each other. Automatic search of tie points can be done by using different detection algorithms such as: SIFT, SURF and ASIFT (Bjuggner F. 2023). These algorithms can automatically identify a very large amount of tie points and so, the outliers can be easily filtered out (Girod L. 2018).
2. **Interior Orientation.** In this step the parameters of the calibrated photogrammetric camera are used, and the images are brought together in a unique geometric coordinate system. The structure-from-motion (SfM) method can do both operations, separately or together, by using tie points (Snaveely N. 2010)
3. **Exterior Orientation.** With the images oriented relative to each other in a unique geometric coordinate system, an "absolute" reference must be done. This involves referencing the dataset to a local system or to a cartographic system. Using Ground Control Points (GCPs) allows to obtain the precise information needed, because the GCPs are points with known coordinates in the desired coordinate system. The GCPs can be acquired through different surveying methods, like GNSS survey (Giordano S. 2018).

Traditionally, bundle adjustment algorithms may impose constraints such as fixed camera positions, fixed point coordinates, or others.

For projects with low accuracy requirements, utilizing system-integrated sensors like GNSS/IMU (Global Navigation Satellite System/Inertial Measurement Unit) systems for bundle adjustment can be a practical approach (Bernecker L. 2022). GNSS can serve as a first approximation due to its widespread availability and relatively low cost. However, it's important to note that GNSS/IMU systems may have limitations in accuracy, especially in challenging environments like urban canyons or dense foliage, where satellite signals can be obstructed. Additionally, IMUs can suffer from drift over time, leading to inaccuracies in long-term measurements (Xiao C. 2018). In this context, the method is called "orientation without constraints" and it consists of determining relative orientation of images without imposing any prior constraints or assumptions. In challenging scenarios such as dynamic scenes, or scenes with significant occlusions or ambiguities, algorithms for orientation without constraints it is used to improve the accuracy and robustness of photogrammetric reconstructions (Rupnika E. 2013).

The accuracy of the photogrammetric products, 2D maps and 3D models, depend on various factors, including the ground sampling distance, the number of images, the image overlap, the aerial camera quality, the atmospheric conditions (wind speed, air pressure, air density, and the sun elevation angle), and the number and distribution of ground control points (GCPs).

Considering the theoretical limits, the block adjustment requires at least two horizontal points and three vertical control points, but for reliable and accurate results the number of GCPs must be increased. So, the number of GCPs depends on the scale and accuracy requirements of the geospatial project.

In all the photogrammetric projects the GCPs play a crucial role. It doesn't matter if the sensor is mounted on a plane, or on an unmanned aerial vehicle, if the flight is made at lower or higher flying heights, the field measurements must be done, in order to resolve absolute exterior orientation issues.

The GCPs can be represented by natural points, which can increase the cost-effectiveness of the project, but can lead to ambiguity in their precise identification in the field. Considering this aspect, it can be stated that natural points as GCPs measurement could be contaminated with an identification error (Kurczyński Z. 2019). This type of error does not apply to artificial targets, premarked in the field. In this sense, in the literature are many guidelines to give a framework for premarking (NJDOT 1998).

The most important requirements of a premarked GCP are the size, visibility, location, distinctiveness, durable materials, accuracy of field measurements. Points must be painted with high-contrast colors from the natural environment, the size of the premarking must be established proportional to the image resolution and the materials used should be durable (paint or vinyl flooring tiles). The locations used for the GCPs is very important and must be considered accordingly when planning the activities in the project. So, for good results the sites with repetitive patterns like lines along roads, areas with seasonal changes, temporary structures, vegetation, or shadows must be avoided.

Accuracy assessment is an important part of a photogrammetric process. For this step, check points (CHs) are used to give a

measure of reliability of the products in respect to the ground truth. These points can be natural targets and must respect all the requirements described above.

There are many studies for UAV projects that evaluate the optimal number of GCPs and the most suitable placement pattern and all of them concluded that these requirements are essential in delivering accurate products (Bhatsada A. 2022). In the article (Oniga V-E 2020) the authors concluded that: GCPs in the corners are indispensable, placing all of the points at the block boundary decreases the accuracy, and GCPs in the block interior improve the accuracy significantly.

Some common products in an aerial photogrammetric project are:

- **Orthophotomap:** This step involves correcting the geometric distortions in the aerial imagery caused by terrain variations and camera angles. In this case the product can be used for feature extraction and mapping, by using automated algorithms or manual digitization to develop a database with geospatial objects (GIS).
- **Digital Elevation Model (DEM):** Generating a digital representation of the terrain surface, often through processes like stereo matching or LiDAR data integration. DEMs are crucial for various applications such as 3D modeling, topographic mapping, and flood modeling.

Quality Control (QC) is a mandatory step in a photogrammetric pipeline. This process consists in thorough checks to ensure the accuracy, completeness, and consistency of the final products. QC procedures may involve visual inspection, statistical analysis, and comparison with ground truth data to validate the results of the photogrammetric workflow (Verykokou S. 2018).

By completing these steps, the aerial photogrammetric workflow transforms raw aerial imagery into valuable geospatial information that can be used for various applications such as urban planning, environmental monitoring, infrastructure development, and natural resource management (Geoinfotech n.d.).

2. NATIONAL PROJECT FOR HIGH RESOLUTION IMAGE ACQUISITION IN ROMANIA

The data used for the case study is part of the on-going *National project for high resolution image acquisition in Romania* (CNC 2022). The main project activities are acquiring aerial images with high spatial resolutions, performing bundle block adjustment and dense image matching, generating the digital surface models and the true-orthophotos. The quality control checks are done by a team from the National Center of Cartography, who is also the Beneficiary.

In figure 1 are displayed the project areas covering all the cities in Romania. The aerial data acquisition is done using nadir photogrammetric sensors for 319 cities and oblique ones for the capital city of Romania, Bucharest. The spectral resolution of the images is composed of four bands (red, green, blue, near-infrared) and the spatial resolution depends on the city dimension, with values like 4, 9 and 15 cm. The on-going project, splitted into two contracts, started in 2022.

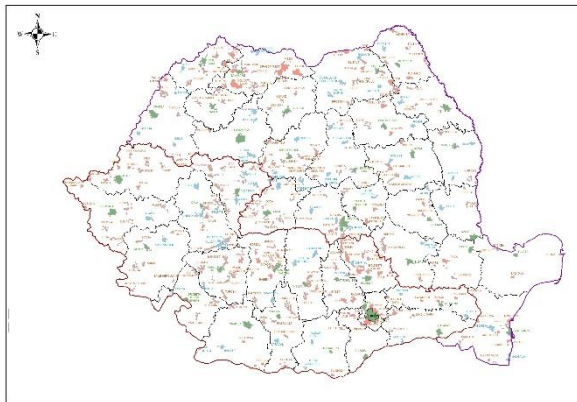


Figure 1. True-orthophoto generation in Romania

The control and check points are premarked using white paint and T shaped form. For the first contract, the requirements for filed measurements are: the X, Y coordinates are measured using GNSS static determinations of 2 hours and the H coordinate are obtained by geometric leveling. The distribution of GCPs must follow the following requirements: one GCP in each corner of the block, 2 GCPs in the center of the block and the rest of the points must be placed uniformly inside the block. The CHKs should be positioned in the areas that are not covered by GCPs, and their number should be directly proportional with the control points.

The main products are images, dense image point clouds, digital surface models (DSM), and orthophotos. All products must be delivered in the national reference system (Krasovski ellipsoid 1940, stereographic projection 1970 and Black Sea Normal Altitude System 1975). The requirements for DSM and orthophotos are displayed in Table 1.

	True-orthophoto resolution (cm)	True-orthophoto accuracy (cm)	DSM resolution (cm)	DSM accuracy (cm)
Bucharest	6	± 15	10	± 20
Big cities	5	± 12	10	± 20
Medium cities	10	± 15	12.5	± 25
Small cities	12.5	± 20	20	± 30

Table 1. Resolution and accuracy of products

3. CURRENT STATE OF THE QUASIGEOID DETERMINATION AT NATIONAL LEVEL IN ROMANIA

At national level, Romania does not have a geoid model determined by gravimetric measurements. The project of the National Center of Cartography consists of determining a quasigeoid model over Romania using terrestrial gravity measurement, GNSS observations, and points from the Geometric Leveling Network. The method used to calculate the quasigeoid model, using terrestrial gravity dataset in our case is Remove-Compute-Restore (RCR). The input data used in the national project is composed of:

- new points determined gravimetrically;
- free-air anomalies;
- Bouguer anomalies;
- detailed digital terrain model and reference models SRTM;
- corrections of polar coordinates.

For determining the transformation grid at national level, the Bicubic Spline interpolation method was used. The results were implemented in the national TransDatRO transformation software (published on the ANCPI and CNC website - (CNC 2020). At present, a gravimetric quasigeoid is generated for the counties of Bihor, Arad, Hunedoara, Cluj, Alba, Mureș, Sibiu, Harghita, Brașov, Covasna, Gorj, Dolj, Olt, Giurgiu, Teleorman, Argeș, Caraș-Severin, Vâlcea, Mehedinți, Timiș, Dâmbovița, Prahova, Buzău, Ilfov and București (Figure 2) and for these counties the average transformation accuracy of the new points is around ± 10 -12 cm.

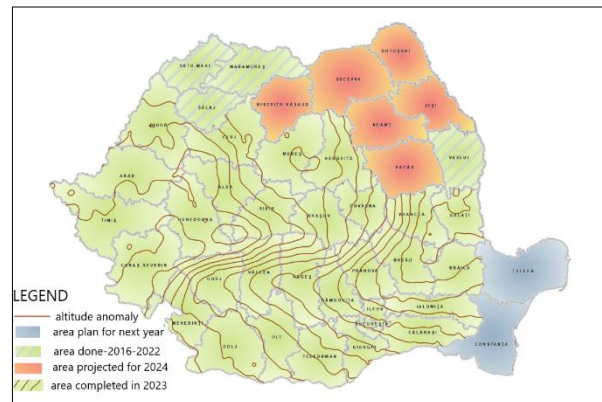


Figure 2. Quasigeoid model over Romania

4. CASE STUDY

4.1. DATA COLLECTION

A Rockwell Commander 690A with an engine 2x Garrett AirResearch turboprops was used for the aerial survey. The images were acquired using UltraCam Eagle Prime camera (Figure 3) with a focal length of 100.5 mm and a pixel size of 4.6 μm , mounted on a Somag GSM4000 gyrostabilized platform. The POS system comprises of an inertial measurement unit, Applanix Direct Georeferencing System 510, equipped with 3 gyros and 3 accelerometers, and a GNSS antenna Trimble AV39.



Figure 3. Platform and photogrammetric camera used

The 2 cities, Tismana and Baia de Aramă, have been included in a photogrammetric block of 303 km² (Figure 4).

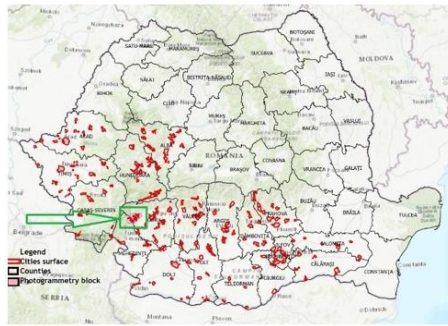


Figure 4. Geographic location of the photogrammetric block

The case study area is situated in a complex terrain, with a difference of terrain heights of approximately 1000 meters (Figure 5).

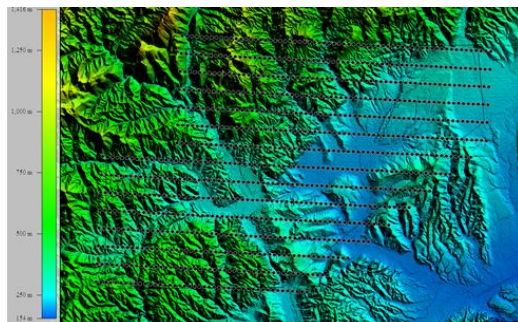


Figure 5. Centers of projection on DTM

The flight was done on the 13th of April 2022, between 08:29 and 10:01 UTC time. The two reference stations used from the Romanian ROMPOS network are TJIU (30 km) and DRTS (46 km). 909 images were acquired on 15 flight lines, with a forward overlap of 80%, and a side overlap of 60%. The maximum GSD of the images is 15.7 cm.

All GCPs and CHKs were T shaped premarked using white paint (Figure 6). The field measurements were done using GNSS equipment (E -Survey E300 PRO, Spectra Precision) with static determinations of 2 hours and digital levels (FOCUS DL-15) for geometric leveling.



Figure 6. Example of premarked GCP

4.2. FIRST CASE STUDY

The bundle adjustment was done in Vexcel Imaging's software UltraMap. The process is a semi-automated step that performs precise georeferencing by using image tie points (generated automatically), ground control points (measured manually) and POS data. The bundle block adjustment was performed using 8

scenarios (Table 2), by considering different points as GCPs (Figure 7), and all other points as CHKs.

Scenario	Scenarios for GCPs
1	all
2	corners + center
3	only 4 corners + center
4	no center + no 1 corner
5	no center + no 2 corners
6	no GCPs in North
7	no GCPs in West
8	GCPs only on road

Table 2. Scenarios of GCPs patterns

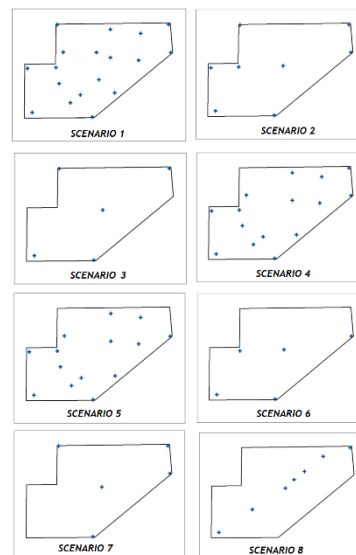


Figure 7. Scenarios for GCP distribution

After performing 8 bundle block adjustments, the indicators of AT accuracy, root mean square error (RMSE) in GCPs and CHKs and maximum errors in CHKs, are displayed in Figure 8.

	ULTRACAM EAGLE PRIME	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
	Number of GCPs	18	8	5	15	14	5	5	7
	Number of CHKs	18	28	31	21	22	31	31	29
GCP	X	62	61	64	65	65	66	47	32
RMSE	Y	67	74	47	71	71	67	69	19
[mm]	H	17	21	17	18	15	10	25	14
CHK	X	109	113	163	106	105	122	134	173
RMSE	Y	105	109	97	101	114	144	114	153
[mm]	2D (planimetric)	151	157	190	146	155	189	176	231
	H (altimetric)	108	103	128	103	123	147	157	116
CHK max	X	207	218	319	225	208	225	285	374
error	Y	203	208	239	188	206	279	257	349
[mm]	H	256	281	334	263	267	342	390	299

Figure 8. AT evaluation indicators

Analysing the results presented in the table above, we can conclude that the number of points, but also the pattern of the distribution, influences the RMSE in the CHKs. So, in scenarios with 5 GCPs in different positions, scenario 3, scenario 6, and scenario 7, the planimetric RMSE value is 18-19 cm and the altimetric RMSE value varies from 13 cm to 16 cm.

Considering the patterns, in figure 9 the areas with bigger errors in CHKs can be easily distinguished. So, outside the area covered by GCPs the errors increase for X, Y and H coordinates. For scenario 7 the errors are bigger in the western part of the block which is not covered by control points.

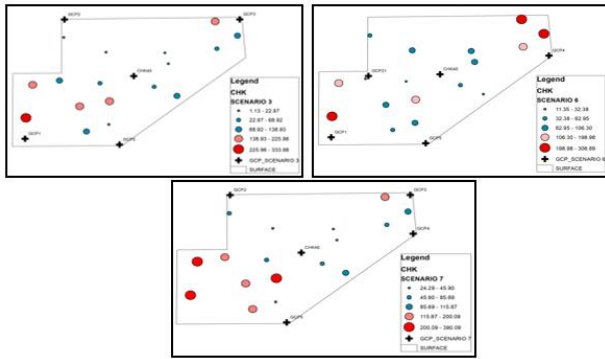


Figure 9. Errors on H coordinate measured in CHKs

In scenario 8, all the control points are placed on the national road DN67D that splits the block from SW to NE (Figure 10). The errors in the NW part of the block have values of more than 30 cm for the X coordinate and more than 10 cm for the Y coordinate. So, we can see bigger planimetric errors for this type of GCPs configuration (corridor mapping).

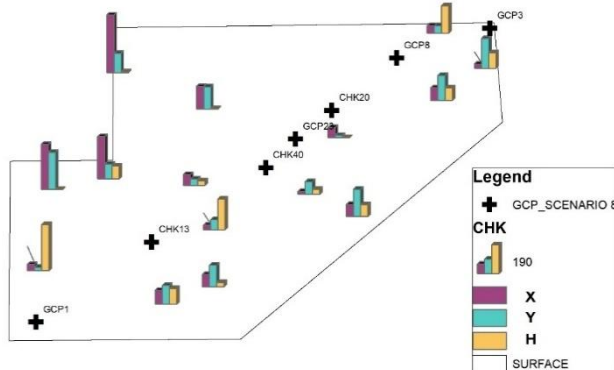


Figure 10. Errors in CHKs in Scenario 8

4.3. SECOND CASE STUDY

The study was carried out in 3 scenarios, using all the GCPs, with only 5 control points (4 corners and 1 center) or without any GCP (Table 3).

Number of the scenario	Number of the GCPs	Number of CHKs
1	18	18
2	0	
3	5	

Table 3. Scenarios for case study two

For each individual scenario, the bundle block adjustment was performed, and the final exterior parameters of orientation were extracted (. To determine the accuracy of the AT process, the Erdas Imagine 2020 software was used and 3D measurements in stereomodels for all CHKs were performed (Figure 11). This evaluation gives a better understanding of the errors derived from the data and the processes done so far and a clear view of the quality of the 3D reconstruction of the block.

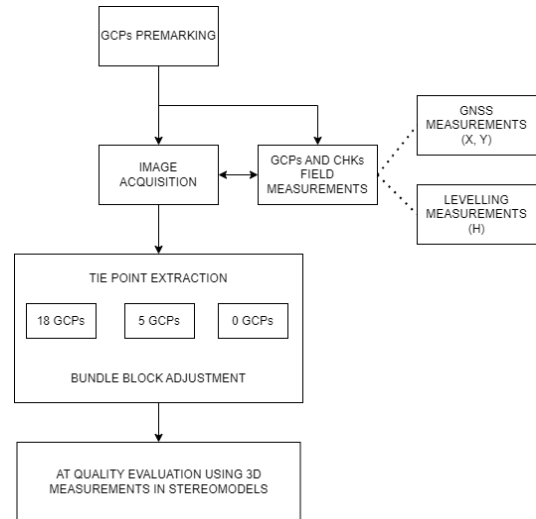


Figure 11. Photogrammetric workflow

The accuracy of the produced 3D stereomodels can be evaluated using various methods. In this study, the accuracy of X, Y, H, and XY were evaluated using the root mean square errors (RMSE) between the field measurements and the 3D measurements in the CHKs. RMSE indicates the overall accuracy of the results by combining individual errors and is one of the generally used criteria for position accuracy (ASPRS 2015).

$$RMSE_X = \sqrt{\frac{\sum (X_{field} - X_{stereo})^2}{n}} \quad (1)$$

$$RMSE_Y = \sqrt{\frac{\sum (Y_{field} - Y_{stereo})^2}{n}} \quad (2)$$

$$RMSE_H = \sqrt{\frac{\sum (H_{field} - H_{stereo})^2}{n}} \quad (3)$$

$$RMSE_{XY} = \sqrt{RMSE_X^2 + RMSE_Y^2} \quad (4)$$

Where:

$X_{field}, Y_{field}, H_{field}$ = coordinate values measured in the field

$X_{stereo}, Y_{stereo}, H_{stereo}$ = coordinate values measured in the stereomodels

n = number of points

$RMSE_X, RMSE_Y, RMSE_H$ = root mean square error on the X, Y, H

$RMSE_{XY}$ = planimetric root mean square error

For the bundle adjustment in Scenario 1 all the 18 GCPs in the block were used. The distribution of the points is displayed in Figure 12. After the processing, the generated reports give an overview of the AT results, like sigma naught value, residuals errors for the GCPs and CHKs points (Figure 13) and tie points, the errors obtained for the GCPs and CHKs after AT, the exterior orientation parameters.

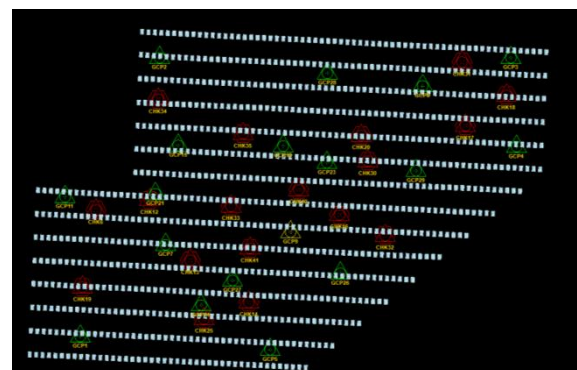


Figure 12. GCPs distribution in Scenario 1

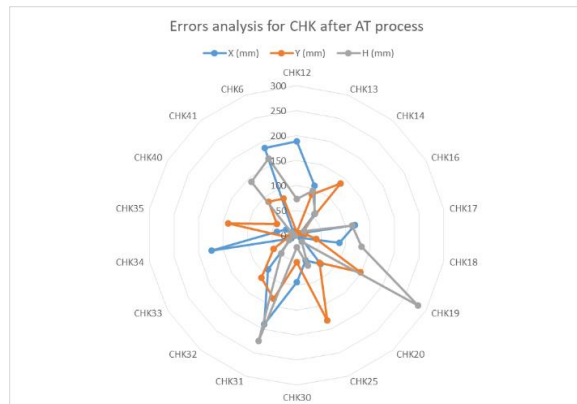


Figure 13. Error analysis in CHKs - Scenario 1

After measurements in 3D stereomodels for all the CHKs, the value of the $RMSE_{XY}$ is 13 cm and the $RMSE_H$ is 10 cm. For the bundle adjustment in Scenario 2 no GCP in the block was used, so the adjustment was done based on the GNSS in the photogrammetric system. After performing the 3D measurements in all CHKs, the value of the $RMSE_{XY}$ is 25 cm and the $RMSE_H$ is 42 cm.

For the bundle adjustment in Scenario 3 5 GCPs in the block, 4 points in the corners and one point in the centre were used. The distribution of the points is displayed in Figure 14. Residual errors for the CHKs points in Scenario 3 are displayed in Figure 15.

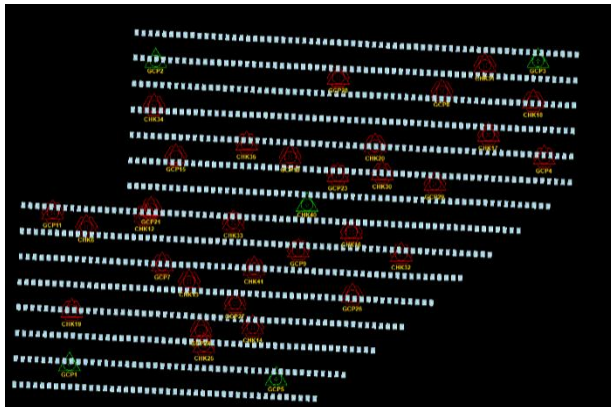


Figure 14. GCPs distribution in Scenario 3

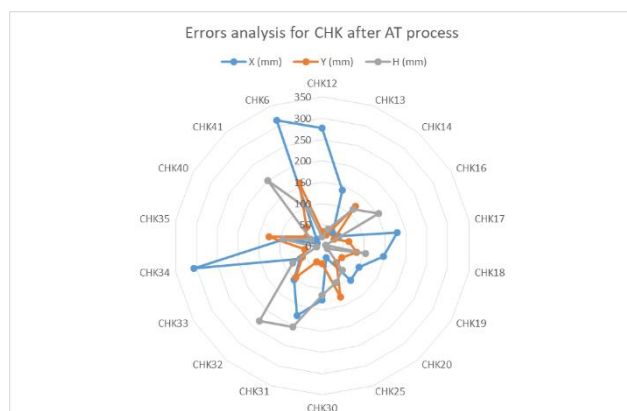


Figure 15. Error analysis in CHKs - Scenario 3

The measurements in 3D reveal the value of the $RMSE_{XY}$ of 19 cm and the $RMSE_H$ of 30 cm.

By evaluating the RMSE values at block level, scenario 1 gives the best results of AT. When talking about decreasing the number of points from 18 to 5, the RMSE values are doubled for planimetry and tripled for altimetry. In the case with no GCP, the errors on height reached more than 40 cm (Figure 16). The values shown here will lead to even bigger errors in the final products (e.g. orthophotos).

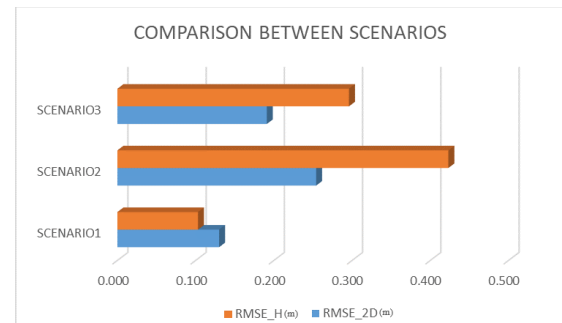


Figure 16. Comparison of planimetric and altimetric RMSE between different scenarios

Based on the measurements of 3D coordinates in all scenarios, a comparison for every coordinate (X, Y, H) in the CHKs was performed, showing the average values in differences between field measurements and measurements done in stereomodels (Figure 17).

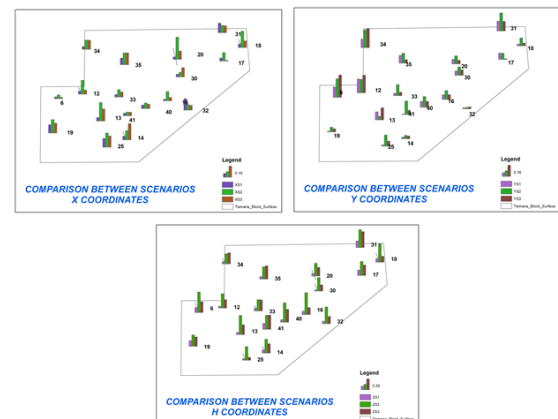


Figure 17. Comparison between different scenarios in CHKs coordinate values

4.4. THIRD CASE STUDY

This case study wants to show the importance of precise determination methods for GCPs. For Romania, the quasigeoid model is not finished yet. So, for determining the normal heights, leveling measurements remain the most suitable method. Starting from the national grid with gravity measurements, for the study area, the values for the anomalies in height are shown in the figure 18.

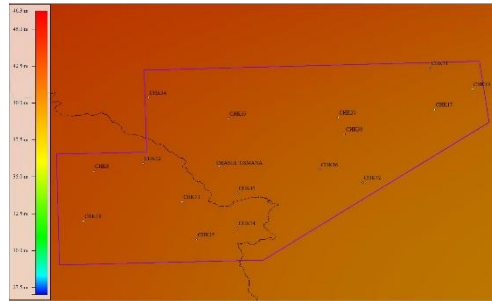


Figure 18. National grid of anomalies - case study area

From the national level we moved to local analysis of differences between ellipsoidal heights and normal heights. The bundle adjustment was performed using all the 18 GCPs with coordinates obtained only from static GNSS measurements.

The transformation from ETRS89 to the national reference system was performed using the software TransDatRo. Based on the field measurements performed, using GNSS and geometric levelling observation for all the points, a raster that reveals the values for the height anomalies in the study case area was generated. So, more than a third part of the block has differences bigger than 30 cm (Figure 19).

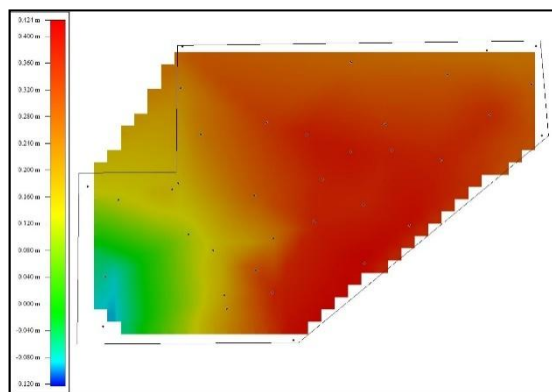


Figure 19. Differences between ellipsoidal and normal heights

In this case study, the workflow (Figure 20) is the same as in previous scenarios; the only parameter changed is the height of the GCPs that was determined by GNSS measurements.

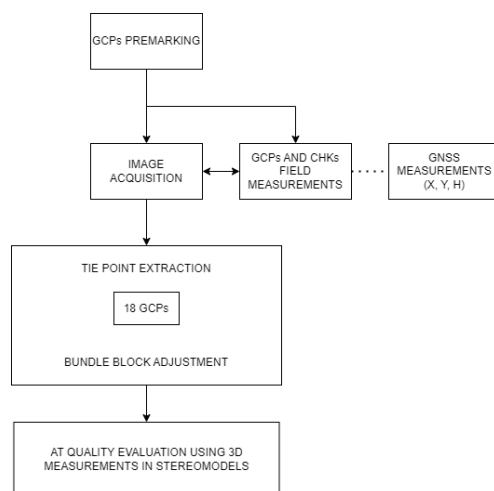


Figure 20. Workflow for scenario 10

So, these new data derived from AT process became the input for Scenario 10 that will be highlighted in the following.

The bundle adjustment was performed using all the 18 GCPs with coordinates obtained only from static GNSS measurements, but for the evaluation of the AT process, the CHKS used had the same coordinates measured with GNSS and geometric levelling, like all the case studies previously presented. For the AT process, the RMSE for GCPs has values that do not exceed 7 cm (Figure 21).

Software version for the AT	UltraMap v6.0.3 (Build 40.6.2305.1003)
No. of tie points	183316
Mean Photo Scale	34448
Sigma naught	0.97
Ground Control Points (X/Y/Z) [1/1000]	18 (GNSS-measurement)
RMS (mm)	63/67/21
MAX (mm)	136/109/52

Figure 21. Overview of AT report - scenario 10

The values obtained show that measurement method of heights influences also the planimetric coordinates (X and Y in Figure 22). The RMSE_H value obtained in Scenario 10, where the GCPs were measured using only GNSS observations, is 2.5 times bigger than the RMSE_H value obtained in Scenario 1, where the GCPs were measured using precise leveling for height and GNSS observation for X and Y coordinates.



Figure 22. RMSE for scenarios 1 and 10

5. CONCLUSIONS

The paper presented a research investigation for determining the optimal distribution and pattern of ground control points in an aerial photogrammetric project. The evaluation results of the study cases show that the GCPs placement patterns affected the planimetric and altimetric accuracy. Even if the evaluation was done only for AT results, one must understand that the photogrammetric products, like dense image point clouds, digital surface models, and orthophotomaps, will be generated with accuracies starting from the ones shown in this paper.

The products obtained from this data, can be classified into 3 groups:

- products with high required precision - Scenario 1;
- products for cartography and GIS projects, with lower required precision – Scenarios 3 and 10;
- products used only as basemaps for viewing purposes with low required precision – Scenario 2.

The test with no GCPs has the worst results. This can be seen from the AT report, where the errors are highlighted for the checkpoints on all the 3 dimensions. For altitude, the RMSE is almost half a meter. Occasionally there are areas where the differences between the terrain and the 3D point measurements exceed 60 cm. This can only generate low quality products.

The quality of the photogrammetric products depends mostly on the GCPs. For good results, the control points must be well distributed inside the area of the photogrammetric block and measurements in the field should be performed using precise methods.

In countries like Romania, where there is no precise model of a gravimetric geoid on the entire surface of the country, the method for determining the altitude is essential in order to obtain precise final products.

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