RESEARCH PAPER

INACCURACY OF RELATIVE ELEVATIONS ON UAV-BASED DIGITAL ELEVATION MODELS WITHOUT PRECISE REFERENCE INFORMATION

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ABSTRACT. Imagery obtained from unmanned aerial vehicle (UAV) is widely used for land surface modelling. Recent research prove that digital elevation models (DEMs) created from UAV imagery are characterized by a high rate of accuracy and reliability. Most of these studies are focused on assessing absolute elevation accuracy of the UAV DEMs, but the accuracy of relative elevations (i.e., accuracy of reproducing of local elevation differences within DEM) also should be considered. In this paper, we focus on the precision of replicating relative elevations in DEMs derived from imagery captured via UAVs without precise coordinate reference. To evaluate this accuracy, we use datasets of aerial images processed in two different methods: one with on-board coordinates obtained from a GNSS receiver, and the other based on precise coordinates calculated with the Post-Processing Kinematic (PPK) method. The sites selected for assessment are not look like each other in terms of terrain and forest cover characteristics to track the difference of modelling in the divergent areas. Constructed DEMs were compared with reference fragments of global DEMs by the statistical indices for the difference fields. The findings indicate that the absence of an accurate coordinate reference does not have a substantial impact on the precision of reproducing relative elevations in the DEM. This makes it possible to use UAV materials without precise coordinate reference for modelling in most geographical studies, where the error of terrain steepness values of 0.9° can be considered acceptable.

KEYWORDS: unmanned aerial vehicles (UAV); unmanned aerial imagery; digital elevation model (DEM); digital surface model (DSM); GNSS; post-processing kinematic; accuracy; relative elevations

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INTRODUCTION

Digital elevation models (DEMs) and digital surface models (DSMs) are a valuable source of information for geographical research in various fields. UAV photography is one of the leading methods for construction high spatial resolution DEMs. UAVs provide spatial data of a very high resolution, which allows for large-scale geographic research, i.e., creation of thematic and topographic maps, surveying, and other engineering applications (Guan et al. 2022; Mohamad et al. 2022; Uysal et al. 2015). Many researchers conducted in geography to investigate large-scale geographic phenomena, use unmanned aerial imagery materials (Biljecki et al. 2016; Deev et al. 2023; Suchilin et al. 2021; Svistunov et al. 2022).

UAV-derived digital elevation models are used to obtain accurate quantitative elevation characteristics, modelling and forecasting of external land forming phenomena. To leverage the outcomes of UAV imagery in scientific research, it is crucial to verify the precision of the generated DEMs. In this context, accuracy pertains to the congruence of relative DEM elevations and elevations of real Earth surface, as well as the correct representation of landforms. Many research tasks require assessment of DEM accuracy, especially in terms of corresponding between absolute elevations of DEM and actual terrain. This is accomplished by ensuring that survey materials are provided with precise coordinate reference (Benassi et al. 2017; Eisenbeiss 2009). The primary techniques for precise georeferencing of aerial surveys involve the measurement of ground control points' coordinates or equipping the UAV with a geodetic-class GNSS receiver, enabling it to operate in PPK (Post Processing Kinematic) or RTK (Real Time Kinematic) mode with satellite systems (Famiglietti et al. 2021; Padró et al. 2019; Tomaštík et al. 2019). However, the use of UAVs with a high-precision GNSS receiver is more expensive (including in case of loss or damage of the device) and may also require higher operator skills level, so low-cost UAVs weighing up to 2 kg are widely used in geographical surveys.

Low-cost UAVs are usually small-size quadcopters which are available for users with different pilot experience level and for different types of demands. The most popular of them are drones made by DJI, Xiaomi, Autel, etc (DJI - Official Website 2023). However, these devices cannot provide aerial imagery materials with accurate georeferencing without ground control points: the coordinates measured by the onboard GNSS receiver are accurate to a few meters, depending on the DEM and survey conditions. Therefore, surveys are often carried out without precise georeferencing, which can lead to errors and inaccuracies in the results when the survey results are used in the future research (Neitzel and Klonowski 2012; Szypuła 2023).

In recent years, several studies have assessed the precision and accuracy of DEMs and DEMs derived from UAV imagery. These studies have focused on assessing the accuracy of absolute elevations of the DEMs (Barba et al. 2019; Benassi et al. 2017; Liu et al. 2022). The papers conduct a statistical analysis of georeferencing accuracy, examining its correlation with the chosen coordinate referencing technique, the quantity of ground control points employed, and various other contributing factors. Horizontal accuracy (X and Y model shifts) and elevation accuracy (absolute errors) is calculated. Simultaneously, it is important to highlight that the aspects of DEM reliability, such as the accuracy of relative elevations representations and DEM orientation in relation to the terrain, have not received adequate research attention.

This research aims to evaluate the precision of relative elevation replication in DEMs generated from UAV imagery without precise coordinate reference. To achieve this objective, we conduct a comparative analysis between DEMs obtained from UAV imagery and reference sections extracted from available global DEMs. The choice of reference global DEMs of much lower detail is determined by the inaccessibility of higher resolution materials. As we analyse the general trend of distortions and geometric deformations of DEMs from unmanned aerial imagery data, the use of detailed materials is not necessary. Two sets of DEMs derived from the same aerial imagery data are used for comparison, but one group was processed without precise georeferencing and the other using data from a high-precision on-board GNSS receiver. The height difference between the created and reference models is calculated and investigated. In addition to the absolute values of the difference, we are interested in the presence of noticeable trends in the difference fields. Expressed spatial trends of the difference may indicate the inclination of the created DEM relative to the reference one and, consequently, the mismatch of elevations, which, in our opinion, reduces the reliability of the DEM.

MATERIALS AND METHODS

We estimate DEM relative elevation accuracy using unmanned aerial imagery data on two sites with distinct topographical features. The first site, with an area of 0.6 km^2, is located on the slope of the Kurai Ridge, Chuya River basin, Altai Republic, near the village of Chagan-Uzun. It is characterised by steep slopes (up to 12°), and there are also landforms with much steeper slopes. Elevations of the site vary from 1500 to 2500 m a.s.l. The site lacks dense forestation, with limited herbaceous cover and occasional shrubs, making the area open and facilitating easy access to terrain information. There is also a landslide body captured on relatively recent UAV's data. Global elevation models do not capture this landslide because the data for these models were acquired much earlier. An overview of the site is shown on Fig. 1. The second site, with an area of 0.3 km^2, is located on the Karelian shore of the Kandalaksha Bay of the White Sea, Kindo Peninsula. It is characterised by gentle topography (slope steepness up to 5°) with little roughness. Due to the point cloud class export and subsequent lack of overlap, the majority of the second site, characterized by a significant forest cover, is excluded from the image creation process. Thus, only the marine littoral along the coast is considered as a surface without vegetation. An overview of the site 2 is shown on Fig. 2.

UAV materials. The materials of two large-scale unmanned aerial surveys obtained from the Geoscan Gemini geodetic aerial survey complex (Geoscan Group of

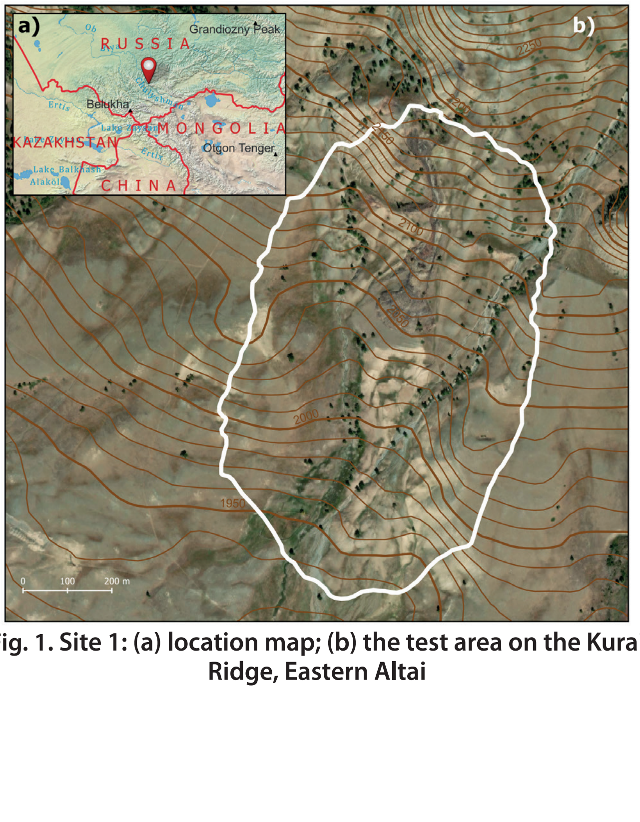

Fig. 1. Site 1: (a) location map; (b) the test area on the Kurai Ridge, Eastern Altai

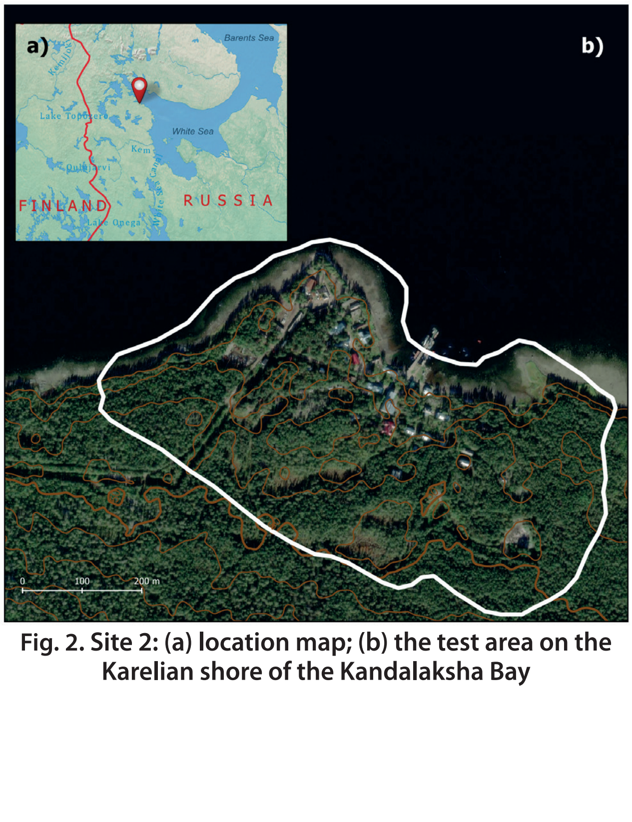

Fig. 2. Site 2: (a) location map; (b) the test area on the Karelian shore of the Kandalaksha Bay

Companies 2023) were used in the study. The complex is designed to perform aerial survey works with obtaining high-precision spatial data. The UAV is a quadcopter with 1.9 kg weight, maximum altitude 500 m and flight time up to 40 minutes. It carries a Sony UMC-R10C Camera, an optical camera mounted on a gimbal. The maximum resolution of the camera is 20.1 megapixels; the sensor size is 23.2 x 15.4 mm; the focal length is 20 mm. The direction of nadir shooting is provided by tilting the vehicle when moving forward. The UAV is equipped with a high-precision GNSS receiver U-blox ZED-F9. The receiver tracks GPS, GLONASS, Galileo and BeiDou signals; position accuracy in differential mode is about 10 mm (Geoscan Gemini Manual 2023). It should be noted that in autonomous mode (without the use of a base station), the position accuracy is reduced. Topcon HiPer V satellite receiver is used as a base station for aerial surveying Topcon HiPer V (Topcon HiPer V 2012).

Geoscan Gemini is classified as a professional unmanned aerial photography device. The GNSS receiver installed on it allows making observations in phase mode. This distinguishes Gemini from low-cost UAVs, such as DJI Phantom or DJI Mavic, equipped with a coded GNSS receiver. In our opinion, the accuracy of the "raw" coordinates measured by the phase receiver in autonomous mode is comparable to the accuracy of the coordinates determined by the code receiver (Kaplan and Hegarty 2017). Therefore, the evaluation of unmanned aerial imagery materials with Geoscan based on coordinates without post-processing allows us to approximate the accuracy characteristics of materials from a low-cost UAV without plan-altitude justification.

The aerial survey materials for each site include an array of aerial images, an observation file from the base station and a GNSS observation file from the on-board receiver. For the first site, 402 images were acquired from an altitude of 100 m, front overlap of 80% and side overlap of 60%. For the second site, 447 images were acquired from an altitude of 120 m, front overlap 80% and side overlap 60%. It's also worth noting that the Geoscan planner used during the survey allows us to plan the fly-task with the terrain in mind - this keeps roughly the same height above the surface over the entire survey area.

Selection of reference DEMs providing comparative analysis of unmanned aerial imagery results. Global digital elevation DEMs, which are publicly available for users, were used as reference DEMs (Table 1).

SRTM is an elevation model obtained by radar topographic survey, the resolution of the DEM is 1´´ (about 30 m). SRTM data were submitted in 2000: the survey was carried out in February 2000 for 11 days. Elevation is measured from the EGM96 geoid. The vertical accuracy of the DEM published in the official documentation, is 16 m. The use of the DEM is limited by the geographical location of the study areas: coverage is limited to the area between 60°N and 54°S (Farr et al. 2007).

ASTER GDEM. The model is a result of processing of stereoscopic imagery by a satellite thermal emission and reflection radiometer. The ASTER GDEM creation methodology consisted of automated processing of the entire ASTER archive, stereo correlation, cloud masking to remove cloud pixels, data summarisation followed by averaging of pixel values and extraction of artefacts The spatial resolution of the DEM is 1´´ (about 30 m), Elevation is measured from the EGM 96 geoid. The mean vertical error of the DEM is 20 m. Available to users since 2009, with an improved DEM released in 2019 (Fujisada et al. 2012).

ALOS PALSAR DEM is an elevation model with a spatial resolution of 12.5 m, obtained by resampling existing elevation models, mostly SRTM. It is available since 2015. The DEM undergoes elevation correction: elevations are measured from an ellipsoid (as opposed to SRTM, which uses the EGM96 geoid model), then resampled. The Alaska Satellite Facility, which provides the data, warns users that the materials are intended to interpret the results of radiometric terrain correction, and its using instead of DEM is not recommended (ALOS PALSAR - Radiometric Terrain Correction 2023). Thus, vertical height errors are not given in the official DEM documentation. However, research studies have evaluated the possibility of using ALOS PALSAR DEM as a digital elevation model. The results of these studies conclude that it is acceptable to use ALOS in geographical research, based on the scale of the results obtained (Ferreira and Cabral 2021; Ihsan 2021; Ngula Niipele and Chen 2019). The use of the DEM is limited by the geographical location of the study sites: coverage is restricted to 60°N and 54°S, as the coverage of the ALOS PALSAR DEM is directly dependent on the coverage of the product used for oversampling (SRTMGL1). The vertical accuracy of the DEM is 16 m.

ALOS WORLD 3D-30 (AW3D30) is a global digital surface model dataset with a spatial resolution of 1´´ (about 30 m), released in 2015 by Japan Aerospace Exploration Agency (JAXA). Based on panchromatic stereo images from the ALOS satellite acquired between 2006 and 2011. Available to users since 2016 and the dataset is currently being updated and improved. The vertical accuracy of these models is on the order of 5 m, with elevations measured from geoid EGM96 (Takaku et al. 2014).

ArcticDEM is an elevation model constructed for the entire Arctic from stereo pairs of very high resolution Maxar satellite imagery, includes data from WorldView-1, WorldView-2, WorldView-3 and GeoEye-1 acquired between 2007 and 2022 during March and April months. Individual DEM strips are compiled from DigitalGlobe images. It has a 2-metre spatial resolution. Elevations are measured from an ellipsoid. Average vertical DEM error is up to 4 meters. Available to users since 2017 (Noh and Howat 2017; Porter 2018).

FABDEM is an elevation model with a spatial resolution of 1´´ (about 30 m). It is available to users from 2021 and is currently being updated. The model is obtained by removing the elevation values of non-relief objects (buildings, forests) from the Copernicus GLO-30 DEM. The elevation is measured from the EGM2008 geoid. Machine learning techniques are used to derive the DEM, where the systematic error of the heights of buildings and trees is removed from the COPDEM30 model. Once non-relief heights are removed, the DEM is post-processed, where a median pixel value filter is applied (Hawker et al. 2022). According to the cited study, 90% of errors of elevation values for open areas are up to 8 m, for slightly sloping open areas are up to 5 m, for densely built-up and heavily forested areas of terrain, where significant removal of "non-relief" elevation values was carried out, the value of vertical error is about 10 m.

For the first site, 4 reference DEMs were selected: SRTM DEM 1 arc-second; ALOS PALSAR DEM; AW3D30 DEM; FABDEM. For the second site, 4 reference DEMs were selected: ASTER GDEM V3; AW3D30 DEM; Arctic DEM; FABDEM. DEMs have acceptable values of absolute elevation accuracy indicators, which can guarantee a reliable result of relative elevation estimation, i.e. the difference fields between UAV DEM and reference DEM (Uuemaa et al. 2020; Karlson et al. 2021; Saberi et al. 2023; Meadows et al. 2024). An estimate of the accuracy of the relative elevation of the reference DEM has not been reported previously in the literature. Most studies are focused on estimation of absolute elevation

Table 1. Comparative characteristics of reference DEMs

Reference DEM	Horizontal datum	Vertical datum	Resolution	Vertical accuracy	Source
SRTM DEM (1 arc-second)	EPSG:4326 WGS84	Geoid EGM96	1 arc -second ~ 30 m	± 16 m	(Siemonsma 2015)
ASTER GDEM	EPSG:4326 WGS84	Geoid EGM96	1 arc -second ~ 30 m	± 20m	(ASTER Global DEM Validation Summary Report 2009)
ALOS PALSAR DEM	EPSG:32645 WGS 84 / UTM zone 45N	Ellipsoid	12.5 m	± 16 m	(ASF engineering 2015)
ALOS WORLD 3D-30 (AW3D30)	EPSG:4326 WGS84	Geoid EGM96	1 arc -second ~ 30 m	± 5 m	(ALOS Global Digital Surface Model (DSM) Product Description 2019)
ArcticDEM	EPSG:3413 WGS 84 / NSIDC Sea Ice Polar Stereographic North	Ellipsoid	2 m	± 4 m	(ArcticDEM - Polar Geospatial Centre 2023)
FABDEM	EPSG:4326 WGS84	Geoid EGM2008	1 arc -second ~ 30 m	± 10 m	(Hawker et al. 2022)

and comparison is made with GNSS and LiDAR data. But we can compare the differences between the elevations of reference and UAV DEMs, leaving out possible inaccuracies of global DEMs. When comparing global DEM in pairs with UAV DEM, one of the models is known to be reliable (UAV DEM with PPK coordinates).

Research methods. For the study it is necessary to carry out photogrammetric processing of aerial imagery arrays for each site in two ways: based on "raw" onboard coordinates of GNSS receiver and with coordinates refined by PPK method. For this purpose, the kinematics track obtained from the GNSS receiver is post-processed first. Then the photogrammetric processing is performed directly, the purpose of which is to obtain dense point clouds. For each reference DEM, two-point clouds (based on "raw" and PPK coordinates, respectively) were obtained, and the processing was carried out in the coordinate and elevation system of the target DEM. The point clouds were classified to identify points belonging to the ground surface, after which DEMs geometrically aligned with the reference DEMs were constructed based on these points. Then, for each pair of DEMs (constructed and reference DEMs), the difference of elevation at each point was calculated. The obtained differences were analysed: characteristics such as standard deviation and mean of the difference surfaces were calculated and compared, the linear trend of the surface and the slope angle of the resulting plane were calculated. If the DEM obtained without precise coordinate referencing exhibits characteristics comparable to the DEM obtained from precise coordinates, this indicates the validity of the first DEM. More detailed description of each of the steps is given below.

Processing of GNSS receiver coordinates and UAV onboard coordinates was performed in CREDO GNSS software. The processing consisted in calculating the coordinates of external event points of the onboard GNSS receiver track. For this purpose, observations at the base station, the coordinates of which were determined in advance, were used. As a result of processing, the refined coordinates of the image projection centers were obtained.

UAV imagery data processing was performed in Agisoft Metashape Professional software. For DEM sets using raw coordinates, the following operations were performed: setting the target coordinate and elevation system, mutual orientation of the images, building a dense point cloud, and finally classification to determine the points of the bare earth class. For DEM sets using exact coordinates, the difference was that before mutual orientation, the import of exact coordinates of the centers of the image projections obtained in the previous step was performed. The processing resulted in point clouds of class "Ground", which were exported in LAS format. The point density of cloud was 26.6 points/m^2 for the first site and 14.7 points/m^2 for the second site.

Construction of DEM for comparison with benchmarks. Creation of raster (gridded) DEMs was performed in SAGA GIS using the Shapes to Grid tool. Point clouds in LAS format exported at the previous step were used as source data. The cell size and coverage of the target rasters were set according to the reference DEM fragments. Cell elevations of the target rasters were calculated as mean values of elevation of points falling within a cell.

Calculation and analysis of height differences between constructed and reference DEMs. We calculate algebraic difference between UAV DEM and reference DEM. Since point clouds are characterised by much higher spatial resolution than fragments of reference DEMs, we can neglect possible planned displacement of these materials relative to each other.

Due to the forested nature of Site 2, the forested area is completely excluded from the analysis. Non-forested fragments include the littoral, adjacent shoreline areas and isolated glades in the forest.

The nature of elevation displacement of the constructed DEM relative to the reference DEM determines other more complex deformations of DEM: tilt and geometric deformation. The range of values of *algebraic raster difference* is from below to above zero numbers. Values below zero indicate that elevations of the constructed DEM are less than elevations of the reference DEM (underestimated relative to the reference DEM); values above zero for the constructed DEM is overestimated relative to the reference DEM; zero values indicate coincidence of elevations of both DEMs.

For each difference field, mean and standard deviation (STD) were determined. *Mean* determines the measure of mixing of the distribution density of relative elevation values to a certain value; this value will be an indicator of the difference between two surfaces (constructed and reference). The closer the value is to zero, the greater the coincidence of the compared DEMs. The *standard deviation* determines the nature of this bias: the closer the value is to zero, the higher the density of distribution of values close to the mean, and, accordingly, the values of the difference fields in most cases are equal to the mean. In addition, linear trend surfaces were constructed for each difference field. The trend was constructed using the Trend tool from the ArcGIS Pro Spatial Analyst module. The steepness of the trend surface was calculated to estimate the slope of the constructed DEM surface relative to the reference DEM. The purpose of trend in this study is to show a pattern of the difference in elevation values of the constructed and reference DEMs to higher or lower values. The trend thus determines whether the slope of the interpolated surface is observed or not. *The Slope* calculation function is then applied to the trend to obtain a certain number which is a measure of the slope of the trend surface and, consequently, of the DEM surface from unmanned aerial imagery data.

RESULTS

Site 1: slope of the Kurai Ridge, Chuya River basin, Altai Republic (near Chagan-Uzun village). For Site 1, 8 difference rasters were calculated from the data of unmanned aerial imagery and reference DEMs: 4 differences for DEMs based on "raw" coordinates and 4 differences for DEMs based on PPK coordinates. Images of the difference images are shown in Fig. 3. Comparative analyses were performed on three characteristics for each algebraic difference image. The listed characteristics for site 1 are summarised in Table 2.

SRTM DEM. When calculating the characteristics for the first two pairs of comparisons with the reference DEM, the mean difference values were obtained: –1.4 m for the "Raw" DEM and 1.1 m for the PPK DEM. The values of the constructed DEMs differ from the reference DEM by one order of magnitude (underestimation of the "Raw" DEM, overestimation of the PPK DEM), it is assumed that the use of accurate coordinate referencing does not improve the modelling result. This is also evidenced by the value of the STD, which is similar for both differences (3.41 and 3.22 respectively). However, the value of the slope of the trend surface slightly improved after PPK coordinate processing: 0.19° for the DEM using raw coordinates, 0.04° for the DEM using processed coordinates. Both differences are characterised by an overestimation of positive landform

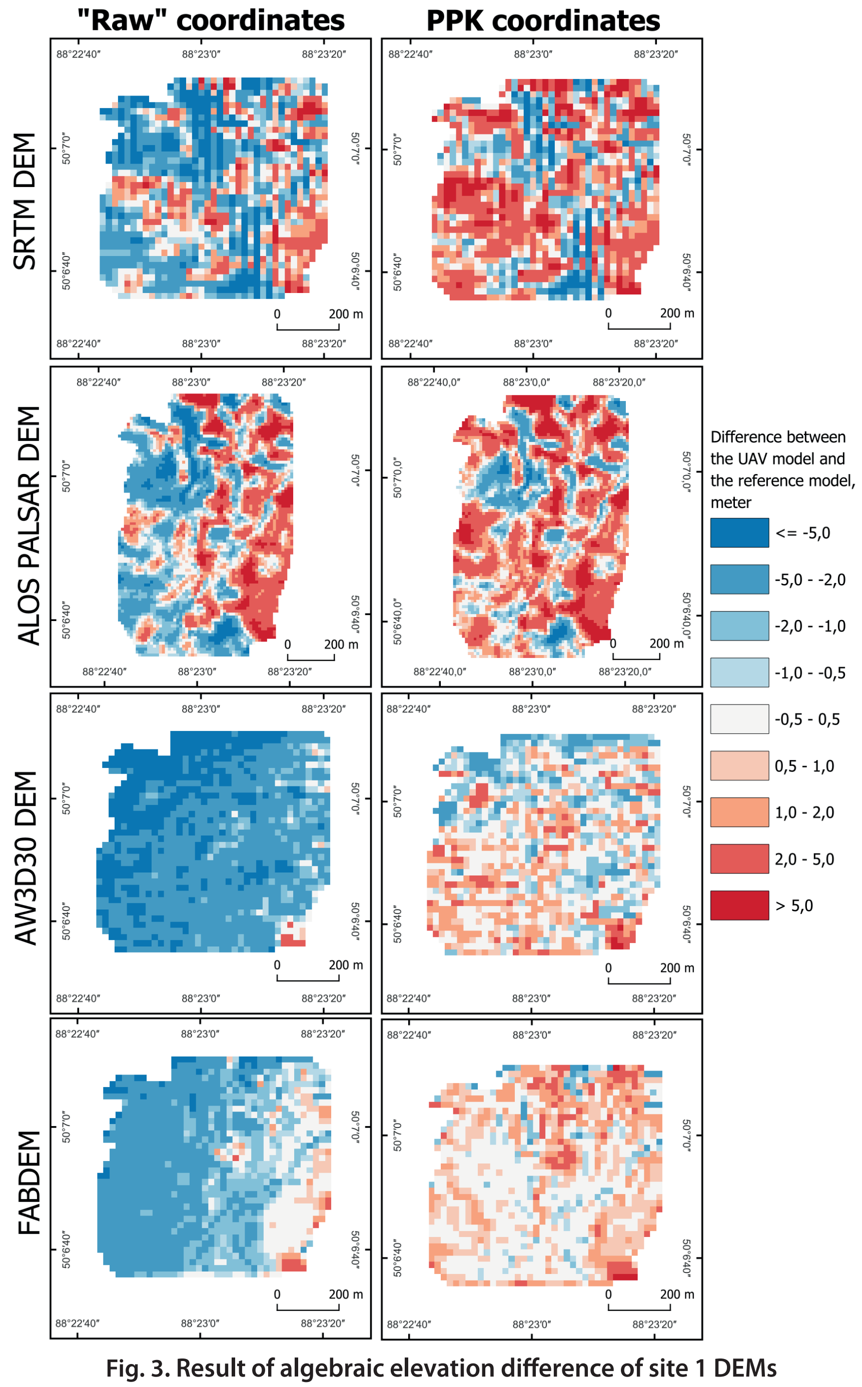

Fig. 3. Result of algebraic elevation difference of site 1 DEMs

Table 2. Statistical analysis of site 1

	"Raw" coordinates		PPK coordinates	
SRTM DEM	MEAN, m	-1.4	MEAN, m	1.1
	STD	3.41	STD	3.22
	SLOPE, °	0.19	SLOPE, °	0.04
ALOS PALSAR DEM	"Raw" coordinates		PPK coordinates	
	MEAN, m	-0.04	MEAN, m	1.47
	STD	3.1	STD	2.91
	SLOPE, °	0.4	SLOPE, °	0.08
AW3D30 DEM	"Raw" coordinates		PPK coordinates	
	MEAN, m	-4.06	MEAN, m	0.08
	STD	1.97	STD	1.44
	SLOPE, °	0.26	SLOPE, °	0.09
FABDEM	"Raw" coordinates		PPK coordinates	
	MEAN, m	-1.95	MEAN, m	0.53
	STD	1.67	STD	1.11
	SLOPE, °	0.25	SLOPE, °	0.02

areas and an underestimation of negative landforms: thus, the DEMs from unmanned aerial photography data appear more dissected relief, compared to the reference DEM (Fig. 3). When evaluating the results from the "Raw" data and PPK data, it is noted that the difference between the "Raw" data has lower values for the western part of the DEM, some areas are 5 meters or lower. The slope angle of the elevation difference trend plane (Table 2) for the DEM with "Raw" coordinates is 0.19° and for the DEM with accurate coordinates is 0.04°. This indicates that the DEM built based on "Raw" coordinates of image projection centers is insignificantly tilted relative to the terrain. The change of values by an order of magnitude confirms the theory of DEM inclination in the western, north-western direction. Mean is significantly more distant from zero values at one order of SRTM. Compared to SRTM, the DEM for the original coordinates is generally lower than expected and is tilted in the west, northwest direction. When PPK coordinates are processed, the elevation DEM is levelled, but the overall DEM becomes higher than the reference DEM, on average, by a meter, but for individual positive and negative landforms the difference is between 2 and 5 m with positive (about 32% of the area) and negative (less than 10% of the area) character, respectively.

ALOS PALSAR DEM. The performance calculation for the second two pairs of comparisons with the reference DEM yielded mean difference values of –0.04 m for the "Raw" coordinates DEM and 1.47 m for the PPK coordinates DEM. The mean difference value for the DEM by "Raw" coordinates is better than that of the DEM with accurate coordinate referencing and the STD value is similar for both differences (3.1 and 2.91 respectively). When comparing the values of the slope of the trend surface, there is also a noticeable improvement after PPK coordinate processing: 0.4° for the DEM using raw coordinates versus 0.08° for the DEM using processed coordinates. ALOS is constructed by resampling SRTM, so the results of comparison with these two DEMs are visually similar. The difference values for the underestimation sites are predominantly between –2 and –5 m; overestimations, similarly, between 2 and 5 m, which is systematic (Table 2). The slope trend of the DEM from the original data is preserved. For the DEM from PPK data there is a shift of the mean value to the area of positive values, the DEM is generally higher than expected (about 70% of the territory).

AW3D30 DEM. When calculating the characteristics for the third two pairs of comparisons with the reference DEM, the mean difference values were obtained: –4.06 m for the DEM by "Raw" coordinates and 0.08 m for the DEM by PPK coordinates. From this comparison, it can be concluded that the result of the DEM construction with accurate coordinate referencing is comparatively better. However, the value of STD, which is similar for both differences (1.97 and 1.44 respectively) also indicate the heterogeneity of the distribution of the mean difference index. The value of the slope of the trend surface improved slightly after PPK coordinate processing, 0.26° versus 0.09°. The trend of the slope of the DEM on the original data is maintained. When the coordinates are processed, the DEM is levelled, the values of the steepness index of the trend surface decrease by an order of magnitude, leading to values negligibly small (Table 2). Before coordinate recalculation, the DEM has a mean significantly far from zero, indicating an underestimation of height values relative to the reference DEM. Post-processing of coordinates of image projection centers allows to bring expectation values almost to zero, thus, most difference values are (more than 50% of the territory) in the range from –1 to 1 meter, which for DEM resolution of 30 m/pix can be considered acceptable and the relief DEM is generally correct.

FABDEM. When calculating the characteristics for the last two pairs of comparisons with the reference DEM for the first site, the mean difference values were obtained: –1.95 m for the DEM using "Raw" coordinates and 0.53 m for the DEM using PPK coordinates. The use of accurate coordinate referencing slightly improves the modelling result. However, the value of STD, which is 1.67 and 1.11 for both differences, respectively, also indicates the heterogeneity of the distribution of the mean difference index. The value of the slope of the trend surface slightly improved after PPK coordinate processing, 0.25° versus 0.02°. Similar to the previous three comparisons, there is a slope of the UAV DEM over the initial elevation values and an underestimation relative to the reference DEM by a value of about 2 m. The recalculation of the coordinates brings the expectation value closer to zero (Table 2), but indicates an average excess of values of 0.5 m. These values are concentrated mainly on positive landforms and the landslide body, which represents an abrupt change in topography: the body is absent on the reference DEMs, the landslide is fresh and recorded only on the UAV DEMs (Fig. 3). The majority of elevation difference values for the PPK DEM are in the range of 0.5 to 1 meters (more than 45% of the area), which can also be considered acceptable for the DEM resolution of 30 m/pix, the constructed relief DEM is generally correct.

Site 2: Karelian coast of the Kandalaksha Bay of the White Sea, Kindo Peninsula (area of Primorsky settlement). Similarly, the assessment methodology was tested at Site 2: calculations were carried out using 4 references DEMs in two versions, for the original georeferenced data and post-processed data (Fig. 4). Comparative analyses were performed on three characteristics for each algebraic difference image. The listed characteristics for site 2 are prepared separate sets of characteristics are for the whole territory (Table 3) and for non-forested areas (Table 4).

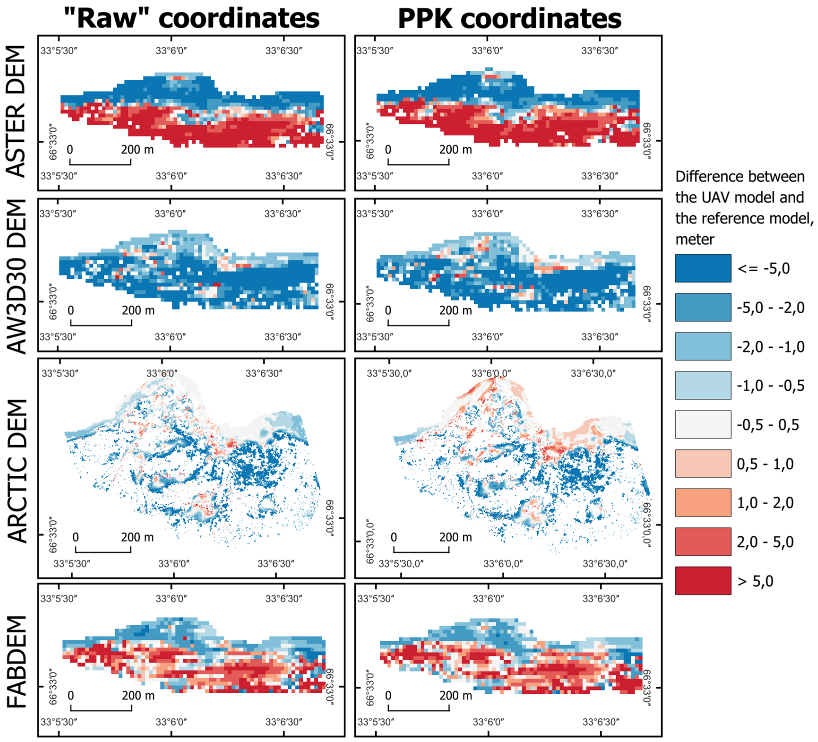

Fig. 4. Result of algebraic elevation difference of site 2 DEMs

Table 3. Statistical analysis of site 2

	"Raw" coordinates		PPK coordinates	
ASTER DEM	MEAN, m	1.59	MEAN, m	1.97
	STD	7.63	STD	7.53
	SLOPE, °	2.51	SLOPE, °	2.43
AW3D30 DEM	"Raw" coordinates		PPK coordinates	
	MEAN, m	-5.64	MEAN, m	-5.25
	STD	5.05	STD	5.03
	SLOPE, °	0.74	SLOPE, °	0.89
ARCTIC DEM	"Raw" coordinates		PPK coordinates	
	MEAN, m	-3.44	MEAN, m	–2.91
	STD	4.89	STD	4.93
	SLOPE, °	0.71	SLOPE, °	0.9
FABDEM	"Raw" coordinates		PPK coordinates	
	MEAN, m	1.13	MEAN, m	1.35
	STD	4.31	STD	4.31
	SLOPE, °	0.82	SLOPE, °	0.76

Table 4. Statistical analysis of site 2 (littoral)

	"Raw" coordinates		PPK coordinates	
ASTER DEM	MEAN, m	-6.65	MEAN, m	-6.32
	STD	2.44	STD	2.45
	SLOPE, °	0.87	SLOPE, °	0.86
AW3D30 DEM	"Raw" coordinates		PPK coordinates	
	MEAN, m	-1.45	MEAN, m	-1.08
	STD	0.78	STD	0.64
	SLOPE, °	0.06	SLOPE, °	0.03
ARCTIC DEM	"Raw" coordinates		PPK coordinates	
	MEAN, m	-0.36	MEAN, m	0.14
	STD	0.55	STD	0.71
	SLOPE, °	0.17	SLOPE, °	0.32
FABDEM	"Raw" coordinates		PPK coordinates	
	MEAN, m	-1.82	MEAN, m	-1.41
	STD	1.06	STD	1.1
	SLOPE, °	0.06	SLOPE, °	0.06

ASTER GDEM V3. For the second group of comparisons for site 2, the first pair of difference fields for the non-forested part of the territory, the mean difference values were obtained: -6.65 m for the DEM using "Raw" coordinates and –6.32 m for the DEM using PPK coordinates. The use of precise coordinate reference has no qualitative effect on the modelling result. This is also evidenced by the value of STD, which is similar for both differences (2.44 and 2.45 respectively), the value of the slope of the trend surface (0.87° and 0.86° respectively). When compared with ASTER, both DEMs show a similar result (Fig. 4): The littoral is underestimated relative to the reference DEM, with elevation difference values exceeding –5 m, more than 85% of the littoral plot for the original coordinates and more than 78% of the littoral plot for the equated coordinates. The difference values for the littoral section (Table 4) also demonstrate systematic underestimation of the DEM.

AW3D30 DEM. Similarly, for the second comparison, the use of precise coordinate referencing has no qualitative effect on the modelling result: the mean difference values are –1.45 m and –1.08 m for the "Raw" coordinates DEM and the PPK coordinates DEM, respectively; the STD values are 0.78 and 0.64; the slope angles of the trend surface are 0.06° and 0.03°. The values of elevation differences in the littoral area for both DEMs range from –2 to –1 meters (69% of the area for the PPK DEM, 45% of the area for equated coordinates), in some places slightly exceeding the value of –0.5 meters (13% of the area vs. 27% of the area). The UAV DEMs are underestimated relative to the reference DEM but are within the 30 m/pix resolution of the original DEM (Fig. 4). The overall slope of the DEM, captured by the steepness value of the interpolated trend surface, is not corrected through coordinate post-processing (Table 3), but the parameter value is negligible for the littoral section (Table 4). AW3D is a surface DEM that contains information not only on topography but also on vegetation. For the vegetation plot, the UAV DEM is underestimated by values of about 10 m, which is acceptable. When exporting the point cloud, only terrain elevation points were used, the reference DEM in these plots is represented by vegetation heights. Thus, we can conclude that the classification of the point cloud and the subsequent filtering of UAV survey data into "relief" and "non-relief" is correct.

Arctic DEM. This comparison is the most reliable, as the initial resolution of the reference DEM of 2m/pix is close to the resolution of the DEMs obtained by unmanned aerial imagery, compared to the rest of the global elevation DEMs (Fig. 4). The comparison with the Arctic DEM shows a slightly different result: while the mean difference improves by 0.14 m for the PPK DEM (–0.36 m for the "Raw" DEM), the STD and slope values of the trend surface deteriorate when using precise coordinate referencing. Thus, these values are 0.55 and 0.17° for the "Raw" DEM, respectively, and 0.71 and 0.32° for the DEM with accurate coordinate referencing. The littoral at this site for both DEMs, with GNSS initial values and equated through PPK, is within the range of values from -0.5 to 0.5 m (about 58% of the littoral area for the initial and equated DEMs), only in some areas from -1 to 1 meters (27% vs. 32% of the littoral area). The values of mean and STD are as close to zero values as possible (Table 4). Thus, the highest density of distribution is observed at values of –0.36 m of height difference for the original coordinates and 0.14 m for the equated coordinates. The use of accurate coordinate reference does not significantly but improves the vertical accuracy of the digital elevation DEM. It can be concluded that the values of DEM heights from unmanned aerial imagery data are correct, with the post-processing coordinates not significantly affecting the result. However, the overall slope of the DEM, fixed by the steepness value of the interpolated trend surface, is not corrected by coordinates post-processing (Table 3).

FABDEM. When calculating the characteristics for the last two pairs of comparisons with the reference DEM for the second site, the mean difference values were obtained: –1.82 m for the DEM using "Raw" coordinates and –1.41 m for the DEM using PPK coordinates. The use of accurate coordinate referencing slightly improves the modelling result. However, the value of STD deteriorates slightly after PPK coordinates processing: 1.06 and 1.1, respectively. The value of the slope of the trend surface remains unchanged, the exact coordinate reference does not affect the overall slope of the DEM is 0.06°. The values of elevation differences in the littoral area for both DEMs also range from –2 to –1 m (44% of the littoral area for the DEM based on the original coordinate values, 35% of the littoral area for the DEM based on the equated coordinate values), in places reducing this value to –0.5 m (13% vs. 25% of the littoral area, respectively). The UAV DEMs are underestimated relative to the reference DEM over the littoral area but are within the 30 m/pix resolution of the original DEM for this area (Fig. 4). The general slope of the DEM, fixed by the steepness value of the interpolated trend surface, is not corrected by post-processing of the coordinates (Table 3); for the littoral section the value of the parameter is negligibly small (Table 4). It is also worth noting the excess of elevation values for the forested section of the DEM up to 10 m. Since FABDEM assumes the absence of vegetation and buildings on the DEM, and the UAV DEMs were filtered for "non-relief" values, it is probably possible to judge possible errors in removing vegetation heights from FABDEM for a particular site. The statistics collected on vegetation and building values for the subsequent filtering of the reference DEM are collected in a highly discrete manner and interpolated for areas where these values are insufficient.

DISCUSSION

Evaluation of terrain modelling results using unmanned aerial imagery data was carried out on two sites differing in the character of relief and vegetation: one site is devoid of vegetation and has a complex terrain; the second site, with a relatively simple terrain, is 80% forested and partially built up. The change of elevations during DEM creation by the initial data received from the onboard GNSS receiver and by the equated PPK coordinates is considered. For the area with gentle relief the use of equated coordinates does not significantly affect the DEM height accuracy. However, we cannot rule out that this result was the result of a random coincidence of mathematical calculations, but it allows to use the materials constructed from the original data of unmanned aerial imagery. Geometrical features of the relief are considered, the DEM can be considered reliable. It is acceptable to use DEM for relief classifications, calculations of morphometric and morphological characteristics of terrain. The limitation will be a few tasks in which the calculation of multi-temporal dynamics of terrain is carried out. Thus, when analysing multi-temporal relief DEMs, the use of initial data requires accurate agreement not only of elevation values, but also the plan accuracy of all the DEMs used.

The situation is different for the territory with more complex relief. When building elevation DEMs for slopes using the original data, geometric deformations may occur, due to which the correctness of the results obtained based on these DEMs may not be achieved. In such cases it is recommended to use high-precision survey complexes or plan-altitude substantiation of the surveyed area. The study has shown that the altitude accuracy after coordinates post-processing increases, and minor geometric deformation of DEM in the form of inclination of the whole surface is corrected.

The point clouds obtained from photogrammetric processing of UAV imagery arrays are characterised by very high spatial resolution of about 10 points/m^2, which corresponds to large mapping scales. The reference DEMs taken for comparison in this study have incomparably lower spatial resolution. Consequently, comparison of these materials does not allow us to characterise the accuracy of representation of individual landforms (and especially micro- and nano-forms, which are not reflected in the fragments of global DEMs), but the presence of systematic trends in height differences may indicate distortions of detailed DEMs in general. In our case, the slope of the difference trend surface is noteworthy: for area 2, the difference of this characteristic between the DEMs obtained from the "raw" and accurate coordinates of the image projection centers is insignificant, while for area 1, a systematic slope of the "Raw" DEM of the order of 0.2° (an order of magnitude larger than for the PPK DEM) is observed. As far as we can judge, such deviation is insignificant for the most research tasks of local coverage, but we should keep in mind the influence of this deviation when carrying out diagnostic or monitoring works using low-cost UAVs.

It should be noted that the study did not cover areas with more complex and dissected relief with different degrees of forest cover, as well as with flat and slightly sloping relief with different degrees of forest cover and built-up areas. Therefore, we cannot unequivocally judge the applicability of the study conclusions for absolutely all surveyed areas. In order to obtain a reliable modelling result from unmanned aerial photography data for heavily forested or built-up areas, additional data on the height of buildings or vegetation cover may be required, which, in turn, should be coordinated with the corrected DEM. Tasks that require precise referencing of several types of cartographic and thematic materials, multi-temporal spatial data, are performed under the condition of minimum error of relative heights of analysed DEMs, as well as reliability of topography generation. Absolute georeferencing accuracy of unmanned aerial survey materials contributes to the reduction of this error. These tasks may include: assessment of the landform dynamics, landform detection, modelling of hazardous geological processes. However, it is worth noting the importance of understanding the peculiarities of tectonic processes on the studied sites. Also, the conclusions of the study may not be applicable to the tasks where unmanned aerial imagery are used as part of topographic and geodetic works.

Summing up the comparative and statistical analysis of the DEM results for both sites, we can conclude that post-processing of the coordinates of the image projection centers during unmanned aerial imagery does not significantly affect the elevation accuracy of the elevation modelling results, provided that the methodology is followed, and the parameters of UAV imagery correspond to the parameters of aerial imagery used for photogrammetric terrain modelling.

CONCLUSIONS

The paper studies possible distortions of relative heights on DEMs created from UAV photography without precise coordinate reference. For this purpose, a comparative analysis of DEMs constructed from unmanned aerial imagery data using two variants of projection center coordinates was carried out: based on "Raw" coordinates obtained from the onboard GNSS receiver and based on coordinates processed relative to the ground base station. As reference DEMs for comparison, we used fragments of global DEMs and DSMs: SRTM DEM, ASTER GDEM, ALOS PALSAR DEM, ArcticDEM, FABDEM. Such characteristics as algebraic raster difference, linear trend of the raster surface, slope angle of the trend surface, standard deviation, mean was considered when comparing the reference DEMs and the constructed ones. The study allowed to establish that relative elevations on DEMs obtained from UAV imagery data without precise coordinate reference are reproduced reliably. At the same time, the vertical accuracy of the obtained DEMs is acceptable for the most geographical studies, where the error of steepness values up to 0.9° can be considered acceptable. Nevertheless, for orographically complex and highly dissected terrain, additional research is required to absolutely exclude the influence of terrain character on the results of modelling based on unmanned aerial imagery data without accurate georeferencing.

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