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Methods of mapping the lands disturbed by mining operations and accuracy of cartographic images obtained from Unmanned Aerial Vehicles: A review

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Abstract

Purpose. Analyzing the land disturbance consequences caused by surface mining operations and methods for mapping these lands, as well as studying the accuracy of point coordinates of digital images obtained from materials of aerial photographic surveys using Unmanned Aerial Vehicles (UAVs). Performing a quantitative assessment of the Root Mean Square Error (RMSE) of point coordinates on cartographic images and determining the dependences of the RMSE of point coordinates on the photogrammetric parameters.

Methods. The review of previous research publications within the framework of the presented subject is performed in the following sequence: analysis of ecosystem disbalance as a result of surface mining operations; based on previous studies, collecting the data for quantitative assessment of accuracy in the form of RMSE of point coordinates on cartographic images obtained from the materials of aerial photographic survey using UAVs; statistical study of the relationship between the RMSE and photographic survey parameters.

Findings. The methods for mapping the disturbed lands to return them to their natural state after the consequences of surface mining operations are presented, based on a review of previous research publications on the subject of the work. According to the previous studies, the RMSE of point coordinates of cartographic images has been systematized, and, based on this, the accuracy of topographic plans has been determined for them. Statistical studies of the relationship between the quantitative assessment of the RMSE (xy) and RMSE (z) accuracy in relation to the photographic survey parameters have been performed. In addition, the scattering diagrams of the correlation dependence and the range of RMSE relative frequency have been presented.

Originality. Based on a critical analysis of previous studies on the lack of quantitative accuracy regulation of cartographic images obtained from aerial photographic survey using UAVs, the RMSE systematics has been performed in terms of the photographic survey height. Based on this, the accuracy of topographic plans, the relative frequency of horizontal and vertical distribution of errors, the mean value $\bar{x}$ and the root mean square error (σ) have been determined.

Practical implications. The systematics of the RMSE values of cartographic image point coordinates for certain photographic survey parameters and the scale of topographic images makes it possible to take this into account in the project of aerial photographic survey using UAVs of lands for various purposes, as well as to choose the height and photographic equipment according to the required accuracy.

Keywords: *surface mining, cartographic image, aerial photographic survey using UAVs, ground control points, root mean square error, orthophotomap accuracy*

1. Introduction

Mining of mineral deposits occupy a significant place on the territory of Ukraine, but surface amber mining has become the most popular. In the forests of Rivne, Zhytomyr and Volyn regions, due to illegal mining of amber on forestry lands, the area of coniferous forests is decreasing and the area of disturbed lands in need of reclamation is increasing [1]-[3].

Surface mining of amber on forestry fund lands has led to irreparable consequences. The vegetation cover has lost the integrity of the grass cover, as well as the destruction of tree plantations and the drying out of the forest stand are taking place [1], [5]. The damage from illegal mining has affected the environment, leading to the degradation of the existing relief structure, pollution of underground and surface water resources, etc. As a result of surface mining, small artificial lakes emerge in the form of openings, where water pumps directly flood the holes that facilitate the formation of small lakes [6], [7]. Turkish scientists [8] have developed a methodology to determine the prospects for land use of disturbed areas to reduce environmental damage, using the example of marble mining in the regions of Antalya, Burdur and Isparta. The influence of tin mining on changes in the environment and natural landscape on the Belitung Island in Indonesia has been studied. Therefore, all disturbed lands, as well as areas adjacent to them, which have completely or partially lost productivity, caused by surface mining, are subject to recla-

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mation. The latter is important for ensuring and returning these lands to their natural state [9]-[11].

Taking into account the ecological catastrophe in the areas of amber mining, the Cabinet of Ministers of Ukraine in 2017 adopted a resolution approving the "Procedure for the implementation of a pilot project for reclamation of forestry lands disturbed by illegal amber mining", using the example of forest areas of the No. 59 division of Dubrovytsia Forestry in Dubrovytsia District of Rivne Oblast. According to the data of the report "On environmental impact assessment of reclamation of lands disturbed by illegal amber mining", the total area of disturbed forestry lands in the No. 59 division of Dubrovytsia Forestry is 71 hectares, and the total area of disturbed plots is 69.9 hectares, that is, 98% of the division area (Fig. 1). A significant part of the forestry land area is disturbed by the use of motor pumps in pits and hydrodynamic bell-pits during illegal mining of amber, which leads to the destruction of the natural landscape [12].

Figure 1. The location of land plots disturbed by amber mining within the No. 59 division

At the stage of planning the reclamation works, it is important to determine the expediency of further use of these land areas and substantiate the direction of reclamation [13]. Based on the example of a mining site in Liaoning Province, China, a reclamation strategy has been developed that includes the land suitability analysis and assessment of ecosystem services. Assessment of ecosystem services helps to make decisions and implement forestry methods for reclamation of forest areas after technogenic processes caused by human activities [14].

For the design of engineering structures for reclamation systems and reclamation projects, it is necessary to have high-quality topographic and cartographic material that would make it possible to draw up rational projects for planning the disturbed lands with the required accuracy. Today, cartographic images in the form of topographic maps and plans are obtained using modern methods of the Earth's Remote Sensing (ERS), in particular, from Unmanned Aerial Vehicles (UAVs), which are an alternative to traditional methods. In recent years, satellite survey method has been used to map lands and study environmental changes caused by surface mining. The satellite survey method is important for monitoring the lands disturbed by illegal mining, as well as identifying and tracking of reclamation sites, and assessing changes in soil cover [15]. Monitoring for the disturbed lands within the No. 59 division of Dubrovytsia Forestry was performed using multi-temporal satellite survey method of the Landsat-5TM, Sentinel-2A and Sentinel-2B series of 2009, 2015 and 2017. As a result, the forest areas to be recultivated in the first place, and which areas should be left for natural restoration, have been determined. The restrictions in the use of satellite survey method for land mapping are the spatial resolution of materials, the cost and time required to process them, and weather conditions, including thick clouds. According to aerial photographic survey data from UAVs, digital elevation models (DEM) with high spatial resolution can be obtained, requiring field inspection to obtain high-precision topographic materials [16], [17].

Digital terrain mapping is a complex of processes for collecting and processing digital topographic information, forming a digital elevation model in software, which makes it possible to obtain various analytical and graphical materials. Digital surface models (DSM) are created in such a way that it is possible to select from them a model of terrain relief, building, structure, communication, hydrography, vegetation cover. Digital information about the terrain can be obtained in different ways: ground based geodetic method using electronic tacheometers and Global Positioning System (GPS); cartographic method, for which ordinary topographic maps serve as digital information about the terrain. The advent of small and inexpensive UAVs for aerial photographic survey has contributed to the development of new methods and technologies of digital mapping. Aerial photographic survey using UAVs has an advantage over satellite survey method; based on satellite survey data, the maps have an overall accuracy of 78.1%, and the accuracy of maps based on UAV data is 92.3%. The data obtained from UAV provide better detail of topographic images, including relief elements (hills, slopes, ravines, landslides, orographic lines), for land management [18]. Aerial photographic survey using UAV does not fundamentally differ from photography from manned aircraft, but it has its own characteristics in terms of its cruising speed, range of flight altitudes, conducting and installing main and additional equipment on UAV board. Land mapping using UAV is possible only if the geometric parameters of traditional aerial photographic survey are observed. The accuracy of such mapping can increase tens of times and be about a pixel (ground sample distance – GSD) for both conventional aerial photographic survey and satellite survey method [19]. It is known from traditional photogrammetry that the accuracy of aerial photographs depends on the photographing altitude, camera calibration and the accuracy of the control point coordinates connected with the ground geodetic network. The cost of mapping using traditional aerial photogrammetry is very high. Thanks to the introduction of small-format aerial photogrammetry technology, it became possible to obtain a digital map from digital aerial photographs of a small-format camera mounted on a lightweight UAV platform [20], [21]. Aerial photographic survey using UAVs has found its use for mapping the forest lands, monitoring and controlling the expansion of violations from illegal mining, forestry management, etc. Remote sensing from UAVs in forestry is still in the experimental stage, but it is expected to expand rapidly [22].

Over the last decade, a significant amount of research has been performed on the accuracy of mapping and 3-D modeling based on UAV data. The accuracy and substantiation of mapping materials is the main requirement for any new method of constructing topographic plans, digital surface models (DSM) and digital elevation models (DEM), including aerial photographic survey using UAV [23]. Remote sensing materials obtained from UAV are important for monitoring, including calculating the volume of soil displaced during construction and surface mining, studying the patterns of vegetation development, as well as observing the topographic changes, including subsidence, erosion and the development of streams [24]. The restriction in the Earth's remote sensing takes for the accurate identification of small areas and linear objects, the spatial resolution of a raster grid, which must be many times more accurate than an object in order to dtermine its peculiarities in detail. Accurate large-scale mapping of small, fragmented and linear vegetation areas depends on their area and extent [25]. Aerial photographic survey using UAV is used to create digital topographic plans of settlements at a scale of 1:2000, therefore, new ways to improve the use of small UAV systems for aerial photographic survey have been identified in [26]. Recently, digital elevation models (DEM) and orthophotomaps have been supplied in digital format and used in combination as an alternative to traditional topographic and contour maps. Large-scale topographic plans and DEMs are used to draw up projects for drainage, irrigation, land reclamation for agricultural and forestry purposes, in the mining and oil industries, as well as for predicting the hazards in the ecological system, which makes their accurate creation very important [27]-[29].

Land mapping using UAV makes it possible to obtain high-quality digital cartographic images, if to observe certain requirements for the process of implementation and setting photogrammetric equipment for aerial photographic survey, as well as the image processing algorithm. Aerial photographic survey using UAV provides spatial and temporal resolution for mapping and monitoring of natural landscapes and lands for various purposes. Modern specialized software makes it possible to automatically obtain DSM and DEM in the form of a dense 3D cloud of digital points based on aerial photographic survey data using UAV. Recently, studies on assessing the accuracy of cartographic images obtained from UAV data according to the number and distribution of ground control points (GCP), obtained in the course of work (VAU-RRK-SfM), have become widespread. Processing of aerial photographic survey materials obtained from UAV using Structure from Motion (SfM) software has become widespread in different countries around the world. The application of VAU-RRK-SfM makes it possible to obtain point clouds for a 3D-model based on high-resolution aerial photographs from UAV. The georeference of the point cloud to the GCP can achieve an accuracy of up to 25-40 mm based on images obtained from a flight altitude of approximately 50 m [30]-[33]. Therefore, obtaining the coordinates of ground control points remains today a very important, but time-consuming task. Conventional georeference using GCPs provides reliable positioning, but geometric accuracy is critically dependent on the number and distribution of GCPs. Direct georeferencing of images from UAV using a GNSS differential correction such as PPK (post-processing kinematics), overcomes these restrictions by providing accurate and directly georeferenced mappings [34]. It is indicated in the previous studies that with the use of modern equipment and GNSS geodetic sensor on UAV board, pixel accuracy of up to 3-5 cm can be achieved without GCPs [35], [36]. The issue of using the ground control points (GCP) for georeferencing of cartographic images is still relevant today. According to a review of publications, many previous studies are devoted to this problem with different approaches to its solution [37], [38].

Modern software for digital photogrammetry is capable of creating digital orthophotomaps and digital maps for both large-format metric camera and small-format digital camera. As for the accuracy assessment, it cannot be denied that the accuracy for a large-format metric camera is higher. During the review of previous studies, it has been substantiated that high accuracy can be achieved with a large-format metric camera compared to the accuracy of a small-format digital camera. Today, using a small-format digital camera, submeter accuracy can be achieved [21]. In recent years, as can be seen from the review of publications, previous studies have shown the validity of assessing the accuracy of cartographic images obtained from UAV data. From the analysis of previous studies, it has been found that the quantitative accuracy is somewhat different, and the accuracy of each individual research differs from the other. In the presence of a significant number of the RMSE of point coordinates and photogrammetric parameters, it is possible to reveal the actual RMSE range of quantitative accuracy of the cartographic image point coordinates. The lack of analysis and systematization of the disparate quantitative RMSEs of point coordinates is the motivation for our research.

Thus, the purpose of this paper is to review methods for mapping the lands disturbed by mining operations for their further reclamation and to systematize the RMSEs of point positions of the cartographic images obtained from UAV materials, taking into account the influencing factors, and also to determine the correlation between them based on an analytical review of previous research publications on this subject.

To achieve this purpose it is necessary to solve the following tasks:

– to review the methods of mapping the lands disturbed by mining operations;

– to systematize quantitative RMSEs of point coordinates of cartographic images obtained from UAV materials and determine the scale accuracy of topographic plans;

– performing a statistical analysis of the ratio between the RMSE accuracy of cartographic image points and photographic survey parameters.

Today this task is relevant and requires further research.

2. Materials and methods

When performing the research, the authors use regulatory legal documents of the state authorities of Ukraine, the materials of the report "Environmental Impact Assessment" made by the Institute of Environmental Geochemistry of the National Academy of Sciences of Ukraine, a review of research publications on the methods for accurately mapping of lands disturbed by surface mining of domestic and foreign authors, special literature, etc. This research is performed in the following sequence:

– analysis of the accuracy of cartographic images obtained from aerial photographic survey materials using UAV;

– an overview of the factors influencing the accuracy of digital cartographic images;

– analysis of root mean square errors of cartographic image points and their systematization by flight altitude.

2.1. Analysis of the accuracy of cartographic images obtained from aerial photographic survey materials using UAV

One of the criteria for assessing the accuracy of creating a digital elevation model based on UAV results is the RMSE of determining the point coordinates of cartographic images or the mean deviation of the referencing point coordinates in the triple overlap area of aerial photographs. In classical photogrammetry, the accuracy of the digital orthophotomap m_{ofp} is characterized by the error in measuring the position of the contour points on the orthophotomap:

$$m_{ofp} = \sqrt{\left(m_f M_{sn}\right)^2 + m_r^2 + \left(m_{\Delta r} M_{ofp}\right)^2}, \tag{1}$$

where:

M_{sn} and M_{ofp} – denominator of the scales of the original photographs and orthophotoplan;

$m_{\Delta r}$ – error of orthophotomap images, conditioned by the influence of the terrain relief;

m_f and m_r – errors of photogrammetric and geodetic measurements.

The permissible accuracy of the relief influence $m_{\Delta r}^{dop}$ on the DEM is determined by the measurement errors and the permissible orthophotomap error m_{ofp}^{dop} [39].

According to the Instruction for Topographic Survey at scales of 1:5000, 1:2000, 1:1000 and 1:500, “the maximum error of planned survey network points (including identification marks) relative to points of the state geodetic network and extensive geodetic networks should not exceed 0.2 mm at a scale of the plan in open and in the built-up areas, and 0.3 mm in the area covered with trees and shrubs” [40].

The mapping accuracy of aerial photographic survey using UAV depends on the RMSE accuracy of coordinates of ground control points, their number and distribution [41], [42]. For the most part, the RMSE quantitative accuracy is calculated as the difference between the coordinates of ground control points obtained from processing the images and the coordinates of these points from field measurements. It should be noted that in order to obtain an accurate orthophotomap and DSM, it is necessary to see this model stereoscopically, control the digital elevation model (DEM) using selected points for constructing the relief and performing metric measurements in absolute project coordinates, etc. At the present stage, stereoscopic observation of photographs from UAV is implemented in the software algorithms of digital photogrammetic stations (DPS). For example, the software for processing the images obtained from UAV is implemented in PHOTOMOD UAS by Rakurs Company, which makes it possible to create correct orthophotomaps for cartographic purposes [42].

The accuracy of cartographic images improves significantly depending on GSD (ground sample distance) resolution. Since the GSD (m/pixels) of images is calculated relative to the flight altitude and camera resolution, the vertical error increases as the GSD decreases [42]. The spatial resolution (GSD) of the image is higher for a lower altitude and, vice versa, it is lower for a higher flight altitude. The resolution from the ground surface of 24 and 50 mm can be achieved from the UAV flight altitude of approximately 80 and 160 m. Based on the previous studies, it has been revealed that the resolution of digital elevation model (DEM) is determined not only by the flight altitude, but also by the software used to process the research data. For example, for processing data obtained from UAV, the PhotoScan software package for computer vision with a height resolution of 10-17 mm is the most effective in flat terrain, while the photogrammetric Rapid Terrain with a resolution of 30-40 mm has advantages in high-relief terrain [33], [43].

2.2. An overview of factors influencing the accuracy of digital cartographic images

In a review of most previous research publications, it is noted that the accuracy of digital surface model (DSM) and orthophotoplan mainly depends on the quality and stability of photogrammetric equipment, photographing altitude, image scale, image overlap percentage, number and distribution of GCP, as well as processing algorithm. Based on a review of previous research publications, a significant influence on the accuracy of the constructed DSM has been noted not only by such factors as the photographing altitude, the number of planned and high-altitude ground control points, but also by the accuracy of determining the GCP coordinates. The accuracy of topographic images, orthophotoplan and digital surface model depends on the number of GCP, their distribution over the area and the configuration of the studied object [44]-[48]. In separate publications, the relationship between the errors of digital surface model points, their horizontal distance to the nearest GCP and flight altitude has been studied [42]. Although sometimes a higher flight altitude gives better accuracy based on other factors: the presence and number of GCPs, a geodetic receiver on the UAV platform, the percentage of image overlap, weather conditions and software for data processing [42], [49]. However, increasing the image overlap percentage has a positive influence on DSM accuracy, but leads to an increase in the number of images and the time to process them. Therefore, the image overlap percentage and scope for processing during an aerial photographic survey project is a trade-off between DSM accuracy and time spent for processing [48], [50]. The difference in time and cost of processing the aerial photographic survey projects with minimum and maximum image overlap percentages does not make a big difference in the survey data [28]. In order to reduce the number of images by increasing the UAV flight altitude, processing time and not degrading the DSM accuracy, a method for the radiometric transformation of images obtained using UAV at a high flight altitude (500 m) has been studied and compared with photogrammetric materials obtained from UAV at a low flight altitude. Such a new approach to studying the influence of radiometric transformation on the images obtained from UAV at a relatively high altitude can overcome the problems with low flight altitude [49], [50].

2.3. Analysis of root mean square errors of cartographic image points and their systematization by flight altitude

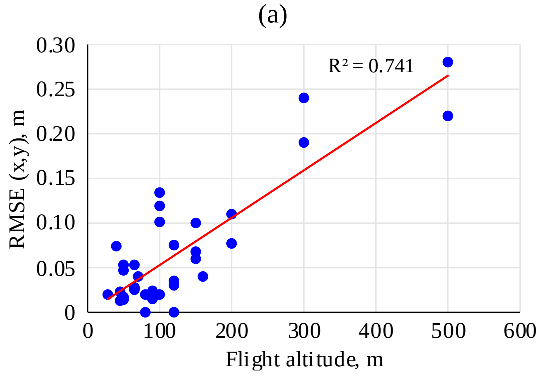
The purpose of this paper is to provide a review of the previous research publications on the accuracy of cartographic images obtained using UAV in the form of RMSE of point coordinates. The RMSE of point coordinates is used as a criterion for assessing the accuracy of cartographic images obtained using UAV.

Based on the previous studies, it has been revealed that most often the analysis of digital surface model (DSM) accuracy is performed by ground control points, which are recognized on the orthophotoplan to obtain X and Y coordinates, and the *Z* height is found by DSM. In some studies, RMSE of point coordinates is determined as the difference between the coordinates of ground control points measured on the orthophotoplan and those measured in-situ using the ground method, or as the difference between the referencing points of the photogrammetric network on different images. As previous studies have shown, the difference in the control point coordinates obtained by traditional ground methods and using aerial photographic survey from UAV does not exceed 1-3 cm in plan and 10 cm in height [42]. The research results [46] have confirmed that the horizontal accuracy of RMSE *xy* of point coordinates is not depend on the flight altitude and terrain relief, and their accuracy increases with an increase in the number of GCPs. The vertical accuracy of RMSE *z* of a point is not depend on the relief, but the flight altitude and the number of ground high-altitude GCPs have a significant influence [30], [34], [48]. According to the research results [42], the value of the vertical accuracy of the digital elevation model (DEM) for flight altitude 300 m is 0.11 m, and for altitude 500 m – 0.15 m. Similar image accuracies have been obtained for high and low flight altitude due to radiometric transformations [49], [50]. According to the Instruction for Topographic Survey, the mean errors in the position of GCPs (taking into account the recognition error on the images) should not exceed 0.1 mm at a scale of the developed map, and the maximum error should be 0.2 mm. The maximum errors in determining the coordinates of the planned GCPs in-situ should not exceed 0.14 mm on the map scale, and in areas covered with forests or bushes, the maximum error is 0.30 mm. The mean errors in determining the heights of GCPs (taking into account the recognition error on the images) should not exceed 0.1 of the contour interval height, and the maximum error should not exceed 0.2 of the contour interval height.

A review of previous research publications on quantitative accuracy has shown that the accuracy of the point positions for the same flight altitude is different, and the accuracy of an individual research can differ significantly from the other. Thus, for example, RMSE in studies [21] for a flight altitude of 100 m in plan is 0.28 m, and for a flight altitude of 0.32 m, in studies [41], it is 0.02 and 0.04 m, respectively. The discrepancies are 0.262 in plan and 0.284 m in height, which do not meet the requirements for photogrammetric works. In order to substantiate the reliable values of cartographic images obtained from UAV, it is necessary to have a significant number of samples for assessing the accuracy of previous studies. Taking into account the indicated previous research publications, in particular [22], [34], the RMSE have been supplemented with preliminary studies [51]-[55].

3. Results and discussion

In order to determine the actual accuracy of point coordinates on cartographic images according to the scale, based on preliminary studies, quantitative RMSE of point coordinates and photographic survey parameters have been collected, which are presented in Table 1. The quantitative RMSE values and the flight altitude of previous studies have been grouped to determine correlation dependence between them. The value of the approximation authenticity (R^2) and the correlation coefficient (r) are taken as indicators of statistical relationship. The statistical studies performed according to data in Table 1 have revealed that the correlation ratios between the quantitative horizontal RMSE (*xy*) and vertical RMSE (*z*) of point coordinates and flight altitude are $r_{x,y} = 0.86$ and $r_z = 0.62$, respectively. The correlation dependence of vertical RMSE (*z*) is less, which can be related to the number and accuracy of in-situ control points for high-altitude georeferencing of the network (Fig. 4a, b).



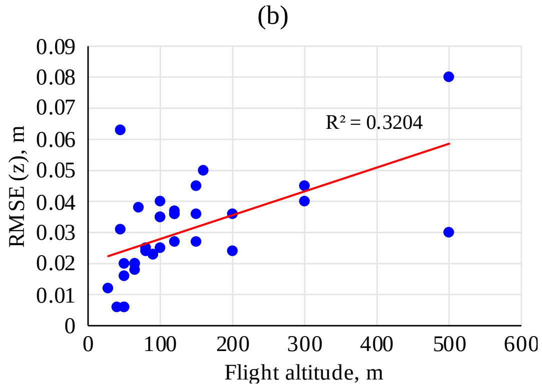


Figure 4. Accuracy scattering diagram: RMSE (xy) and RMSE (z) errors relative to flight altitude (a) and (b) based on the results of previous studies

Figure 5a, b shows that there is no a correlation ratio between the quantitative accuracy of horizontal RMSE (*xy*) and vertical RMSE (*z*) and resolution (GSD), as evidenced by (R^2) correlation coefficients of $rxy = 0.44$ and $rz = 0.32$. This means that the accuracy of point coordinates is dependent on more significant factors, such as: the accuracy of determining the GCP coordinates in-situ and the image processing algorithm. There is a closer ratio between GSD and flight altitude, the correlation coefficient is $r_{(GSDA)} = 0.59$ (Fig. 5c), which is confirmed by a review of previous research publications. The scattering diagram of the vertical accuracy of RMSE (*z*) relative to the number of GCPs shows that the results of previous studies do not show closeness of the ratio (Fig. 5d).

Figure 6 presents a histogram of the relative frequency of the vertical and horizontal distribution of RMSE obtained from previous studies of the quantitative accuracy of cartographic images. According to statistical analysis, the vertical distribution of RMSE (*z*) for most of the previous studies ranges from 0.02 to 0.07 m, the mean value of errors is 0.07 m, and the standard deviation (σ) of these vertical errors is $\sigma_z = 0.05$ m. The horizontal distribution of RMSE (*xy*) ranges from 0.01 to 0.10 m, but the mean value is 0.07 m and the standard deviation is $\sigma_{xy} = 0.07$ m. In both cases, the mean values are 0.07, and the standard deviations differ $\sigma_z = 0.05$, and $\sigma_{xy} = 0.07$ m, that is, they are different. The values of these indicators have been influenced by different instability of RMSE in the sample.

Table 1. The result of a review of previous studies on quantitative RMSE of point coordinates of cartographic images obtained from UAV

UAVs	Camera	GSD (*px*)	Overlapping images, %		Avg flight, height, m	Number GCP	*RMSE, m*		Scale, height of section of a relief h, m	References
			Px	*Py*			RMSE (*xy*)	RMSE (*z*)	0.1 mm M – 0.2 mm M; 0.1-0.2 *h*, m	
Ptero E4	Canon EOS5D (18MP)	0.080	80	40	500	14	0.22	0.12	1:1000, *h* = 1 m	[19]
Rotary-wing Octocopter	Canon550D (18MP)	0.008 0.008 0.008	75	65	50 50 50	12 10 21	0.017 0.056 0.023	0.049 0.075 0.034	1:500, *h* = 0.5 m	[30]
Rotary-wing Octocopter	Canon 550D (18MP)	0.006			40	24	0.074	0.062	1:500, *h* = 0.5-1 m	[31]
Fixed-wing	Samsung NX100 (20MP)	0.025			118		0.039	0.044	1:500, *h* = 0.5 m	[54]
BPLAY6	SonyAlpha NEX-5N	0.024	60 60 60 60	30 30 30 30	40 60 80 100	10 10 10 10	0.283 0.287 0.284 0.282	0.178 0.212 0.287 0.324	1:1000, *h* = 1 m 1:1000, *h* = 1 m 1:2000, *h* = 1-1.5 m	[21]
Fixed-wing	Canon IXUS (16.1 MP)	0.035			122		0.50	0.03	1:500, *h* = 0.5 m	[55]
Agriculture land	Sony NEX 5R	0,036 0,045			120 150		0.030 0.068	0.028 0.070	1:500, *h* = 0.5 m	[35]
Supercam-S250	Sony Alpha ILCE6000	0.024	80	60	200	16	0.077	0.082	1:500, *h* = 0.5-1 m	[42]
Trlmble UX-5	Sony NEX 5R	0.036 0.036 0.045			150 200 300	22 24 22	0.06 0.11 0.19	0.10 0.14 0.26	1:500, *h* = 0.5 m 1:1000, *h* = 0.5-1 m	[27]
Fixed-wing	Canon550D (18MP)	0.024			120		0.132	0.203	1000, *h* = 1 m	[38]
Trlmble UX5	Sony NEX 5R	0.040			100		0.020	0.040	1:500, *h* = 0.5 m	[41]
Gravel quarry Fixed-wing	Canon S100 (12 MP)	0.024 0.050			80 160		0.020 0.040	0,020 0,080	1:500, *h* = 0.5 m 1:1000, *h* = 0.5-1 m	[43]
Rotary-wing Quadcopter	DJI Phantom 3 Pro (12.2MP)	0.020	15	20	50		0.047	0.115	1:500, *h* = 1 m	[29]
DJI Phantom 4 Pro	Nikon 3100 (14.8 MP)	0.020 0,020 0,020	80	60	50 120 120	10 15 20	0.053 0.049 0.047	0.049 0.070 0.056	1:500, *h* = 0.5 m 1:1000, *h* = 0.5-1 m	[44]
Rotary-wing Octocopter	Nikon 3100 (14.8 MP)	0,016 0.035			50 100		0.088 0.134	0.061 0.101	1:500, *h* = 0.5-1 m	[45]
Rotary-wing Octocopter	Nikon 3100 (14.8 MP)	0.023 0.023			90 90		0.024 0.015	0.046 0.023	1:500, *h* = 0.5 m	[50]
Rotary-wing Octocopter	Nikon D3100 (14.2)	0.037	70	35	120		0.035	0.048	1:500, *h* = 0.5 m	[45]
Fixed-wing	Sony A6000	0.025			100		0.101	0.087	1:500, *h* = 0.5-1 m	[47]
Rotary-wing Quadcopter	DJI Phantom 4 Pro (20 MP)	0.018			65		0.040	0.050	1:500, *h* = 0.5-1 m	[52]
Fixed-wing	IXCE-QX1	0.025			80		0.013	0.011	1:500, *h* = 0.5-1 m	[9]
UAC-PPK-Sfm	SLR (EOS Action (GoPro)	0.063 0.031			45 45	8 8	0.023 0.013	0.026 0.026	1:500, *h* = 0.5-1 m	[32]
Rotary-wing Quadcopter	Canon S110	0.035			100		0.119	0,129	1:500, *h* = 0.5-1 m	[33]
Fixed-wing and Qcto-copter	ILCE-QX1	0.038 0.027 0.027			70 120 150		0.040 0.075 0.100	0.037 0.052 0.060	1:500, *h* = 0.5-1 m	[51]
DJI Phantom 4 Pro	Nikon 3100 (14.2MP)	0.020 0.020 0.020			65 65 65	9 11 18	0.025 0.028 0.027	0.055 0.055 0.057	1:500, *h* = 0.5-1 m	[46]
Rotary-wing Quadcopter	DJI Phantom 3 Standard	0.012	80	60	28	15	0.020	0.040	1:500, *h* = 0.5-1 m	[37]
Ricopter	(20 MP)	0.040 0.030			300 500	18 18	0.24 0.28	0,11 0.15	1:1000, *h* = 1.0-1.5 m	[48]

*For the overall analysis, these RMSEs are not taken into account because their discrepancy with the others is out of tolerance limit

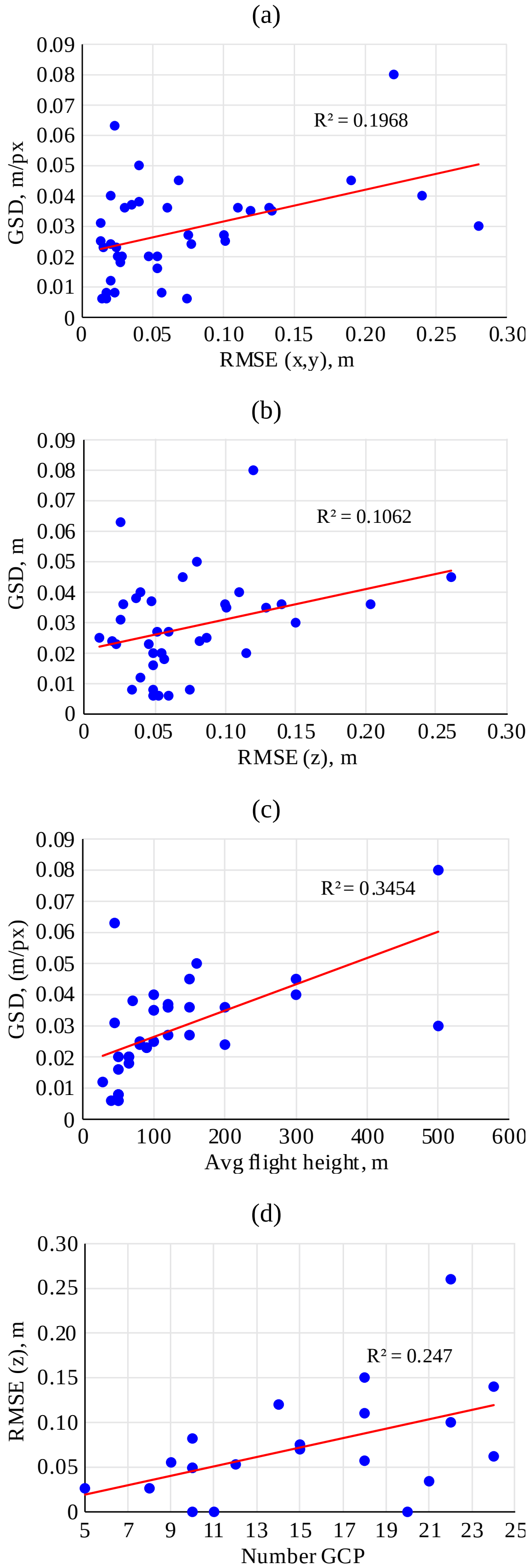


Figure 5. Resolution scattering diagram of GSD (m/px): relative to accuracy of RMSE (xy) and RMSE (z) errors (a), (b); relative to flight altitude (c); scattering of vertical RMSE (z) error relative to the number of GCPs (d) based on the results of previous studies

In addition, the quantitative RMSEs of point coordinates relative to the UAV flight altitude have been systematized, taking into account the requirements of the Instruction on the accuracy of positions of cartographic image points (Table 2).

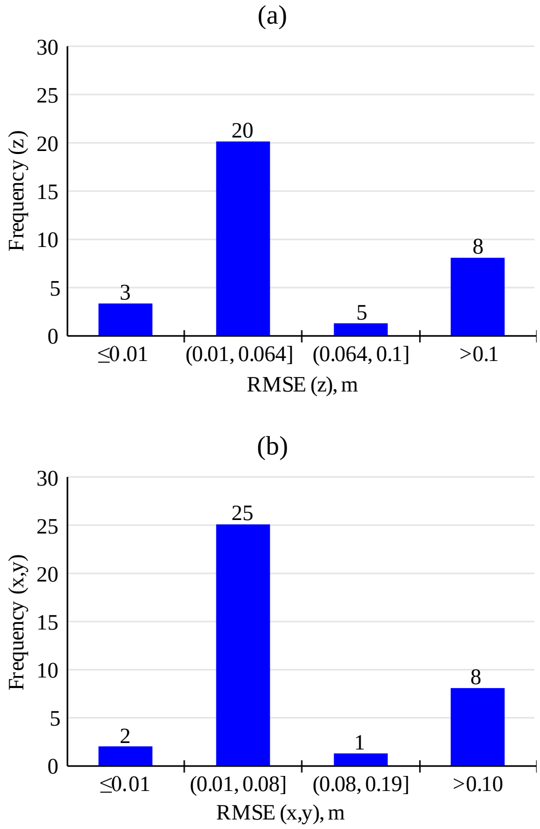


Figure 6. Histograms of relative frequency of quantitative RMSE: vertical (a); horizontal (b), constructed on the basis of collected previous studies

From the statistical analysis of RMSE by UAV flight altitude, it has been determined that for a flight altitude of 28-90 m, horizontal RMSE (*xy*) of 0.01-0.05 m are most common (mean value of errors $\bar{x}$ = 0.03 m, standard deviation σ_{xy} = 0.02 m) and correspond to the accuracy of a scale of 1:500, vertical RMSE (*z*) are from 0.04 to 0.07 m ($\bar{x}$ = 0.04, σ_z = 0.02 m) and contour interval – 0.5 and 1 m.

Based on statistical analysis, the vertical root mean square error in most previous studies for a flight altitude of 100-120 m is most often in the range of 0.02-0.05 m, the mean value of RMSE (*z*) – $\bar{x}$ = 0.06 m, standard deviation σ_z = 0.04, horizontal RMSE (*xy*) for most studies is 0.02-0.08 m, $\bar{x}$ = 0.06 and σ_z = 0.04 m. The standard deviations are the same, so the values of these indicators are not dependent on the variability of the data in the sample. The RMSE (*xy*) values for a flight altitude of 150-200 m are 0.04-0.9, $\bar{x}$ = 0.08, σ_z = 0.03 m, and for RMSE (*z*) – 0.06-0.10, $\bar{x}$ = 0.06 and σ_z = 0.03 m, corresponding to the accuracy of topographic plans of scale 1:500-1:1000 and a contour interval of 0.5 and 1 m. Based on these studies, it should be noted that 150-200 m are the best flight altitudes for aerial photographic surveys using UAV.

The relative frequency of accuracy of horizontal RMSE (*xy*) at a flight altitude of 300-500 m is 0.19-0.27 m ($\bar{x}$ = 0.23 and σ_z = 0.04 m), and the accuracy of vertical RMSE (*z*) is from 0.11 to 0.21 m, ($\bar{x}$ = 0.16 and σ_z = 0.07 m), which correspond to the scale accuracy of 1:2000 and contour interval of 1 and 2 m.

Table 2. Systematics of RMSE of point positions depending on flight altitude and scale of topographic images

Flight altitude, m	RMSE (*xy*), m		Scale of topographic plans	RMSE (*z*), m	Contour interval height, m
	Relative frequency of RMSE (*xy*) accuracy	Specified accuracy: 0.1 mm M, m Maximum: 0.2 mm M, m		Relative frequency of RMSE (*z*) accuracy	Specified: 0.1 h Maximum: 0.2 h
30-90	0.01-0.05 $\begin{pmatrix}\bar{x}=0.03\\ \sigma_{xy}=0.02\end{pmatrix}$	0.05 m Maximum: 0.10 m	1:500	0.04-0.07 $\begin{pmatrix}\bar{x}=0.04\\ \sigma_{xy}=0.02\end{pmatrix}$	*h* = 0.5 m, 0.05 m Maximum: 0.10 m
100, 120	0.02-0.08 $\begin{pmatrix}\bar{x}=0.06\\ \sigma_{xy}=0.04\end{pmatrix}$	0.05, 0.10 m Maximum: 0.10, 0.20 m	1:500, 1:1000	0.02-0.05 $\begin{pmatrix}\bar{x}=0.06\\ \sigma_{xy}=0.04\end{pmatrix}$	*h* = 0.5 m, 0.05 m *h* = 1 m, 0.10 m Maximum: 0.10, 0.20 m
150, 200	0.04-0.09 $\begin{pmatrix}\bar{x}=0.08\\ \sigma_{xy}=0.03\end{pmatrix}$	0.05, 0.10 m Maximum: 0.10, 0.20 m	1:500, 1:1000	0.05-0.10 $\begin{pmatrix}\bar{x}=0.06\\ \sigma_{xy}=0.03\end{pmatrix}$	*h* = 0.5 m, 0.05 m *h* = 1 m, 0.10 m Maximum: 0.10, 0.20 m
300, 500	0.19-0.27 $\begin{pmatrix}\bar{x}=0.23\\ \sigma_{xy}=0.04\end{pmatrix}$	0.20 m Maximum: 0.40 m	1:2000	0.11-0.21 $\begin{pmatrix}\bar{x}=0.16\\ \sigma_{xy}=0.07\end{pmatrix}$	*h* = 1 m, 0.10 m, *h* = 2 m, 0.20 m Maximum: 0.20, 0.40 m

4. Conclusions

Based on a review of previous research publications, it has been noted that the mapping of lands disturbed by surface mining for their further land use is a topical issue for most countries of the world. These publications analyze the methods of land mapping, aerial photographic survey and the accuracy of digital cartographic materials obtained from UAV data.

It has been determined that most of the previous studies have focused on aerial photographic survey projects using UAV, photogrammetric equipment, and image processing software. At the same time, there is a discussion in studies on the availability of GCP. In some studies, it is recommended to use GCP to determine the accuracy of cartographic images, in others, on the contrary, similar accuracy is achieved without GCPs. In our opinion, this problem still requires a thorough statistical analysis.

A review of previous research publications has shown that quantitative assessments of accuracy vary slightly, and the accuracy of each individual research differs from the other. To determine a reliable assessment of the accuracy of point coordinates from previous studies, a significant number (42) of the RMSE of point coordinates and photogrammetric parameters have been collected. Based on this, the RMSEs of point coordinates by the flight altitude have been systematized. To do this, according to the relative frequency statistical histograms, the RMSE values have been found, which are the most common in the sample and taken as the actual RMSE. On this basis, the accuracy of the topographic plan scale and the contour interval height has been determined. The mean values of $\bar{x}$ and standard deviations σ show the constancy or different variability of RMSEs in the samples. Systematization of RMSEs according to statistical analysis has revealed that the best flight altitude of UAV is 150 and 200 m, for which the root mean square errors are 0.05-0.09 m. We have confirmed the statistical dependence of RMSE accuracy and resolution on the UAV flight altitude, but it has not been revealed between RMSE of point coordinates and resolution.

For mapping the forest lands and lands disturbed by surface mining, for their further reclamation, decimeter-scale accuracy can be taken and, therefore, there is no need to use expensive geodetic survey methods, aerial or ground-based laser scanning, and project ground control points.

It is known that the accuracy of topographic plans, digital surface models (DSM) and orthophotomaps depends on the accuracy of ground point coordinates of the planned-high-altitude geodetic network, which is the basis for the development of phototriangulation of an aerial photographic survey project. However, in view of previous studies, the accuracy of determining the coordinates of ground control points is not classified as an influencing factor, which should be taken into account in subsequent studies.

Given the variety of information obtained from land mapping using UAV and the varying accuracy reported in previous studies, further research is needed to assess the accuracy of materials obtained from UAV in geodetic programs.

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References

[1] Malanchuk, Z., Korniyenko, V., Malanchuk, Y., & Khrystyuk, A. (2016). Results of experimental studies of amber extraction by hydromechanical method in Ukraine. *Eastern-European Journal of Enterprise Technologies*, *3*(10(81)), 24-28. https://doi.org/10.15587/1729-4061.2016.72404

[2] Malanchuk, Z., Moshynskyi, V., Malanchuk, Y., & Korniienko, V. (2018). Physico-Mechanical and Chemical Characteristics of Amber. *Solid State Phenomena*, (277), 80-89. https://doi.org/10.4028/www.scientific.net/ssp.277.80

[3] Malanchuk, Z., Korniienko, V., Malanchuk, Y., & Moshynskyi, V. (2019). Analyzing vibration effect on amber buoying up velocity. *E3S Web of Conferences*, (123), 01018. https://doi.org/10.1051/e3sconf/201912301018

[4] Ivanov, Ye.A. (2019). Analiz ekolohichnoi sytuatsii u raionakh nezakonnoho vydobuvannia burshtynu. *Nadrokorystuvannia v Ukraini. Perspektyvy Investuvannia*, 101-107.

[5] Malanchuk, Z., Korniyenko, V., Malanchuk, Y., Khrystyuk, A., & Kozyar, M. (2020). Identification of the process of hydromechanical extraction of amber. *E3S Web of Conferences*, (166), 02008. https://doi.org/10.1051/e3sconf/202016602008

[6] Gurung, K., Yang, J., & Fang, L. (2018). Assessing ecosystem services from the forestry-based reclamation of surface mined areas in the north fork of the Kentucky river watershed. *Forests*, *9*(10), 652. https://doi.org/10.3390/f9100652

[7] Li, X., Barton, C., & Yang, J. (2018). Valuing the environmental benefits from reforestation on reclaimed surface mines in Appalachia.

Journal American Society of Mining and Reclamation, *7*(1), 1-29. https://doi.org/10.21000/JASMR180100029

[8] Cinar, N.C., & Ocalir, E.V. (2019). A reclamation model for post-mining marble quarries. *Gazi University Journal of Science*, *32*(3), 757-774. https://doi.org/10.35378/gujs.475391

[9] Merugu, S., & Kamal, J. (2013). Change detection and estimation of illegal mining using satellite images. *Proceedings of 2nd International Conference on Innovations in Electronics and Communication Engineering*, 246-251.

[10] Kirilov, I., & Banov, M. (2016). Reclamation of lands disturbed by mining activities in Bulgaria. *Agriculture and the Environment*, *8*(4). https://doi.org/10.15547/ast.2016.04.066

[11] Padró, J.C., Carabassa, V., Balagué, J., Brotons, L., Alcañiz, J.M., & Pons, X. (2019). Monitoring opencast mine restorations using Unmanned Aerial System (UAS) imagery. *Science of the Total Environment*, (657), 1602-1614. https://doi.org/10.1016/j.scitotenv.2018.12.156

[12] *Zvit pro otsinku vplyvu na dovkillia rekultyvatsii zemel, porushenykh vnaslidok nelehalnoho vydobutku burshtynu*. (2018). Zvit pro doslidzhennia 2018516794. Kyiv, Ukraina: Instytut heokhimii navkolyshnoho seredovyshcha NAN Ukrainy.

[13] Volokh, P., Kobets, A., & Hrytsan, Yu. (2017). Rekultyvatsiia porushenykh zemel pry vydobutku burshtynu. *Zemlevporiadnyi Visnyk*, (1), 27-29.

[14] Wang, J., Zhao, F., Yang, J., & Li, X. (2017). Mining site reclamation planning based on land suitability analysis and ecosystem services evaluation: A case study in Liaoning Province, China. *Sustainability*, *9*(6), 890. https://doi.org/10.3390/su9060890

[15] Merugu, S., & Kamal, J. (2013). Change detection and estimation of illegal mining using satellite images. *Proceedings of 2nd International Conference on Innovations in Electronics and Communication Engineering*.

[16] Remondino, F., Barazzetti, L., Nex, F., Scaioni, M., & Sarazzi, D. (2011). UAV photogrammetry for mapping and 3D modelling-current status and future perspectives. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, (38), 22-25. https://doi.org/10.5194/isprsarchives-XXXVIII-1-C22-25-2011

[17] Nex, F.C., & Remondino, F. (2014). UAV for 3D mapping applications: A review. *Applied Geomatics*, *6*(1), 1-1-2015. https://doi.org/10.1007/s12518-013-0120-x

[18] Iizuka, K., Watanabe, K., Kato, T., Putri, N.A., Silsigia, S., Kameoka, T., & Kozan, O. (2018). Advantages of Unmanned Aerial Vehicle (UAV) photogrammetry for landscape analysis compared with satellite data: A case study of postmining sites in IndonesiaPilot Test Using Unmanned Aerial Systems (UASs). *Remote Sensing*, *10*(9), 1345. https://doi.org/10.3390/rs10091345

[19] Sechin, A.Yu., Drakin, M.A., & Kiseleva, A.S. (2013). Bespilotnyy letatelnyy apparat: Primenenie v celyah aerofotos'emki dlya kartografirovaniya (Chast 2). Avtomatizirovannye *Tehnologii Izyskaniy i Proektirovaniya*, *3*(50), 56-58.

[20] Ahmad, A. (2011). Digital mapping using low altitude UAV. *Journal of Science & Technology*, *19*(S), 51-58.

[21] Udin, W.S., & Ahmad, A. (2014). Assessment of photogrammetric mapping accuracy based on variation flying altitude using Unmanned Aerial Vehicle. *8th International Symposium of the Digital Earth (ISDE8) IOP Publishing. Series: Earth and Environmental Science*, (18), 1-7. https://doi.org/10.1088/1755-1315/18/1/012027

[22] Tang, L.N., & Shao, G.F. (2015). Drone remote sensing for forestry research and practices. *Journal of Forestry Research*, *26*(4), 791-797. https://doi.org/10.1007/s11676-015-0088-y

[23] Ishaq Deliry, S., & Avdan, U. (2021). Accuracy of unmanned aerial systems photogrammetry and structurefrom motion in surveying and mapping: A review. *Journal of the Indian Society of Remote Sensing*. https://doi.org/10.1007/s12524-021-01366-x

[24] Haskins, J., Endris, C., Thomsen, A.S., Gerbl, F., Fountain, M.C., & Wasson, K. (2021). UAV to inform restoration: A case study from a California Tidal Marsh. *Frontiers in Environmental Science*, (9). https://doi.org/10.3389/fenvs.2021.642906

[25] Lechner, A.M. (2009). Remote sensing of small and linear features: Quantifying the effects of patch size and length, grid position and detectability on land cover mapping. *Remote Sensing of Environment*, (113), 2194-2204. https://doi.org/10.1016/j.rse.2009.06.002

[26] Shevnya, M.S. (2013). Ispolzovanie bespilotnykh letatelnykh apparatov dlya polucheniya materialov distantsionnogo zondirovaniya Zemli. *Geodeziya i Kartografiya*, (1), 44-50.

[27] Vovk, A., Hlotov, V., Hunina, A., Malitskyi, A., Tretyak, K., & Tsyrklevych, A. (2015). Analysis of the results of the use UAV Trimble UX-5 for creation of orthophotomaps and digital model of relief. *Heodeziia, Kartohrafiia ta Aerofotoznimannia*, (81), 90-103. https://doi.org/10.23939/istcgcap2015.01.090

[28] Shults, R.V., Voitenko, S.P., Krelshtein, P.D., & Malina, I.A. (2015). Do pytannia rozrakhunku tochnosti vyznachennia koordynat tochok pid chas aerofotoznimannia z bezpilotnykh litalnykh aparativ. *Inzhenerna Heodeziia*, (62), 124-135.

[29] Ajayi, O.G., Salubi, A.A., Angbas, A.F., & Odigure, M.G. (2017). Generation of accurate digital elevation models from UAV acquired low percentage overlapping images. *International Journal of Remote Sensing*, *38*(8-10), 3113-3134. https://doi.org/10.1080/01431161.2017.1285085

[30] Harwin, S., & Lucieer, A. (2012). Assessing the accuracy of georeferenced point clouds produced via multi-view stereopsis from Unmanned Aerial Vehicle (UAV) imagery. *Remote Sensing*, *4*(6), 1573-1599. https://doi.org/10.3390/rs4061573

[31] Lucieer, A., De Jong, S., & Turner, D. (2013). Mapping landslide displacements using Structure from Motion (SfM) and image correlation of multi-temporal UAV photography. *Progress in Physical Geography*, *38*(1), 97-116. https://doi.org/10.1177/0309133313515293

[32] Sanz-Ablanedo, E, Chandler, J.H., Rodríguez-Pérez, J.R., & Ordóñez, C. (2018). Accuracy of Unmanned Aerial Vehicle (UAV) and SfM photogrammetry survey as a function of the number and location of ground control points used. *Remote Sensing*, *10*(10), 1606. https://doi.org/10.3390/rs10101606

[33] Carrera-Hernandez, J.J., Levresse, G., & Lacan, P. (2020). Is UAVSfM surveying ready to replace traditional surveying techniques? *International Journal of Remote Sensing*, *41*(12), 4820-4837. https://doi.org/10.1080/01431161.2020.1727049

[34] 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 Surface Dynamics*, (7), 807-827. https://doi.org/10.5194/esurf-7-807-2019

[35] Rehak, M., Mabillard, R., & Skaloud, J. (2013). A micro-UAV with the capability of direct georeferencing. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, (40), 317-323. https://doi.org/10.5194/isprsarchives-XL-1-W2-317-2013

[36] Rehak, M., & Skaloud, J. (2015). Fixed-wing micro aerial vehicle for accurate corridor mapping. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 23-31. https://doi.org/10.5194/isprsannals-II-1-W1-23-2015

[37] Oniga, V.-E., Breaban, A.-I., Pfeifer, N., & Chirila, C. (2020). Determining the suitable number of ground control points for UAS images georeferencing by varying number and spatial distribution. *Remote Sensing*, *12*(5), 876. https://doi.org/10.3390/rs12050876

[38] Fazeli, H., Samadzadegan, F., & Dadrasjavan, F. (2016). Evaluating the potential of RTK-UAV for automatic point cloud generation in 3D rapid mapping. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 221-226. https://doi.org/10.5194/isprs-archives-XLI-B6-221-2016

[39] Myishlyaev, V.A. (2005). Otsenka tochnosti tsifrovykh ortofotoplanov. *Geodeziya i Kartografiya*, (5), 25-28.

[40] *Nakaz Ukrheodezkartohrafii "Pro zatverdzhennia instruktsii z topohrafichnoho znimannia u masshtabakh 1:5000, 1:2000, 1:1000 ta 1:500 (HKNTA-2.04-02-98)"*. (1998). Sposib dostupu: http://zakon2.rada.gov.ua/laws/show/z0393-98

[41] Hlotov, V.M., & Hunina, A.V. (2016). Analysis of modern methods surveying in the processing large-scale plans. *Heodeziia, Kartohrafiia i Aerofotoznimannia*, (83), 53-63. https://doi.org/10.23939/istcgcap2016.01.053

[42] Shinkevich, M.V., Vorobeva, N.G., Altyintsev, M.A., Popov, R.A., Arbuzov, S.A., & Florov, A.V. (2015). Otsenka tochnosti plotnoy tsifrovoy modeli poverhnosti i ortofotoplanov, poluchennyih po materialam aerofotos'emki s BLA serii Supercam. *Geomatics*, (4), 37-41.

[43] Reshetyuk, Yu., & Mårtensson, S.-G. (2016). Generation of highly accurate digital elevation models with Unmanned Aerial Vehicles. *Photogrammetric Record*.

[44] Agüera-Vega, F., Carvajal-Ramírez, F., & Martínez-Carricondo, P. (2017). Accuracy of digital surface models and orthophotos derived from Unmanned Aerial Vehicle photogrammetry. *Journal of Surveying Engineering*, *143*(2). https://doi.org/10.1061/(ASCE)SU.1943-5428.0000206

[45] Martínez-Carricondo, P., Agüera-Vega, F., Carvajal-Ramírez, F., Mesas-Carrascosa, F.-J., Garcia-Ferrer, A., & Perez-Porras, F.-J. (2018). Assessment of UAV-photogrammetric mapping accuracy based on variation of ground control points. *International Journal of the Indian Society of Remote Sensing Journal of Applied Earth Observation and Geoinformation*, (72), 1-10. https://doi.org/10.1016/j.jag.2018.05.015

[46] Ferrer-González, E., Agüera-Vega, F., Carvajal-Ramírez, F., & Martínez-Carricondo, P. (2020). UAV photogrammetry accuracy assessment for corridor mapping based on the number and distribution of ground control points. *Remote Sensing*, *12*(15). https://doi.org/10.3390/rs12152447

[47] Hill, A. (2019). Economical drone mapping for archaeology: Comparisons of efficiency and accuracy. *Journal of Archaeological Science: Reports*, (24), 80-91. https://doi.org/10.1016/j.jasrep.2018.12.011
[48] Pessoa, G.G., Carrilho, A.C., Miyoshi, G.T., Amorim, A., Galo, M. (2021). Assessment of UAV-based digital surface model and the effects of quantity and distribution of ground control points. *International Journal of Remote Sensing*, (42). https://doi.org/10.1080/01431161.2020.1800122
[49] Chaudhry, M.H., Anuar, A., Qudsia, G., Muhammad, S., Farid, H.S., & Al-Ansari, N. (2021). Assessment of DSM based on radiometric transformation of UAV data. *Sensors*, *21*(5), 1649. https://doi.org/10.3390/s21051649
[50] Forlani, G., Dall'Asta, E., Diotri, F., Cella, U., Roncella, R., & Santise, M. (2018). Quality assessment of DSMs produced from UAV flights georeferenced with on-board RTK positioning. *Remote Sensing*, *10*(2), 311. https://doi.org/10.3390/rs10020311
[51] Yu, J.J., Kim, D.W., Lee, E.J., & Son, S.W. (2020). Determining the optimal number of ground control points for varying study sites through accuracy evaluation of unmanned aerial system-based 3D point clouds and digital surface models. *Drones*, *4*(3), 49. https://doi.org/10.3390/drones4030049
[52] Laporte-Fauret, Q., Marieu, V., Castelle, B., Michalet, R., Bujan, S., & Rosebery, D. (2019). Low-cost UAV for high-resolution and large-scale coastal dune change monitoring using photogrammetry. *Journal of Marine Science and Engineering*, *7*(3), 63. https://doi.org/10.3390/jmse7030063
[53] Padróa, J.C., Carabassab, V., Balaguéc, J., Brotonsd, L., Alcañize, J.M., & Ponsf, X. (2018). Monitoring opencast mine restorations using Unmanned Aerial System (UAS) imagery. *Science of the Total Environment*, (657), 1602-1614. https://doi.org/10.1016/j.scitotenv.2018.12.156
[54] Cryderman, C., Mah, S., & Shufletoski, A. (2014). Evaluation of UAV photogrammetric accuracy for mapping and earthworks computations. *Geomatica*, (68), 309-317. https://doi.org/10.5623/cig2014-405
[55] Whitehead, K., & Chris, H. (2015). Applying ASPRS accuracy standards to surveys from Small Unmanned Aircraft Systems (UAS). *Photogrammetric Engineering & Remote Sensing*, *81*(10), 787-793. https://doi.org/10.14358/PERS.81.10.787

Методи картографування земель, порушених видобутком корисних копалин, і точність картографічних зображень, отриманих з БПЛА: огляд

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Мета. Аналіз наслідків порушень земель, спричинених поверхневим видобутком корисних копалин, і методів картографування цих земель та дослідження точності координат точок цифрових зображень, отриманих за матеріалами аерофотозйомки з безпілотного літального апарату (БПЛА). Виконання кількісної оцінки середньої квадратичної похибки (RMSE) координат точок картографічних зображень і означення взаємозв'язку між RMSE координат точок і фотограмметричними параметрами.

Методика. Огляд наукових публікацій попередніх досліджень в рамках представленої теми виконано в наступній послідовності: аналіз порушень екосистими внаслідок поверхневого видобутку корисних копалин; збір, за попередніми дослідженнями, даних кількісної оцінки точності у вигляді середньої квадратичної похибки (RMSE) координат точок картографічних зображень, отриманих за матеріалами аерофотозйомки з БПЛА; статистичне дослідження взаємозв'язку RMSE та параметрів фотографування.

Результати. Представлено методи картографування порушених земель для повернення їх у природний стан після наслідків поверхневого видобутку корисних копалин на основі огляду публікацій попередніх досліджень щодо теми роботи. За попередніми дослідженнями систематизовано RMSE координат точок картографічних зображень, на підставі цього визначено точність топографічних планів. Виконано статистичні дослідження взаємозв'язку кількісної оцінки точності RMSE (xy) і RMSE (z) відносно параметрів фотографування, представлено діаграми розсіювання кореляційної залежності та межі відносної частоти RMSE.

Наукова новизна. На підставі критичного аналізу попередніх досліджень щодо неурегульованості кількісної точності картографічних зображень, отриманих за матеріалами аерофотозйомки з БПЛА, за оглядом попередніх досліджень виконано систематику RMSE за висотою фотографування, на підставі цього визначено точність топографічних планів, встановлена відносна частота горизонтального та вертикального розподілу похибок, середнє значення ($\overline{x}$) та середнє квадратичне відхилення (σ).

Практична значимість. Систематика значень RMSE координат точок картографічних зображень для певних параметрів фотографування та масштабу топографічних зображень дає можливість враховувати це для проектування аерофотозйомки з БПЛА земель різного призначенням, вибирати висоту польоту та фотографічне обладнання згідно необхідної точності.

Ключові слова: *поверхневий видобуток, картографічне зображення, аерофотозйомка з БПЛА, наземні опорні точки, середня квадратична похибка, точність ортофотоплана*