Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 129 **2025**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2025.129.17

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Żukowska, M., Krasuski, K., Wierzbicki, D. Determining the accuracy of a digital terrain model based on image data obtained from an unmanned aerial vehicle. *Scientific Journal of Silesian University of Technology. Series Transport*. 2025, **129**, 293-309. ISSN: 0209-3324. DOI: https://doi.org/10.20858/sjsutst.2025.129.17

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DETERMINING THE ACCURACY OF A DIGITAL TERRAIN MODEL BASED ON IMAGE DATA OBTAINED FROM AN UNMANNED AERIAL VEHICLE

Summary. This article presents and describes the results of research on determining the accuracy of a Digital Terrain Model (DTM) developed based on image data obtained from an Unmanned Aerial Vehicle (UAV). The Digital Terrain Model was created using image data acquired by an Unmanned Aerial Vehicle, specifically the fixed-wing with electric propulsion, flying at an altitude of 300 meters. The image data were collected during a photogrammetric survey conducted over a mountainous area in 2021. The final elevation values of the Digital Terrain Model were recorded in a GRID format with a spatial resolution of 5 meters. The article also includes a comparison of the DTM elevations with results obtained from the satellite GPS RTK technique. Based on this, an accuracy of elevation determination for different vertical profiles ranged from 0.19 m to 0.24 m was obtained. Moreover, the study also involves the development of a DTM from data acquired by the Unmanned Aerial Vehicle at an altitude of 150 meters. In this case, the accuracy of determining the elevations of the DTM for different vertical profiles

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ranged from 0.10 m to 0.16 m. The results of the research are very interesting for the application of UAV technology in aerial photogrammetry, particularly in inaccessible areas, especially mountainous regions.

Keywords: low altitude photogrammetry, DTM, Unmanned Aerial Vehicle, interpolation, accuracy

1. INTRODUCTION

Due to the intense development of Unmanned Aerial Vehicle (UAV) technology, these platforms are increasingly being utilized in the field of photogrammetry. Image data obtained from UAVs enables the acquisition of a range of fundamental photogrammetric products that find applications in numerous domains related to spatial information. Moreover, UAVs, owing to their size, constitute an excellent photogrammetric tool for conducting surveys over inaccessible areas such as mountainous terrains [1]. Most such platforms are equipped with gyroscopic stabilization and allow for autonomous flight missions. Additionally, the costs associated with such systems and their operational expenses are significantly lower compared to traditional methods of acquiring aerial photogrammetric data. A significant limitation of this technology for low-altitude image data acquisition is the use of cheap, single-frequency GPS receivers coupled with an INS system. This results in image data being burdened with several-meter positioning errors, which in turn affects the final accuracy of the photogrammetric work.

One of the potential applications of UAVs in aerial photogrammetry is the generation of a Digital Terrain Model (DTM). A DTM is one of the primary sources of information about the topographic surface of the terrain, characterizing the topographic surface through a discrete network of measurement points with known coordinates (X, Y, Z). When it also includes information regarding the surface situation, it is referred to as a Digital Surface Model (DSM). Therefore, a DSM represents the terrain along with its natural (e.g., trees) or artificial (e.g., buildings) coverage [2],[3]. A DTM can be generated based on various data sources. Appropriately processed data should consist of information about the terrain's elevation and accurately represent its shape. Currently, for the purposes of photogrammetric works, the main sources of data are field measurements, aerial laser scanning, and image data from classical aerial photogrammetry [4]. Traditional aerial photogrammetry has long been the main and simultaneously economical source of topographic surface elevation data. In the last decade, this role has been taken over by data obtained through aerial laser scanning LIDAR, and the ability to develop large areas necessitates particular attention to this method. A significant advantage of LIDAR is that some laser pulses reflect off the terrain coverage surface, such as forest canopies, while some (about 30% in summer and 70% in winter) penetrate vegetation and reflect off the topographic surface, providing information about the height of terrain coverage elements and the ability to generate both DTM and DSM [5]. As LIDAR technology remains expensive, many countries prefer to create photogrammetric products like DTM from images acquired with UAVs. In recent years, small UAVs equipped with imaging sensors offer a low-budget form of acquiring low-altitude image data, which can then be processed into a dense point cloud using the Structure from Motion (SfM) algorithm family [6], [7]. This allows for the generation of DTMs and DSMs and, consequently, one of the main products of low-altitude photogrammetry – orthophotomaps.

1.1. Related works

In the literature, there are numerous studies on the accuracy analysis of Digital Terrain Models (DTMs) generated based on images acquired from low altitude. In the research conducted by Udin et al. [8], the accuracy of a DTM created from UAV images captured with a non-metric Canon PENTAX W90 camera was examined. The study established a photogrammetric network consisting of 23 points with known X, Y, and Z coordinates. Sixteen of these were used as ground control points (GCPs), and seven as independent check points (ICPs) to assess accuracy. The analysis of the DTM accuracy was based on the Root Mean Square Error (RMSE) of the Z-coordinate, obtaining an accuracy of less than one meter. In the work of Akturk et al. [1], the accuracy of a DTM for areas with varied terrain was investigated using UAV image data. The results indicated that the DTM accuracy (RMSE value) was 0.57 m. The use of ground control points during the DTM generation process reduced the RMSE value by 0.06 m. Uysal et al. evaluated the DTM accuracy using 30 control points and achieved a total vertical accuracy of 0.062 m at a flying height of 60 m. The findings demonstrate that UAV photogrammetry data can achieve suitable accuracy, very similar to RTK GPS data, thus enabling the use of UAV photogrammetric data for creating maps, geodetic measurements, and other engineering applications at low cost, time savings, and minimal fieldwork. Additional studies [9] on DTM accuracy have proven that factors such as flight planning, fieldwork, camera settings on the UAV platform, and an adequate number of ground control points can enhance the accuracy of the generated terrain models. In research by Jamalulizam et al. [10], the accuracy of a DTM based on UAV data acquired at various flight altitudes was examined, concluding that a flight altitude of 300 m provides a more accurate terrain surface model compared to a flight altitude of 400 m.

1.2. Research Purpose

The objective of the present study is to analyze the accuracy of a Digital Terrain Model (DEM) generated based on low-altitude image data. The research works presented below will address the question of what accuracy can be achieved for a Digital Terrain Model using data acquired by an Unmanned Aerial Vehicle. Accuracy analyses were performed using image data from the UAV. The article is divided into five sections, followed by a reference.

The paper is structured as follows: in Section 2 the research method is explained. Section 3 presents the material and experimental results. In Section 4 the results are discussed. Finally, Section 5 provides a brief summary of this work.

2. METHODS

The process of generating a Digital Terrain Model (Fig. 1) based on data acquired from the UAV consists of the following steps: data import into specialized software, image adjustment, georeferencing of images using check points to optimize camera position and orientation, dense point cloud generation, point cloud filtering (feature classification), DTM generation, DSM generation and orthomosaic creation.

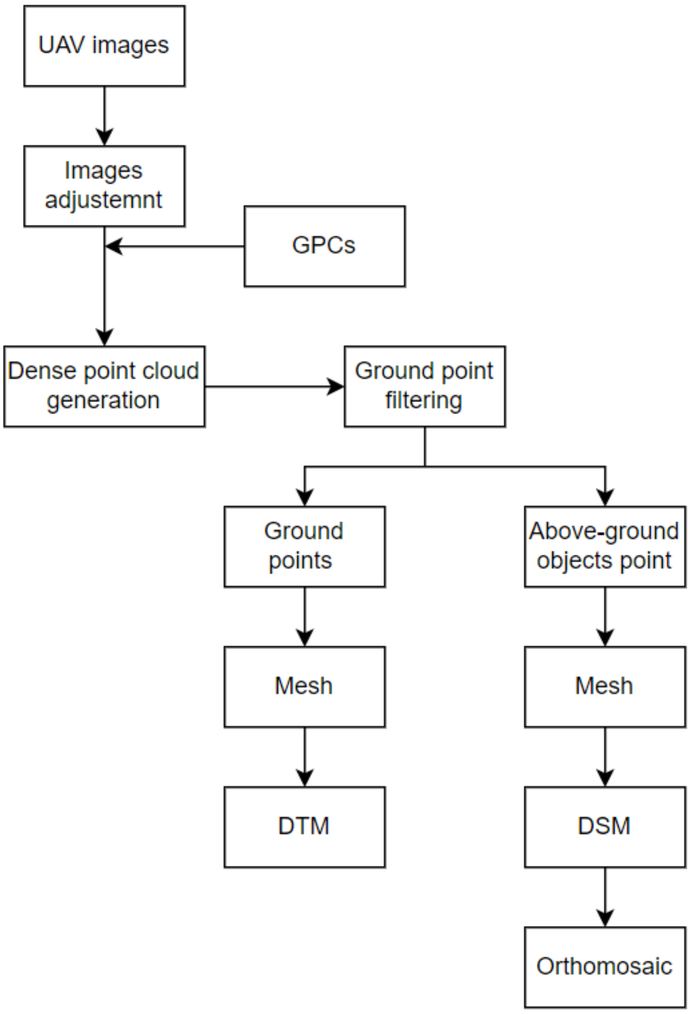

Fig. 1. Workflow to generate DTMs

3. MATERIALS AND EXPERIMENTAL RESULTS

3.1. Study area

Image data for the research experiment was acquired using a fixed-wing system equipped with a Sony camera. The photogrammetric raid was carried out in March 2021 under moderate photographic conditions. The test area was the vicinity of the town (Małopolskie Voivodeship) in southern Poland.

Ten ground control points and five check points were used for the analyses. All points were signaled, and their coordinates were determined using the GPS RTK technique with an accuracy of no worse than 0.05 m (mountainous terrain). The test block consisted of 100 images acquired from an altitude of 300 m (see Fig. 2). The aerial images were arranged in 10 strips and the field pixel size was 0.10 m.

Image data processing was performed in the commercial software UASMaster [11]. After automatic digital aerotriangulation, the mean-square error value of a typical observation was 5.1 µm (1.1 pixels). For the check points, the mean square error values for the X, Y, and Z coordinates were 0.10 m, 0.12 m and 0.23 m, respectively. In a further step, a dense point cloud was generated, which was then subjected to a filtering process. The generated Digital Terrain Model was saved as a regular GRID screen with a spatial resolution of 5 m (see Fig. 3).

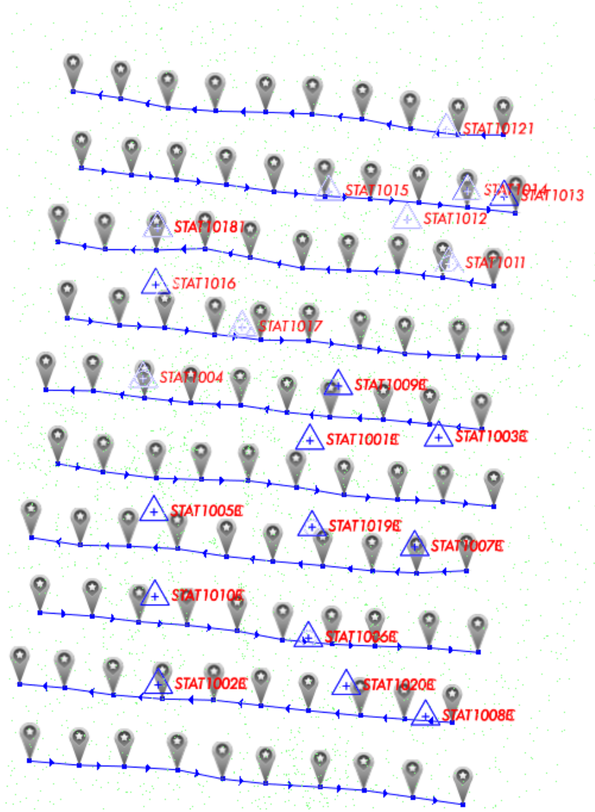

Fig. 2. The visualization of the test photogrammetric block – altitude 300 m

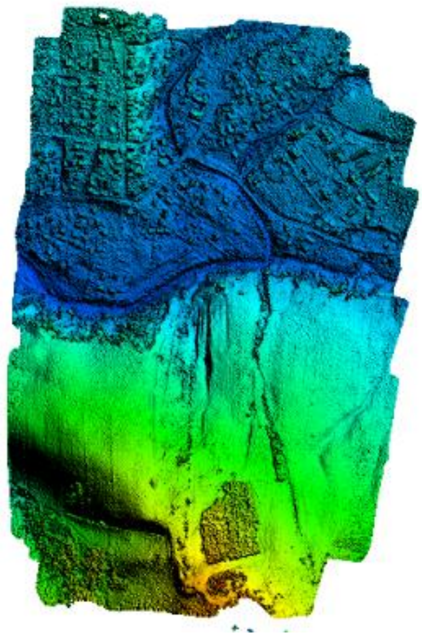

Fig. 3. The visualization of the test photogrammetric block – altitude 300 m

Tab. 1

Parameters of the test block

DTM development area	0.9 km^2
Form of DTM presentation	regular GRID
Number of GRID nodes	34666
Density of points	4 points / 25 m^2
Mesh	5 m
Average elevation	642.40 m
DTM height range	from 604.02 m to 732.06 m

Table 1 shows the basic parameters of the DTM compiled from aerial imagery from the UAV platform. The size of the DTM compilation was approximately 0.9 km^2, assuming a point density of 4 points per 25 m^2. The total number of GRID grid node points in the DTM was 34666 for a grid mesh of 5 m. In addition, the average height of the DTM was 642.40 m, with ground denivelations ranging from 604.02 m to 732.06 m.

3.2. Experimental results

This chapter presents the results of a comparison of selected DTM profiles whose heights were determined by an interpolation model and by GPS RTK satellite measurements. A total of three field profiles of DTM heights were analyzed. For the interpolation model, the nearest neighbor method was used, where the heights of the interpolated profile points were determined based on a weighted average, as follows:

$$H_{int} = \frac{\sum_{i=1}^{n} p_i \cdot \sum_{i=1}^{n} H_i^{GRID}}{\sum_{i=1}^{n} p_i} \tag{1}$$

where:
H_{int} – interpolated height for a given profile point,
p – weight,
$p = \frac{1}{d^2}$,
$d = \sqrt{(X_{int} - X_i^{GRID})^2 + (Y_{int} - Y_i^{GRID})^2}$,
(X_{int}, Y_{int}) – plane rectangular coordinates of the profile point for which the height is being interpolated,
(X_i^{GRID}, Y_i^{GRID}) – rectangular planar coordinates of a neighboring point on the regular GRID grid,
i – serial number,
n – number of points used to interpolate a single height,
H_i^{GRID}– height of a neighboring point from the regular GRID grid.

The interpolation process selects neighboring points with coordinates (X_i^{GRID}, Y_i^{GRID}), whose distance from the interpolated point (X_{int}, Y_{int}) is less than 5 m, i.e. the mesh of the regular GRID. The weight parameter in formula (1) is defined as a function of the inverse distance [13] and expressed in the unit [1/m^2]. The heights of neighboring points from the regular GRID mesh are given in meters.

In the second survey method, the coordinates of the selected DTM profiles were measured using GNSS satellite technology for the GPS RTK difference method. In the GPS RTK method, user coordinates are determined by dual-frequency phased GPS observations at L1/L2 frequencies using a double-difference technique. In the research test, a Leica Viva L1/L2 satellite receiver was used to measure the pickets in the field. The typical accuracy of the terrain elevation coordinate determination was approximately 0.05 m. The GPS RTK solution used correction corrections from the state-owned ASG-EUPOS receiver network.

Figures 5, 6, and 7 show a diagram of the distribution of measured control points for verification of DTM height determination. For profile no. 1, 32 pickets were measured over an area of approximately 0.3 km^2. On the other hand, for profile no. 2, 51 pickets were measured over an area of approximately 0.005 km^2. However, for profile no. 3, 39 pickets were measured over an area of approximately 0.002 km^2.

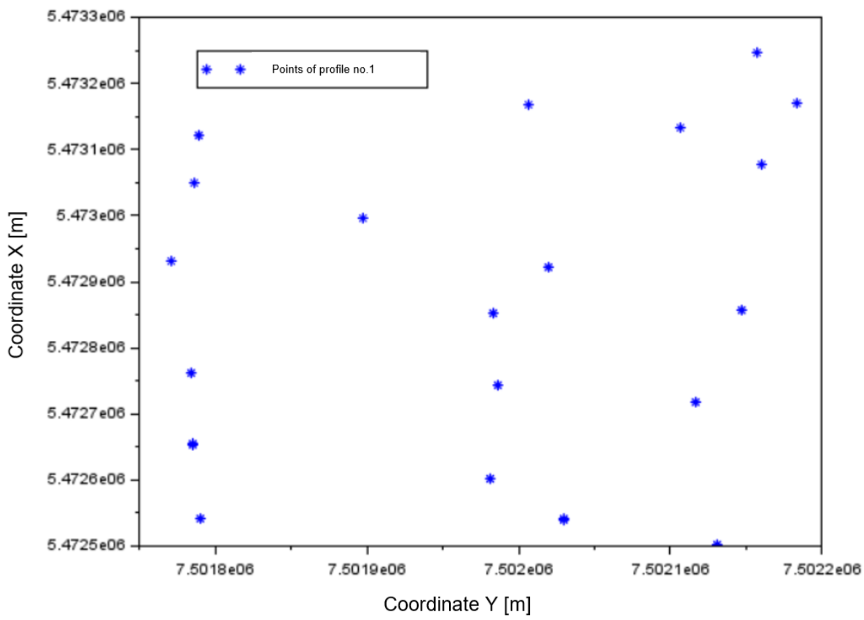

Fig. 4. The measurement points of profile no. 1 in the testing area

Figures 7, 8 and 9 show the DTM profile height values based on the interpolation model and the GPS RTK method. The scatter of the obtained DTM profile height results for the interpolation model is:
- from 608.35 m to 686.01 m for profile no. 1,
- from 643.19 m to 651.78 m for profile no. 2,
- from 644.27 m to 692.80 m for profile no. 3.

For the GPS RTK method, the scatter of DTM profile height results is respectively:
- from 608.46 m to 686.02 m for profile no. 1,
- from 643.01 m to 651.77 m for profile no. 2,
- from 644.20 m to 692.70 m for profile no. 3.

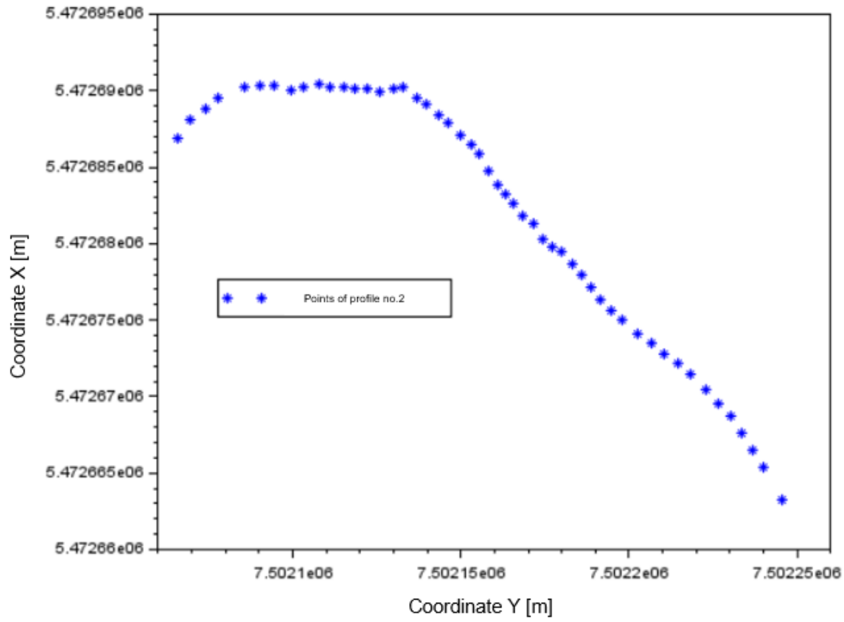

Fig. 5. The measurement points of profile no. 2 in the testing area

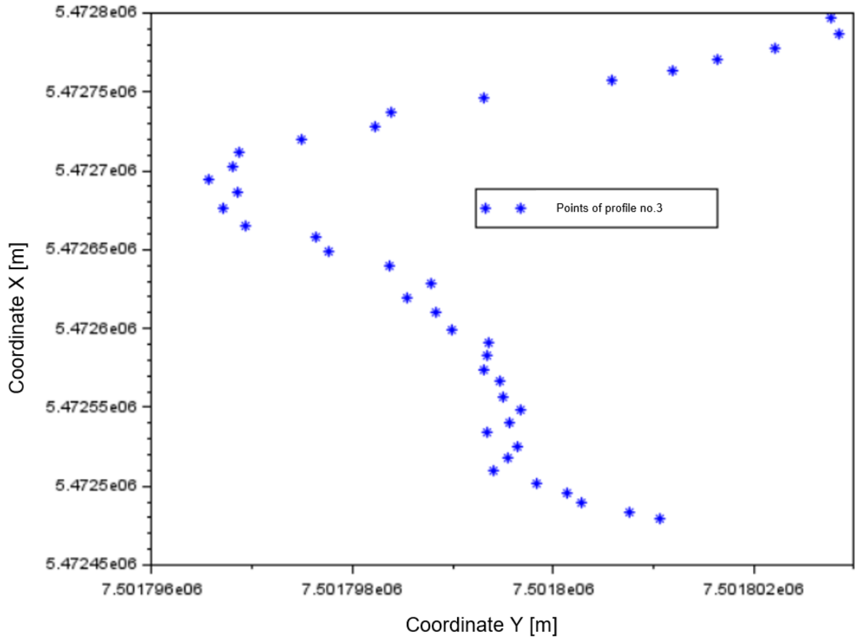

Fig. 6. The measurement points of profile no. 3 in the testing area

Figures 10, 11 and 12 then present the height difference of the measured DTM profile based on the interpolation model and the GPS RTK method. The value of the difference was determined based on the relationship:

$$dH = H_{int} - H_{GPS\ RTK} \tag{2}$$

where:

$H_{GPS\ RTK}$ – altitude from the GPS RTK measurement for a given profile point.

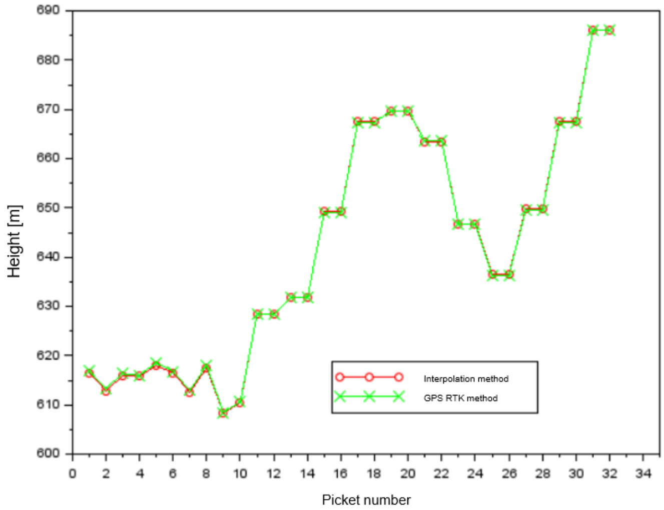

Fig. 7. The elevation of profile no. 1 in the interpolation model and GPS RTK method

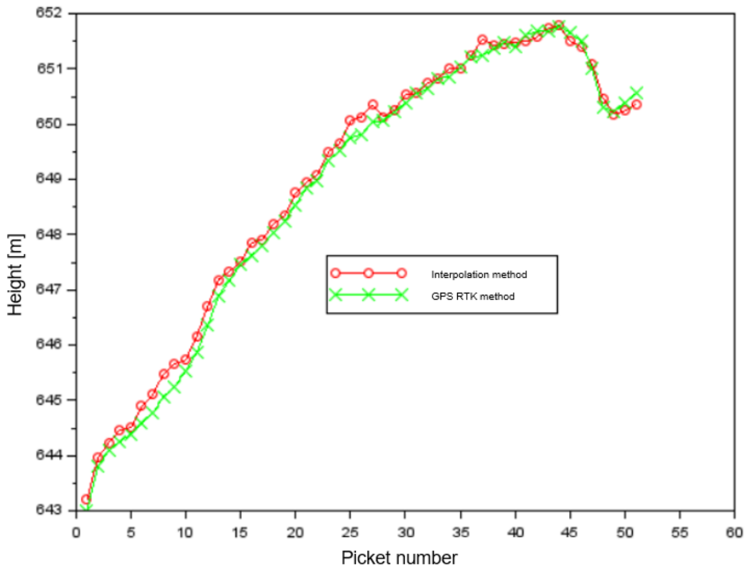

Fig. 8. The elevation of profile no. 2 in the interpolation model and GPS RTK method

In addition, for height difference dH, accuracy parameters were determined in the form of mean absolute error MAE_{dH} and mean squared error RMS_{dH} as recorded below:

$$MAE_{dH} = \frac{|dH|}{ns} \tag{3}$$

and

$$RMS_{dH} = \sqrt{\frac{[dH^2]}{ns}} \tag{4}$$

where:
ns – number of all measured pickets.

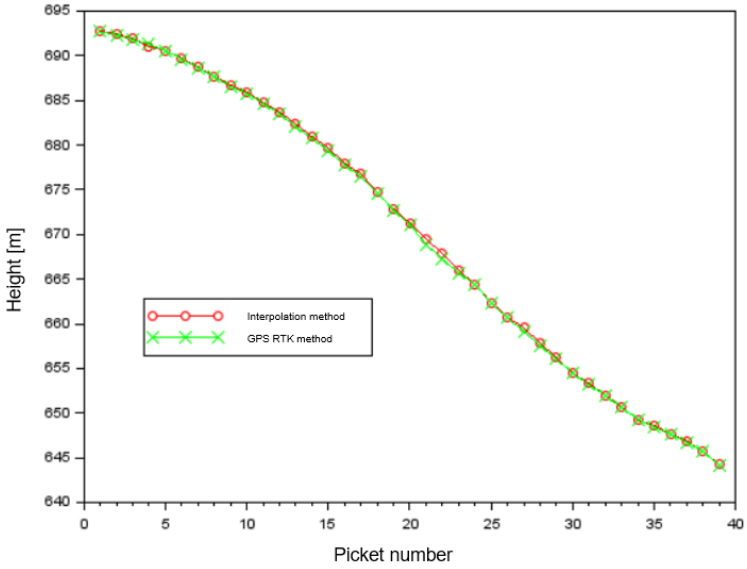

Fig. 9. The elevation of profile no. 3 in the interpolation model and GPS RTK method

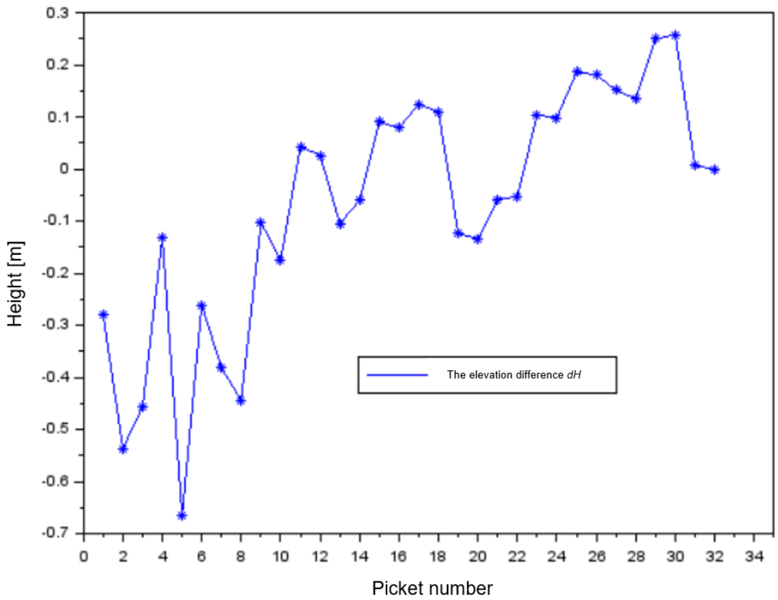

Fig. 10. The elevation difference of profile no. 1 between the interpolation model and GPS RTK method

For profile no. 1 (Fig. 11), the average value of the dH parameter is equal to -0.07 m, with the scatter of the dH parameter results ranging from -0.67 m to almost 0.26 m. The error value of RMS_{dH} is equal to 0.24 m, while the parameter $MAE_{dH}$is equal to 0.18 m.

On the other hand, for profile no. 2 (Fig. 12), the average value of the dH parameter is equal to 0.12 m, with the scatter of the dH parameter results ranging from -0.20 m to almost 0.41 m. The error value of RMS_{dH} is equal to 0.19 m, while the MAE_{dH} parameter is equal to 0.16 m.

In addition, for profile no. 3 (Fig. 12), the average value of the dH parameter is equal to 0.14 m, with the scatter of the dH parameter results ranging from -0.26 m to approximately 0.60 m. The error value of RMS_{dH} is equal to 0.21 m, while the parameter MAE_{dH} is equal to 0.15 m.

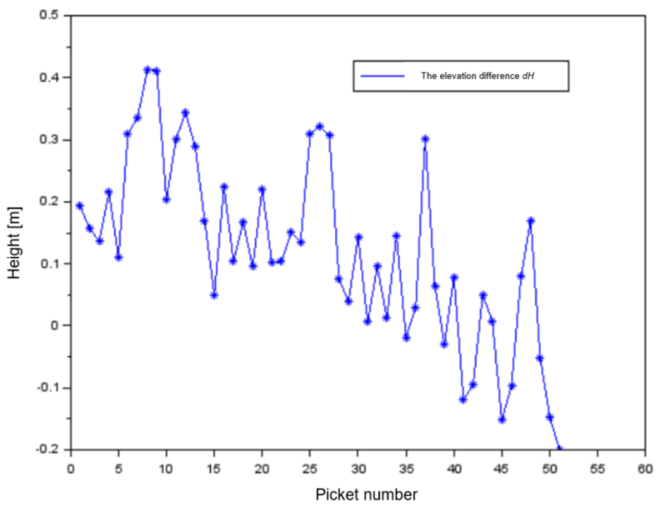

Fig. 11. The elevation difference of profile no. 2 between interpolation model and GPS RTK method

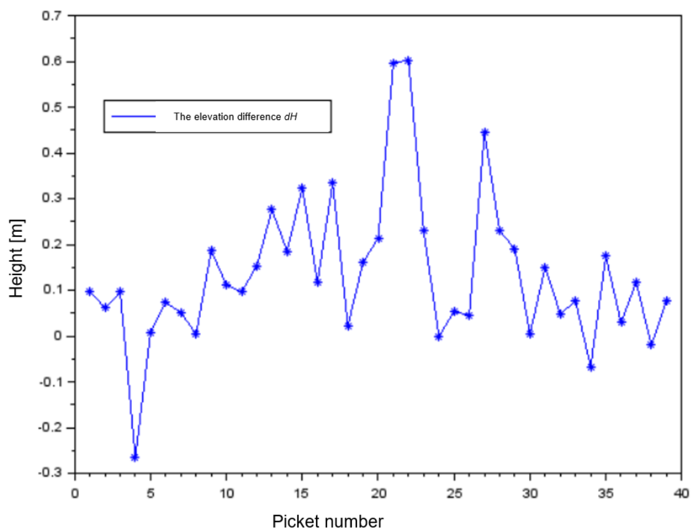

Fig. 12. The elevation difference of profile no. 3 between the interpolation model and GPS RTK method

4. DISCUSSION

The discussion chapter is divided into three parts. In the first part, the trend of change of the DTM height difference was determined in the form of a linear regression. In the second part, the repeatability of the proposed test methodology for the images obtained from the 150 m altitude was performed. The third part of the discussion is a comparison of the obtained survey results in relation to the literature on the subject.

In the first part of the discussion, Figures 15, 16 and 17 show the nature of the variation of the parameter *dH* in the form of a 1st-degree polynomial (linear regression function), which is described by the relation [13]:

$$dH = Q \cdot a + b \tag{5}$$

where:
Q – next picket number,
(a, b) – linear coefficients of the 1-degree polynomial determined.

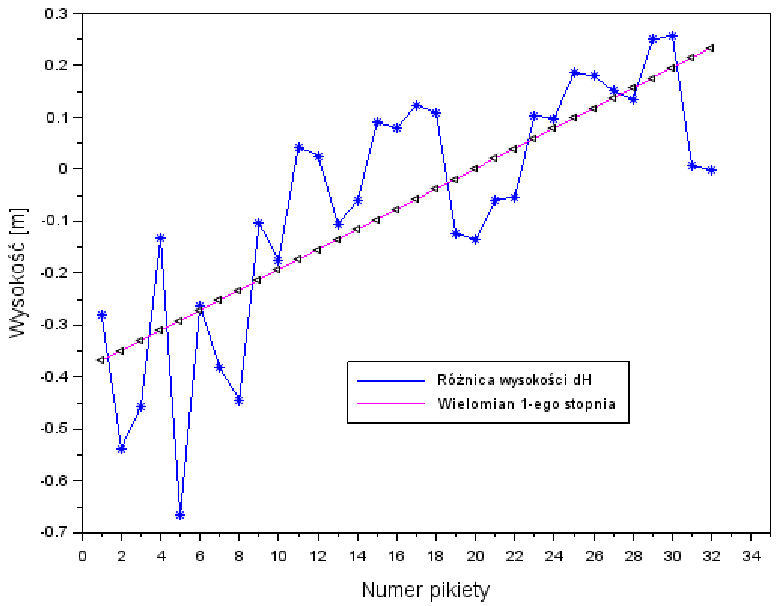

Fig. 13. The linear regression of values of the dH parameter from profile no. 1

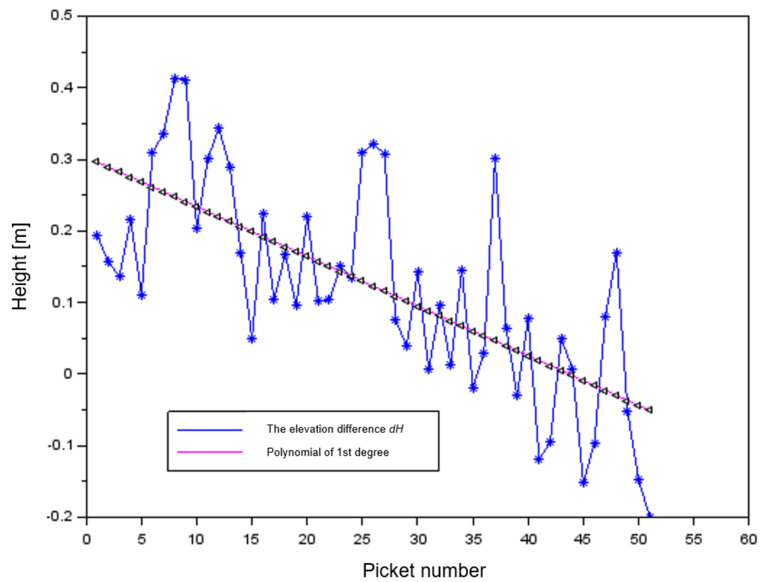

Fig. 14. The linear regression of values of the dH parameter from profile no. 2

The determined coefficients (*a*,*b*) from equation (5) are obtained by applying the method of least squares taking into account the values of dH for all measured pickets. For profile no. 1, the nature of the changes in the parameter is positive, as evidenced by the value of the linear parameter "a" equal to 0.019. The value of the parameter "b" is negative and equal to -0.387 m for the measurements adopted in the calculations. The error of fit of the linear regression function against the actual values of dH is 0.14 m. Furthermore, the distribution of corrections during the numerical calculations ranged from -0.22 m to 0.38 m. Subsequently, for profile no. 2, the nature of the changes in the parameter dH is negative and the values of the linear coefficients are a= -0.007 and b= 0.303, respectively. The error of fit of the linear regression function with respect to the actual values of dH is 0.11 m and the distribution of the corrections is described by the range of values (-0.25 ÷ 0.16) m. Then, for profile no. 3, the nature of the changes in the dH parameter is positive, and the values of the linear coefficients are a= 0.001 and b= 0.118, respectively. The error of fit of the linear regression function with respect to the actual values of dH is 0.16 m, and the distribution of the corrections is described by a range of values from -0.47 m to 0.39 m. The final obtained statistical values of the 1st-degree polynomial parameters for the individual DTM profiles are presented in Table 2.

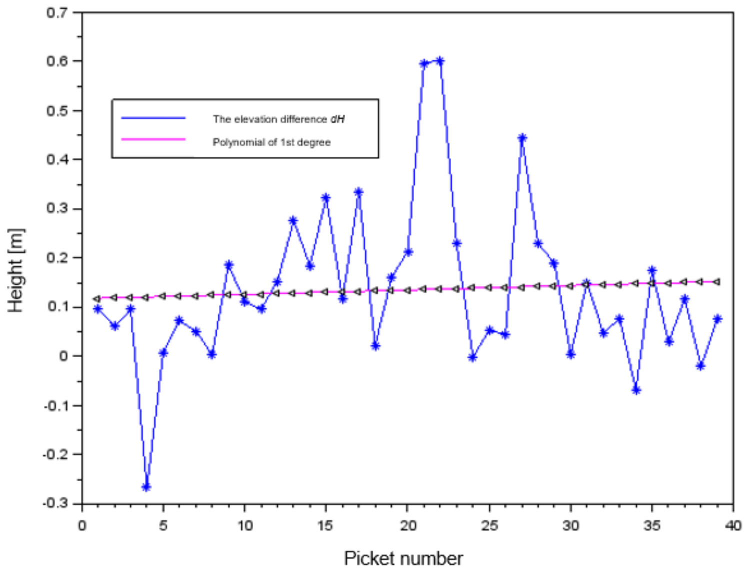

Fig. 15. The linear regression of values of the dH parameter from profile no. 3

Tab. 2
The characteristic of parameters of linear regression for all DTM profiles

Profile	Linear coefficients [m]	Distribution of amendments [m]	Fitting error of linear regression [m]
No. 1	a= 0.019 b= -0.387	-0.22 ÷ 0.38	0.14
No. 2	a= -0.007 b= 0.303	-0.25 ÷ 0.16	0.11
No. 3	a= 0.001 b= 0.118	-0.47 ÷ 0.39	0.16

The second part of the discussion was to determine the accuracy of the DTM generated from aerial photographs acquired from an altitude of 150 m. Figures 17, 18 and 19 show the difference in DTM height from interpolation and GPS RTK measurements for the first profile. In addition, the errors MAE_{dH} and RMS_{dH} were calculated.

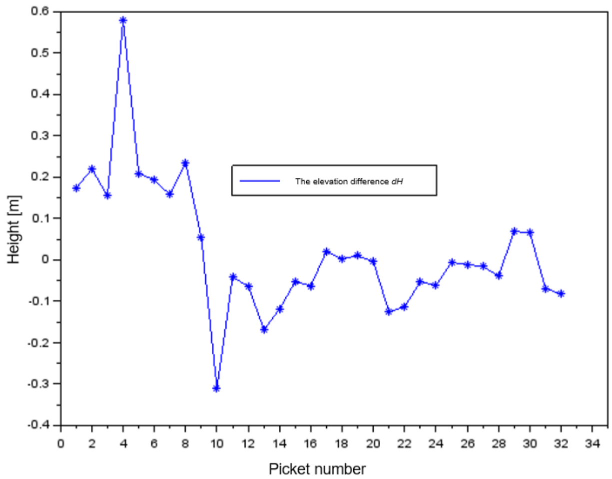

Fig. 16. The elevation difference of profile no. 1 between the interpolation model and GPS RTK method for altitude150 m

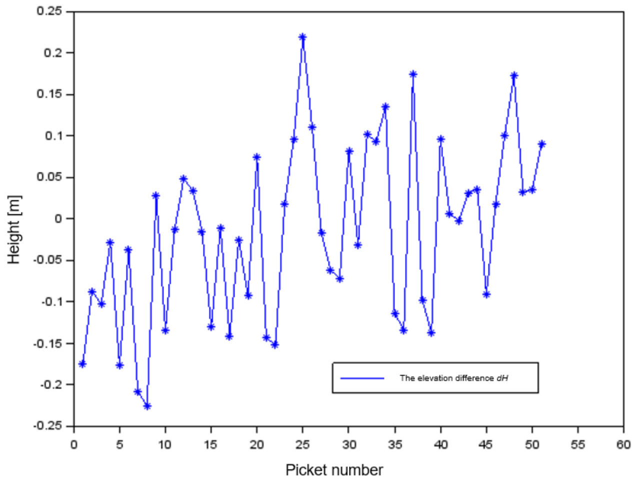

Fig. 17. The elevation difference of profile no. 2 between the interpolation model and GPS RTK method for altitude150 m

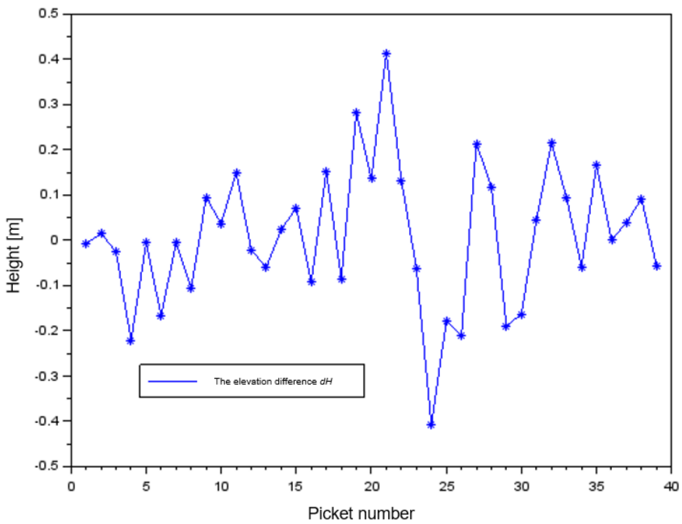

Fig 18. The elevation difference of profile no. 3 between the interpolation model and GPS RTK method for altitude150 m

For Profile no. 1, the scatter of results of the dH parameter ranges from -0.31 m to about 0.58m. The error value of MAE_{dH} is equal to 0.11 m, while the parameter RMS_{dH} is 0.16 m. Next, for profile No. 2, the results of dH difference were from -0.22 m to about 0.22 m, and the individual errors are MAE_{dH}=0.09 m, RMS_{dH}=0.10 m. Finally, for profile no. 3, the values of the dH parameter ranged from -0.41 m to about 0.41 m, and the individual errors are MAE_{dH}=0.12 m, RMS_{dH}=0.15 m. Table 3 shows the summary comparison of MAE_{dH} and RMS_{dH} errors obtained in the process of DTM development for image data acquired from 150 m and 300 m altitude. Based on the obtained results of MAE_{dH} and RMS_{dH} errors, it can be said that:
- the accuracy expressed by the MAE_{dH} parameter increased from 20% to 44% when using image data at the 150 m altitude than from the 300 m altitude,
- the accuracy expressed by the RMS_{dH} parameter increased from 28% to 47% when using image data at the 150 m altitude than from the 300 m altitude.

Tab. 2
Characteristics of the accuracy of the DTM developed from aerial photographs acquired from 150 m and 300 m altitude

Profile	Height 300 m	Height 150 m
No. 1	$MAE_{dH} = 0.18\,m$ $RMS_{dH} = 0.24\,m$	$MAE_{dH} = 0.11\,m$ $RMS_{dH} = 0.16\,m$
No. 2	$MAE_{dH} = 0.16\,m$ $RMS_{dH} = 0.19\,m$	$MAE_{dH} = 0.09\,m$ $RMS_{dH} = 0.10\,m$
No. 3	$MAE_{dH} = 0.15\,m$ $RMS_{dH} = 0.21\,m$	$MAE_{dH} = 0.12\,m$ $RMS_{dH} = 0.15\,m$

The final stage of the discussion concerns the comparison of the results and the presented research method in relation to the analysis of the state of the art.

Referring to the results presented in the article and comparing them with other publications concerning the accuracy of Digital Terrain Models (DTMs) obtained using low-altitude photogrammetry, several important similarities can be observed. When compared to studies presented in publications such as [14], similar challenges and opportunities associated with the use of UAVs in photogrammetry are apparent. Our study indicates the effectiveness of the weighted average method for interpolating heights from a GRID network, which aligns with the findings of other works [6], where the accuracy of models obtained using this method is also emphasized in comparison to standard geodetic techniques like RTK GPS.

In our study, where the experiment was conducted on a sample of 51 points, an average height difference of -0.02 m and an RMS error of 0.11 m are indicators of good quality DTM interpolation. A similar study presented in [5] also demonstrated that low-cost UAV photogrammetry could provide sufficient accuracy for many applications, although it highlighted the need to consider terrain specifics, such as vegetation or topography.

The values of the linear coefficients (*a, b*) determined in our study for different profiles show that the nature of terrain height changes can vary depending on the specifics of the measurement location. This observation is significant in the context of discussions on DTM creation methodology and accuracy assessment, as different areas may require the interpolation method to be adjusted to the data specificity.

5. CONCLUSION

The article demonstrates the feasibility of using Unmanned Aerial Vehicle (UAV) technology, for determining the height of a Digital Terrain Model (DTM) from images acquired at an altitude of 300 meters. The DTM was developed as an additional product of digital aerotriangulation for the aerial photographs obtained. The DTM coordinates for a regular 5 m GRID were used to determine the terrain profile height, which was also measured using GPS RTK technique. The research experiment was conducted on a sample of 51 measured points. The terrain profile height values were interpolated from the regular GRID using the weighted average method and compared with the solution obtained using the GPS RTK technique. The average difference in terrain profile height from the comparison was -0.02 m, with an RMS error of 0.11 m. Additionally, the work describes changes in the height difference parameter of the profile using a first-degree polynomial function, with a polynomial fitting error relative to the determined height difference values of 0.09 m.

Future perspectives for the development of the presented methodology for determining the accuracy of the DTM based on UAV image data could consider several avenues. Firstly, it would be beneficial to investigate the impact of different atmospheric and seasonal conditions on the quality of image data and their effect on DTM accuracy. It is possible that data acquired at different times of the year or under various lighting conditions could influence the results of terrain height interpolation.

Secondly, the application of advanced image processing algorithms and machine learning techniques could improve the automation of the DTM creation process and enhance its precision. In particular, these techniques could assist in better identifying and eliminating potential errors and anomalies in image data.

A third perspective involves the use of a greater number of independent check points (ICPs) measured with GPS RTK technique, which could improve model calibration and increase the accuracy of interpolation. Experiments with different GRID sizes and the application of other interpolation methods, such as kriging or splines, may also yield valuable results.

Moreover, future research could focus on optimizing and automating the entire measurement and computation process to further reduce the time required to develop DTMs and decrease the costs associated with such studies.

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Received 16.06.2025; accepted in revised form 08.09.2025