UDC 528.721

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https://doi.org/10.23939/istcgcap2023.97.056

ANALYSIS OF THE RESIDUAL DISTORTION AND FORWARD MOTION INFLUENCE ON THE ACCURACY OF SPATIAL COORDINATES DETERMINATION BASED ON UAV SURVEY

The purpose of this work is to study the operation of a non-metric digital camera Canon EOS 5D Mark III installed on a DJI S1000 octocopter, regarding the accuracy of spatial coordinates determination on images, and perform the identification and analysis of errors affecting the accuracy of stereophotogrammetry survey. During the experimental part, we conducted the stereophotogrammetric and aerial surveys of the areas including marked points. This served as a source of data for creating stereo models with their subsequent processing with the use of the Delta 2 software. The catalogs of spatial coordinates of the marked points were formed according to measurements taken by the Trimble M3 DR Total Station and from stereo models. We calculated the differences and defined root-mean-square error of determining the spatial coordinates of the points on images. Considering the specifics of the marked points placement on the studied sites, we also calculated the errors of image displacements caused by terrain. Additionally, the research studied the influence of camera's forward motion on the accuracy of survey data of unmanned aerial vehicle (UAV). The obtained results confirm the presence of residual distortion in the optical system of the Canon EOS 5D Mark III digital camera. This leads to the need to calibrate the camera for improving the accuracy of the obtained images for their further use in mapping, monitoring geomorphological processes and phenomena, creating a Digital Elevation Model, etc. Also, the study revealed the influence of forward motion of the survey camera and image displacements caused by the height difference of the survey sites on the accuracy of created stereo models. The authors proposed a configuration and created an experimental site of marked control points on the ground for calibrating a digital non-metric camera in conditions as close as possible to the real survey conditions. Considering the analyzed literary sources, it is more effective than calibration in a laboratory.

Key words: digital non-metric camera, aerial survey, unmanned aerial vehicle (UAV), image motion, residual distortion.

Introduction

Application of unmanned aerial vehicles (UAVs) for mapping, monitoring geomorphological processes and phenomena, the creation of a Digital Elevation Model (DEM) has a number of significant advantages compared to manned aircraft. They involve flexibility, efficiency and relative ease of preparing and performing surveys, high resolution, and economic feasibility [Hlotov et al., 2014; Gerke & Przybilla, 2016]. These factors lead to a wide range of potential UAV applications, including: dealing with disasters (forest fires, earthquakes, floods); environmental protection (monitoring of water and air pollution, landfills, technogenic objects, detection of illegal production); protection of critical infrastructure (oil and gas pipelines; traffic surveillance); precision agriculture; etc. [Mohsan et al., 2022; Niemeyer, 2015].

The number of publications on this topic confirm the rapid growth of UAVs popularity and their application. Thus, on the scientific portal ResearchGate [ResearchGate, n.d.] in 2002, 120 articles were published whose titles contain the word "UAV", and since 2012 till 2022 the number of such papers reached 1000 per year.

The accuracy of the obtained results and the final product is the key point regarding rational use of the UAV for a certain survey. Indeed, in contrast to traditional aerial survey from manned aircraft, the limited dimensions of UAVs and their technical characteristics do not allow the installation of high-quality survey and navigation equipment, replacing them with mass-market non-metric digital cameras and, as a rule, inexpensive Micro Electro-Mechanical System (MEMS) sensors. As a result, UAV survey data can be characterized by different scales of images, significant angles of inclination, deviation of flight routes from the pre-defined ones [Schultz et al., 2015; Ai et al., 2015].

Among the factors affecting the quality of the UAV survey results, the most important technical characteristics of the survey camera are equivalent focal length and coordinates of the image center x0, y0, etc. [Bosak, 2013].

When using non-metric cameras, interior orientation elements are undefined. There is a residual distortion of the optical system, which makes it impossible to obtain accurate and reliable three-dimensional metric information from the image of the object being studied. Therefore, to determine the mentioned elements, non-metric cameras have to be calibrated [Cramer et al., 2017].

There are several ways to calibrate the non-metric cameras, both in the laboratory and in the field, each of them having a number of advantages and disadvantages [Hlotov et al., 2020; Cramer et al., 2017; Griffiths & Burningham, 2019].

Due to the imperfection of an optic system of non-metric cameras, the survey accuracy will vary depending not only on the technical characteristics of the camera, but also on the survey conditions. This necessitates the study of each specific digital non-metric camera used for aerial photogrammetry [Griffiths & Burningham, 2019].

However, the reviewed and analyzed literary sources [Hlotov et al., 2020; Cramer та ін., 2017; Griffiths & Burningham, 2019] do not provide information on a universal methodology for study and calibrating non-metric cameras, moreover researchers focus on the importance of choosing the optimal method depending on the conditions and the subject of the survey. In this aspect, the actual issue is to identify and study the difference in the results of various calibration methods on complex objects with a significant height difference.

Purpose

The main objective of the presented work is to study the operation of the Canon EOS 5D Mark III non-metric digital camera installed on the DJI S1000 octocopter in laboratory and in the field, regarding the accuracy of spatial coordinates determination on images, and perform the identification and analysis of errors affecting the accuracy of stereophotogrammetry survey.

Methodology and results

The methodology for studying the digital camera is based on determining the spatial coordinates of control points with a stereo model and comparing them with the data obtained by a Trimble M3 DR Total Station.

The first survey object was a site of the corresponding marked points, located in the hall of the Department of Photogrammetry and Geoinformatics (FGI) of Lviv Polytechnic National University (Fig. 1). It consists of three planes with a total elevation of 1.5 m and includes 31 marked points (Fig. 2).

Fig. 1. The survey area located in the hall of the FGI department

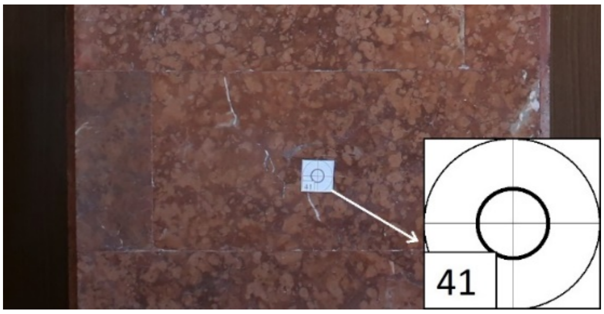

Fig. 2. Example of control point marking

Stereophotogrammetric survey was performed with the Canon EOS 5D Mark III non-metric digital camera. The main technical characteristics of the camera are presented in Table 1.

At the initial stage, a priori accuracy estimation of the spatial coordinates determining by Trimble M3 DR Total Station was conducted according to the formulas 1:

$$m_{X,Y} = \frac{\sqrt{2}}{2}(m_d^2 + d^2 \frac{m_\alpha^2}{\rho^2})^{\frac{1}{2}}, \quad (1)$$

$$m_Z = \frac{\sqrt{2}}{2}(\frac{m_d^2}{d^2} + d^2 \frac{m_\beta^2}{\rho^2})^{\frac{1}{2}},$$

where m_d = 2 mm – accuracy of distance determination; $m_{\alpha,\beta}$ = 5" – accuracy of measuring angles; d – distance to the survey object.

In specific survey conditions at a distance to the object of 4 m, the accuracy of determining spatial coordinates $m_{X,Y} = 1.4$ mm, and $m_Z = 3.4$ mm, according to the a priori accuracy estimation by formulas 1.

Formulae 2 were used for a priori accuracy estimation of determining the spatial coordinates based on images [Vovk, et al., 2015].

Table 1

Specifications of digital camera Canon EOS 5D Mark III

Sensor	36 x 24 mm, CMOS
Max. image size	5760 × 3840
ISO sensitivity	Auto (100–12800) ISO
Shooting speed	30 FPS
Sensor aspect ratio	3:2
Focal length	24 mm
Exposure	30 - 1/8000 s
Battery life	850 shoots
Dims (without lens)	152 x 116.4 x 76.4 mm
Weight (without lens)	950 g

$$m_x = mx_1\left[\left(\frac{m_{x_1}}{x_1}\right)^2 + \left(\frac{m_p}{\frac{f}{H}B}\right)^2 + \left(\frac{x_1^2}{f\left(\frac{f}{H}B\right)}m_{\Delta_\alpha}\right)^2 + \left(\frac{x_1y_1}{f\left(\frac{f}{H}B\right)}m_{\Delta_\omega}\right)^2 + \left(\frac{y_1}{\frac{f}{H}B}m_{\Delta_\chi}\right)^2 m_\omega^2 + \left(\frac{x_1}{f}m_\varphi\right)^2\right]^{1/2};$$

$$m_y = my_1\left[\left(\frac{m_{y_1}}{y_1}\right)^2 + \left(\frac{m_p}{\frac{f}{H}B}\right)^2 + \left(\frac{x_1^2}{f\left(\frac{f}{H}B\right)}m_{\Delta_\alpha}\right)^2 + \left(\frac{x_1y_1}{f\left(\frac{f}{H}B\right)}m_{\Delta_\omega}\right)^2 + \left(\frac{y_1}{\frac{f}{H}B}m_{\Delta_\chi}\right)^2 + \left(\frac{x_1}{f}m_\varphi\right)^2\right]^{1/2} \quad (2)$$

$$m_z = mf\left[\left(\frac{m_p}{\frac{f}{H}B}\right)^2 + \left(\frac{x_1^2}{f\left(\frac{f}{H}B\right)}m_{\Delta_\alpha}\right)^2 + \left(\frac{x_1y_1}{f\left(\frac{f}{H}B\right)}m_{\Delta_\omega}\right)^2 + \left(\frac{y_1}{\frac{f}{H}B}m_{\Delta_\chi}\right)^2 + \left(\frac{x_1}{f}m_\varphi\right)^2\right]^{1/2},$$

where m = 167 – scale denominator of the survey; f = 24 mm – camera focal length; $m_x = m_y = m_p$ = 0.005 mm – accuracy of spatial coordinates measurements in the image; x_1; y_1– abscissa and ordinate of camera sensor ($x_1 =$ 17.9 mm; $y_1 = 12$ mm); B = 50 cm – value of real base; H – distance to the survey object; $m_\alpha = m_\omega = m_\chi = m_\varphi$ = 3" – accuracy of angular coordinates measurements in the image.

The accuracy of determining the spatial coordinates based on images is: $m_X = 5$ mm; $m_Y =$ 4 mm; $m_Z = 7$ mm, by stereophotogrammetry survey with a Canon EOS 5D Mark III camera from a distance of 4 m to the study object.

Bearing in mind that the marked points are located on three different planes to the frontal projection (Fig. 3), it is necessary to consider the image displacements caused by the terrain, applying for this formula 1.3:

$$\delta r_h = \frac{h}{H}r, \quad (3)$$

where H – distance to the survey object; h = 1 m – survey object elevation; r = 21.6 mm – the maximum radial distance in the image from the main point to the offset point.

According to (3), in case of stereophotogrammetry survey, the maximum error value will be at the minimum distance to the study object, and this case will be considered in the experiment. The image displacement caused by the terrain is calculated. If $H = 4$ m and $h = 1$ m, then the displacement $\delta r_h = 6$ mm.

The coordinates of the marked points were determined by a Trimble M3 DR Total Station and by the stereophotogrammetry method with the use of the Canon EOS 5D Mark III digital camera (Fig. 4).

The absolute orientation of the images was done in the Delta 2 software environment based on coordinates of seven marked points which were placed on the middle plane. According to the orientation results x_0 = 0.401 mm, and y_0 = -0.328 mm. The coordinates of the marked points on the images were obtained in a stereo mode.

According to the differences in coordinates of the marked points determined by the Total Station and obtained on images, a root-mean-square error (RMSE) of the deviation of the spatial coordinates of the control points was calculated according to the data of the stereophotogrammetry survey: $m_X = 29$ mm; $m_Y = 36$ mm; $m_Z = 38$ mm.

Fig. 3. The depth of the survey object relative to the plane of focus (a=105 cm; b=50 cm)

Fig. 4. Stereophotogrammetry survey of the control marks with a non-metric camera Canon EOS 5D Mark III

After analyzing the differences, the largest errors in determining the coordinates of marks located on the front plane of the survey site were revealed. They were caused by a significant elevation between the plane of sight and the front plane (1 m). If the control points located on the front plane of the survey site are excluded, the coordinates are: $m_X = 11$ mm; $m_Y = 11$ mm; $m_Z = 9$ mm.

For the investigations of digital cameras, not only the error values, but also their distribution has a significant influence on determining the sources causing them. Fig. 5 presents a vector field of the deviations of coordinates of marked points obtained from the stereo model (indicated by red vectors) from the coordinates determined by the Total Station (indicated by black dots).

Analyzing the vector diagram in Fig. 5, it is difficult to state unequivocally about the presence of a certain type of the camera lens distortion due to insufficient density of control marks. However, the influence of the elevation of a study object on the accuracy of the stereo photogrammetry data is obvious. The greatest deviations are observed on the control marks of the upper row, where the height difference with the plane of sight is 1 m.

To study the operation of the digital camera during the aerial survey, the second survey site of marked points was created in an open area. For this purpose, 60 points were fixed and marked in the Geoterrace, educational geodetic laboratory located on the roof of Building 2, Lviv Polytechnic National University (Fig. 6). An example of point marks is shown in Fig. 7.

Fig. 6. The survey area with marked points which was created in the laboratory Geoterrace

The rectangular configuration of the second survey site and the number of marked points make it possible to calibrate the camera in the field, under the conditions close to the real survey from the UAV.

The aerial survey was conducted with a DJI S1000 octocopter (Fig. 8). The specifications of the octocopter are presented in Table 2.

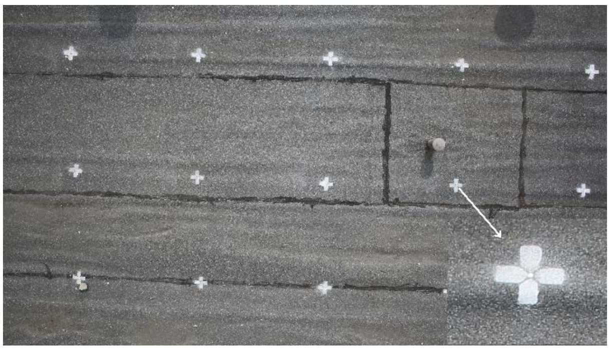

Fig. 7. An example of marking points on the created survey site

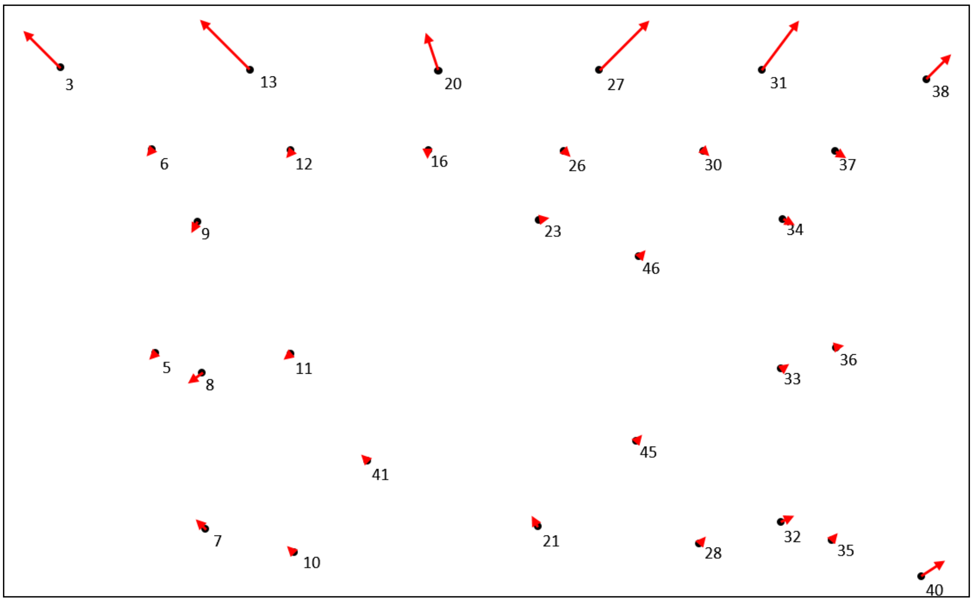

Fig. 5. Vector field of control points displacement in the image based on stereophotogrammetry survey (red vectors) data in relevance to their Total Station coordinates (black dots)

Fig. 8. General view of the octocopter DJI S1000

Table 2

Specifications of the octocopter DJI S1000

Engine type	Electrical
Temperature range	-10 °C ~ +40 °C
Maximum altitude	500 m
Maximum flight time	15 min
Battery capacity	15000 mAh
Dims	460 x 511 x 305 mm
Weight	4.4 kg

The stage of planning included the aerial survey at the minimum altitude of 12 m. This allowed capturing the entire block of marked points with one flight route. A priori accuracy estimation of determining the spatial coordinates on the images was calculated using formulas 2. The errors were: $m_X = 2.8$ cm; $m_Y = 2.1$ cm; $m_Z = 3.3$ cm.

To consider the elevation component, 4 points of the instrument table-stands were used, the height of which from the total block of marked points is approximately 1.5 m (Fig. 9).

Fig. 9. The height component of the marked points survey site in Geoterrace (h=150 cm)

According to (3), the value of the image displacement caused by the terrain was calculated. If

$H = 12$ m and $h = 1.5$ м, the displacement $\delta r_h =$ 2.7 mm. This confirms the need to increase the survey altitude with significant elevation changes of the study objects to reduce the influence of the image displacement caused by terrain.

Aerial survey data were processed in the Delta 2 software environment. Relative orientation of images was performed by 12 points according to the extended scheme. The absolute orientation of the stereo model was performed using 9 points. According to the orientation results, x_0 = 0.401 mm, and y_0 = -0.328 mm.

To study the accuracy of the stereo model, the coordinates of the marked points were measured in the stereo mode. The differences in the coordinates of the marks and the RMSE of the deviation of the spatial coordinates of control points according to aerial survey data were calculated: $m_X = 19.7$ cm; $m_Y = 9.7$ cm; $m_Z = 3.9$ cm.

Fig. 10 shows the vector field of the displacement of the coordinates of the control points in the image of the second survey site in the Geoterrace scientific laboratory according to aerial survey data.

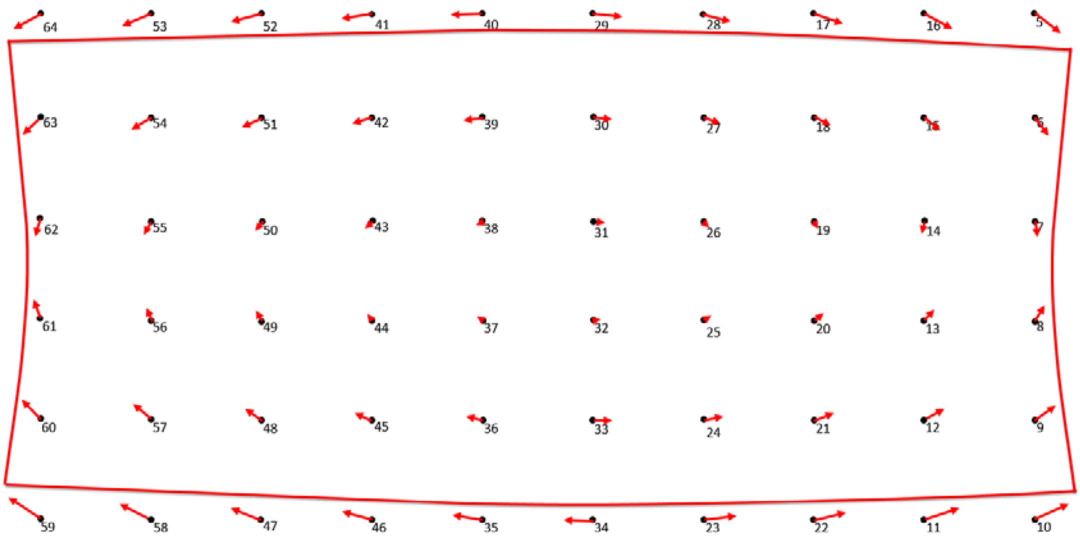

Fig. 10. Vector field of control points displacement in the image based on aerial UAV survey data

A presented vector field confirms the presence of residual distortion of a Canon EOS 5D Mark III lens.

Another factor affecting the accuracy of aerial survey results is the motion blur of the digital image during exposure.

The source of the motion blur of the image is the movement of the camera along the axes X, Y, Z with the speed V_x , V_y , V_z in the direction of a UAV flight route. It occurs through forward movement of the UAV along the route line (in this case, the camera displacement speed will be equal to the UAV flight speed); perpendicular deviation of the UAV from the route line; UAV flight altitude change on the route [Burshtinska, 1999].

To understand the forward motion blur process, let us consider Fig. 11, where a certain point M is fixed on the image P at point m at the moment of opening the camera shutter. During exposure time t the projection center S moves the distance Vt to a point S', where V is the speed of the camera. At that time, the point M continues to be depicted on the image P. At the moment when the shutter is closed, it will be projected into the point m'. As a result, point M will appear on the image as a segment mm'= δ [Ivanov et al., 2004].

Therefore, segment δ represents the image motion in the plane of the applied frame. According to the similarity of triangles MSS' and S'mm', the image motion value is calculated with the formula (4).

$$\delta V_W = Vt\frac{f}{H}, \qquad (4)$$

where f = 24 mm – camera focal length; H = 12 m – survey altitude.

Theoretically calculated motion blur of the image (4) is 0.4 mm at UAV flight speed of 6 m/s, the exposure time of 1/800 s, and a distance to the study object 12 m.

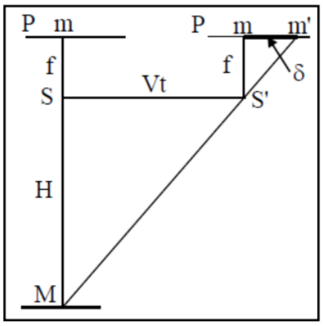

Fig. 11. Image forward motion in the plane of the applied frame

The real value of the image motion blur was measured for each marked point (Fig. 12).

Fig. 12. Linear image motion during aerial survey from the octocopter DJI S1000

It was determined that the practically measured value of the motion blur of the marked points in the image is 4.4 mm. That means reducing the sharpness of the image, which leads to a deterioration in the accuracy of the aerial survey results.

Conclusions

1. The analysis of literary sources confirms the need to calibrate digital non-metric cameras, which is necessary to improve determining the accuracy of the spatial coordinates on the image. There are different views on the feasibility of performing calibration in the laboratory and in the field.

2. The tacheometric and stereophotogrammetry survey of the marked points on the first site was carried out. The RMSE of the deviation of the spatial coordinates of the control points for stereophotogrammetry method: $m_X = 29$ mm; $m_Y = 36$ mm; $m_Z = 38$ mm. The largest errors are caused by points located on the front plane of the survey site, since the relief exists due to an elevation of 1 m at a distance of 4 m to the survey object. In case of excluding the points of the front plane of the survey site, the RMSE is: $m_X = 11$ mm; $m_Y = 11$ mm; $m_Z = 9$ mm.

3. The second experimental site was created in the Geoterrace, educational geodetic laboratory which includes 60 marked points. The site configuration allows exploring and calibrating the non-metric digital cameras under conditions as close as possible to the real field conditions of the earial surveys. The aerial survey of the second site was performed. The RMSE of determining the spatial coordinates of the marked points based on images was calculated: $m_X =$ 19.7 cm; $m_Y =$ 9.7 cm; $m_Z =$ 3.9 cm. The study presents the vector field of the coordinate's displacement of the control points in the image according to aerial survey data. This confirms the existence of residual distortions of the camera lens.

4. The study results of the accuracy of the accuracy of spatial coordinates determination on images demonstrate a significant difference in errors under different survey conditions, which confirms the need to calibrate non-metric cameras in the field. The performed analysis demonstrates the presence of the residual distortion, as well as motion blur and research object elevation. It also shows their significant influence on the accuracy of determining the spatial coordinates with the use of images.

5. For future perspectives, after calibrating the Canon EOS 5D Mark III camera, it is planned to perform the aerial survey of sinkholes using the DJI S1000 octocopter within the territory of the Stebnytsky MMC Polymineral in order to study geomorphological processes caused by anthropogenic activity.

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АНАЛІЗ ВПЛИВУ ЗАЛИШКОВОЇ ДИСТОРСІЇ ТА ЗСУВУ ЗОБРАЖЕННЯ НА ТОЧНІСТЬ ВИЗНАЧЕННЯ КООРДИНАТ МІСЦЕВОСТІ ПІД ЧАС ЗНІМАННЯ З БПЛА

Метою роботи є дослідження цифрової неметричної камери Canon EOS 5D Mark III, що встановлюється на октокоптері DJI S1000 на предмет точності визначення просторових координат за знімками; виявлення та аналіз джерел похибок, що впливають на точність стереофотограмметричного знімання камерою Canon EOS 5D Mark III. Виконано стереофотограмметричне знімання та аерознімання з октокоптера DJI S1000 полігону маркованих точок, що слугували джерелом отримання даних для побудови стереомоделей з їх подальшим опрацюванням в програмному пакеті “Delta 2”. Сформовано каталоги просторових координат маркованих точок досліджуваних полігонів із вимірювань електронним тахеометром Trimble M3 DR і зі стереомоделей, обчислено різниці та СКП визначення просторових координат точок на знімках. Зважаючи на специфіку розміщення маркованих точок на досліджуваних полігонах, також обчислено вплив рельєфу місцевості та лінійного зсуву зображення на точність даних аерознімання. Отримані результати дослідження підтверджують наявність залишкової дисторсії оптичної системи цифрової камери Canon EOS 5D Mark III, що зумовлює необхідність проведення калібрування камери для підвищення точності отриманих знімків задля подальшого використання з метою картографування, моніторингу геоморфологічних процесів та явищ, створення ЦМР тощо. Також виявлено вплив лінійних зсувів та похибок, спричинених перепадом висот місцевості знімання, на точність побудови стереомоделей. Запропоновано конфігурацію та створено полігон маркованих контрольних точок на місцевості для проведення калібрування цифрової неметричної камери в умовах максимально наближених до умов знімання, що, з огляду на проаналізовані літературні джерела, є ефективнішим за калібрування в лабораторії.

Ключові слова: цифрова неметрична камера, аерознімання, безпілотний літальний апарат, зсув зображення, залишкова дисторсія.

Received 22.03.2023