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WAYS OF IMPROVING THE ACCURACY OF DIGITAL AERIAL PHOTOGRAPHY BY THE RAILWAY TRANSPORT INVENTORY

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Summary

The development of railway sector around the world has always been a vital issue, as it plays important social, financial and economical role and influences the development of the country a lot. Because of constant growth and modernizing of the railway sector all processes and items of land and property fund have to be monitored. On the basis of the world experience, trends in the development of methods and technologies of area mapping it has been established that for the inventory of land and property fund objects cartographic material at 1 : 500 or 1 : 1000 scales suits the most. With the large amounts of work (for example area of mapping and number of railroad objects) it is reasonable to use digital aerial photography and technology of digital data processing, in particular methods of digital photogrammetry. In order to increase the accuracy of creating the cartographic component, the authors suggest, when choosing the parameters of aerial photography, taking into account spatial resolution of camera system, its geometrical properties, the influence of external factors and first of all the atmospheric refraction. It has been proved that by highly precise aerial photography the accuracy of fixation of angular elements of camera orientation with the help of Inertial Navigation Systems (INS) may be insufficient. Therefore it is recommended to thicken core network using block phototriangulation. This paper presents the description and results of experimental work, which helped to create cartographic material from digital images at 1 : 3000 scale with an accuracy of 4–5 cm, which fully meets the requirements for holding inventory, monitoring, maintenance, design and construction.

Keywords

railway • inventory • digital aerial camera • spatial resolution (GSD) • atmospheric refraction • phototriangulation

1. Introduction

Technical re-equipping of railway sector requires significant investments and well thought-out technical decisions. Such actions are of irreversible nature. In our opinion it is necessary to monitor lands and railroad objects, plan and design comprehensive measures concerning expansion of the industry.

Creation of cartographic materials, which include all constituent elements of monitoring, detailed project reports and operational tasks, is the basic part of such monitoring and inventory of land and objects.

In some works[Balcer 2010, Барладін et al. 2012] concerning regulatory framework and requirements for cartographic representation of objects it is recommended to create and use cartographic materials at scales from 1 : 500 to 1 : 25000. Choice of concrete value of cartographic material depends on its purpose and further usage [Załącznik do zarządzenia N20/2010, Розенберг et al. 2007].

The highest requirements for minuteness and accuracy of mapping the objects concern plans at 1 : 500 scale. This is based on world experience and on reconstruction and modernisation practices of railways in Europe and Asia as well. In Ukraine such materials have to meet requirements for state land cadastre [Барладін 2012] and also for design, survey, construction and maintenance works. Detailed list of requirements can be found in regulatory documents [Державні будівельні норми 2008a, b].

It is also important to mention that the final product of mapping on the railway is topographical plan, which depicts:

- elements of a situation (objects), which are shown on area including drainage area within conventional boundaries, which are adjusted by executor and employer,
- terrain in the form of contour lines with inscriptions for altitude points, or in the form of digital terrain model (regular or irregular grid),
- all kinds of vegetation (woody, scrub, grass, cultivated, etc.),
- soils and microorganisms of the surface: wetlands, sands, salines, pebbly, clay, and rubbly surfaces and others,
- boundaries of administrative division, protected areas and reserves,
- boundaries of land use,
- schematic information concerning geographical names of the area (towns, railway stations, lakes, rivers, etc.).

The separate specific group is dedicated to data about railway objects, in particular:

- vertices of railway angles of rotation, pickets, signs and lines, pointers of kilometres,
- numerical values of curve elements (angles of rotation, radii etc.),
- utilities,
- stations, passing tracks, overtaking points, crossings, switchers, rail numbers.

This list is rather long as it depends on the elements on the railway in the given area.

In addition to the plan for railway areas with the existing (built) digital model of area (DMA), there can be built longitudinal and cross direction profiles that will meet the applicable requirements of railway services.

It is obvious that the requirements for accuracy of inventory and mapping documents for such an integrated approach are regulated by:

a) requirements for cadastral plans,
b) the requirements for the plans of railways.

For cadastral plans of town areas the recommended scales are 1 : 2000, 1 : 1000 and the scale 1 : 10000 for all others.

The recommended scales for the plans of the railway are 1 : 1000 and 1 : 500 as they need to display detailed information about all of the objects that are mentioned above and also to determine their coordinates with the required accuracy. Among the methods for creating cartographic components distant methods deserve special attention. Their effectiveness for large areas and for large number of objects by inventory is beyond competition.

2. Methods

2.1. General characteristics of effectiveness of digital aerial photography

A number of publications [Załącznik do zarządzenia N20/2010, Balcer 2010, Барладін 2012] and analysis of regulatory framework and requirements for cartographic representation of objects and lands of railway transport that have been carried out before, shows that reconstruction of railway transport is based on project documentation, which requires cartographic materials at scales from 1 : 500 to 1 : 25000. Choice of concrete scale value of cartographic material depends on its purpose and further usage.

After exploring the problems and world tendencies of solving separate problems there appeared a conclusion that digital aerial photography can supply cadastral, project and geoinformation work with high-quality and accurate data [Butowtt and Kaczyński 2003, Casella and Franzini 2005, Kurczynsky 2006, Kurzyński et al. 2012, Paszotta and Szumilo 2007, Дорожинський and Тукай 2008].

The effectiveness of aerial photography depends on correctly chosen and theoretically substantiated choice of aerial photography method, on the type of devices and on parameters of aerial photography. Among latter – the flight altitude for defining the altitude of objects' points and the scale of photography in defining the horizontal location of objects are the most important. Taking into account the current state and tendencies of remote sensing development, aerial photography has been chosen by us as one of the most competitive methods in creation of large-scale maps and plans. Alongside with this all specific conditions of project and cadastral works, where railway functions, have to be taken into account.

Depending on the kind of works with reformation of railway transport there appear different requirements to horizontal and vertical location of objects on the cartographic material. The dominant value at cadastral works is horizontal location of borders of lands that belong to railway. Then altitudes of the points (digital terrain model) are necessary for creation of orthophotomaps or plans. However, for performing project works spatial models (3D models) are required. Moreover, the demands to accuracy of defining the coordinates may be rather high, mainly on the level that can be supplied with engineering geodesy methods.

Modern methods of remote sensing allow to create high quality cartographic materials that are suitable for solving different kinds of applied problems. With comprehensive assessment of input data and methods of processing for creation of cartographic component the question is to meet the main demands that concern accuracy, adequacy (topicality) and economic feasibility. These three components allow to assess the effectiveness of distant methods.

As it has been pointed out, the expected accuracy of digital aerial photography for creation of cartographic component allows to create plans for railway at 1 : 500–1 : 1000 scales. However, a task to improve cartographying accuracy remains important. Its aim is to search for possible ways and methods of improvement of metric characteristics of digital images, taking into account the features of the object, i.e. railway transport.

2.2. Spatial pixel and its role in project designs

The important parameter for project calculations is δ-size of spatial pixel (GSD), which at first approximation can be calculated by [Butowtt and Kaczyński 2003, Kurczynsky 2006, Дорожинський and Тукай 2008]:

$$\delta = \frac{H}{F}, \tag{1}$$

where:

H – flight altitude in cm,

F – focal distance in pixels,

It is known that for digital cameras.

$$F = \frac{f}{\Delta}, \tag{2}$$

where:

f – focal distance in mm,

Δ – size of pixel in matrix in μm.

Taking into account technical parameters of photography systems, we get the sizes of spatial pixel GSD, given in Table 1, for three types of digital cameras at different altitudes of shooting.

Table 1. Spatial pixel GSD for three cameras

Camera	f [mm]	Pixel [μm]	F [pixels]	GSD [cm] at H [m]					
				300	500	1000	1500	2000	3000
ADS80	62.5	6,5	9600	3.1	5.2	10.4	15.6	20.8	31.2
DMCII 140	92	7,2	12800	2.3	3.9	7.8	11.7	15.6	23.4
DMCII 230	92	5.6	16400	1.8	3.0	6.1	9.1	12.2	18.3
DMCII 250	112	5.6	20000	1.5	2.5	5.0	7.5	10.0	15.0
UltraCam	210	5.2	40400	0.7	1.2	2.5	3.7	5.0	7.4
	100	5.2	19200	1.6	2.6	5.2	7.8	10.4	15.6
	80	5.2	15400	1.9	3.2	6.5	9.7	13.0	19.5

Data from Table 1 concern nadir pixel; on the edge of the picture physical pixel is projected at ϕ angle; so that spatial pixel increases. After simple transformations we get

$$(GSD) = (GSD)_N \frac{1}{\cos^2\phi}, \tag{3}$$

where:

ϕ – angle between nadir and tilted beams,
$(GSD)_N$ – size of spatial pixel in nadir.

For example, at the angle that is within the eyesight of the scanner across the flight direction 2ϕ = 64° increase of a pixel in comparison with nadir is equal to 1.4 times. For full-length cameras, indicated in Table 1, with taking into account the angle 2ϕ, we get the value (*GSD*) at the edge (Table 2).

Table 2. Lateral spatial pixel for three cameras

Camera	2ϕ [deg.]	GSD [cm] at the flight altitude H [m]					
		300	500	1000	1500	2000	3000
ADS80	64	4.3	7.2	14,4	21.7	28.9	43.4
DMCII 140	50.7	2.8	4.8	8.8	14.4	19.2	28.8
DMCII 230	49.4	2.0	3.6	7.4	11.0	14.8	22.1
DMCII 250	46.6	1.6	2.7	5.4	8.1	10.8	16.2
UltraCam 210	28	0.7	1.3	2.6	3.9	5.3	7.8
UltraCam 100	28	1.7	2.7	5.5	8.3	11.0	16.5
UltraCam 80	33	2.7	4,5	9.2	13.8	18.5	27.7

The size of spatial pixel GSD is one of the factors which determine and influence the accuracy of photogrammetry works. Each process in the chain "picture – processing – result" makes its errors on obtaining spatial coordinates. The main processes are:

- photography: the quality of photography system, influence of the atmosphere (refraction),
- geodesic binding of the pictures: creation of the net of strong points (accuracy of identification of the points, accuracy of identification of coordinates),
- determining the spatial coordinates of the centre of projection from the (GPS) registration,
- determining the angular orientation of the photography system by INS,
- construction of aerial triangulation,
- construction of CIE, CMR, TSMPT.

That is why the total effect of these factors, on condition of equality, gives general average quadratic error of defining the coordinates in the plan:

$$m_{x,y} = \sum_{1}^{n} m^2_{(x,y)_i} \quad (4)$$

At altitude:

$$m_z = \sum_{1}^{n} m^2_{(z)_i} \quad (5)$$

where:

n – the amount of influential factors.

2.3 The quality of photography system

First of all the distortion of optical system is a source of errors meant [Sitek 1991]. The manufacturers claim that optical systems are without distortions, it means that distortion is not more than 1–3 microns. Special researches for digital cameras have not been carried out or published. Calibration parameters are determined mainly by a paper method with an accuracy of 1–3 microns for the main points and 3–5 microns for the focal distance. This concerns full-length metric cameras. Small-format or amateur cameras are not considered for high-accuracy mapping of the railways.

2.4. Outer factor – atmospheric refraction

Atmospheric refraction was an object for studies in the eighties of the twentieth century. The formulae for calculation the refraction effect for standard atmosphere were made up [Paszotta and Szumilo 2007, Куштин and Лысков 1984]. For digital aerial photography such calculations were not made. That is why we use the formula of Ashenbrener for calculation the refraction angle λ:

$$\lambda'' = 3.1d[1 - 0.035(3Ha - H)], \quad (6)$$

where:

d – is the distance to the point on land from the camera (km),
Ha – the altitude (km),
H – the flight altitude (km).

The shift of the point on the image by refraction effect:

$$\delta r = \frac{f}{\cos\phi} \cdot \frac{\lambda''}{\rho''}, \quad (7)$$

where:

f – focal distance (mm),
ϕ – angle between nadir beam and the beam on the point at the centre of projection.

In Table 3 there are calculations of refractional effect that causes the increase of the size of spatial pixel for digital cameras of three types.

Table 3. Influence of the refraction on extreme pixels in the cameras of three types

Camera	Pixel [μm]	Φ [deg.]	*f* [mm]	GSD, cm at the flight altitude H [m]					
				300	500	1000	1500	2000	3000
ADS80	6.5	22	62.5	0.3	0.5	1.0	1.7	2.3	3.6
DMCII 140	7.2	25.3	92	0.5	0.8	1.7	2.6	3.6	5.6
DMCII 230	5.6	29.7	92	0.5	0.9	1.9	2.8	3.9	6.0
DMCII 250	5.6	23.3	112	0.6	1.0	2.0	3.1	4.2	6.5
UltraCam 210	5.2	14	210	1.0	1.7	3.4	5.2	7.0	10.9
UltraCam 100	5.2	14	100	0.5	0.8	1.6	2.5	3.3	5.2
UltraCam 80	5.2	33	80	0.5	0.8	1.7	2.6	3.6	5.6

Analysis and comparison of received data indicates that images from the camera ADS80 throughout the range of elevation (300÷3000 m) do not undergo decentration larger than ½ pixel. For camera DMCII, focal lengths 230 and 250 mm, decentration exceeds the pixel size, and therefore the effect of refraction must be taken into account. For camera UltraCam altitude of 1500–3000 are already noticeable on the effect of refraction, and therefore such decentrations should be taken into consideration.

In particular, we note that the following recommendations can not be found in literature. Especially it concerns software.

2.5. Fixation of linear and angular elements of external orientation in flight

In the practice of aerial photography GPS data are used for the registration of the plane flight trajectory and linear objects of the centre of projection X_S, Y_S, Z_S. According to the research data, for example [Leberl and Gruber 2005, Kurczynsky 2006], the accuracy of such registration is within 10 cm. Inertial Navigation System INS fixes during the time of flight the acceleration across three axes and changes of angular orientation of the camera, i.e. angles α, ω, κ. If GPS and INS work constantly, then the trajectory of flight is fixed with an accuracy of 2–3 cm.

The drawback of INS is a systematic error (so-called drift) during long flight. However, GPS data allow to correct registered angles, which is one more positive factor of GPS usage. In its turn INS data are used to correct the trajectory, i.e. the GPS data, when the connection with the satellites is lost for a short time, perhaps during banked turn of a plane or other reasons.

That is why the important thing is the recommendation to use GPS+INS data during the photography of the area and railway objects.

Let us make the analysis of requirements for the registration of angular elements of external orientation.

Starting position is minimal size of photography system pixel Δ.

From the centre of projection this angle is seen at the angle:

$$(\delta\phi)'' = \frac{\Delta \cdot \rho''}{f}, \tag{8}$$

where:

f – focal distance of the system.

Taking into account the parameters of the camera, given in Table 2, we get angular resolution for the next cameras and their modifications.

ADS80: $\delta\phi = 20''.8$

DMCII(140): $\delta\phi = 15''.6$

DMCII(230): $\delta\phi = 15''.6$

DMCII(250): $\delta\phi = 10''.0$

UltraCam (210): $\delta\phi = 4''.9$

UltraCam (100): $\delta\phi = 10''.4$

UltraCam (80): $\delta\phi = 13''.0$

Test researches of INS, conducted by different researchers [Casella and Franzini 2005] suggest that the real accuracy of INS angles registration is within 30″. Means that angular elements of external orientation, recorded in flight have insufficient accuracy. Therefore INS data can be used only with some restrictions, and the angles need to be defined more precisely. One of such approaches is the usage of aerial triangulation.

2.6. Experimental researches of photo triangulation constructions for railroad

It is known [Butowtt and Kaczynski 2003, Дорожинський and Тукай 2008, Куштин and Лысков 1984] that in comparison with route photo triangulation block photo triangulation gives better results. It is achieved because of additional photogrammetry conditions and because of self calibration of the images.

At the photo shooting of railway as a linear object it is more convenient to take picture in one way. That is why there appears a contradiction between factors – accuracy – economy, which requires research at the railway.

Such studies were conducted by us and their results are given below.

For experimental verification of photo triangulation accuracy as a component of the overall technological scheme of mapping the railway objects, the digital aerial photography materials made with UltraCam-D camera at 1 : 3000 scale on four areas of railroad and the data of field binding (in the arbitrary coordinate system) are used. Scheme of the road and placing of strong points (object number 1) are shown in Figure 1. Processing of digital images was performed by us at digital photogrammetric station and a network of photo triangulation covering the railroad with length of 21 km was built.

Methodology of measurements and calculations is the same as given in Дорожинський and Тукай [2008].

The assessment of accuracy was held with the help of 26 control points, coordinates of which are defined with an accuracy to 2 cm and with usage of forced centring of geodesic equipment. At photogrammetric calculations each strong point has undergone several sightings (3–4 times). Arithmetical mean has been taken as the last value.

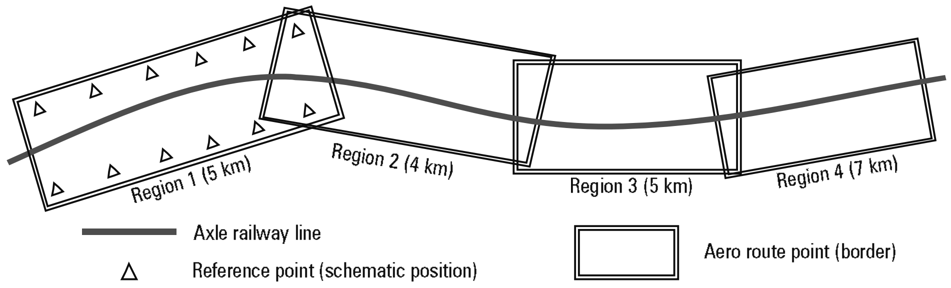

Fig. 1. Scheme of aerial photography and field binding for the area of the railroad (object no. 1)

Data from assessment of photogrammetry construction accuracy are given in the Table 4.

Table 4. Data from assessment of photogrammetry construction accuracy

No. section	No. point	Absolute values of errors at control points [cm]		
		δx	δy	δz
1	1	5.0	6.0	2.0
	2	4.0	5.0	4.0
	3	5.0	5.0	6.0
	4	3.0	6.0	6.0
	5	4.0	1.0	4.0
	6	5.0	2.0	5.0
2	7	6.0	4.0	5.0
	8	4.0	4.0	4.0
	9	1.0	5.0	6.0
	10	5.0	5.0	2.0
	11	5.0	6.0	6.0
	12	4.0	1.0	6.0
3	13	3.0	4.0	6.0
	14	6.0	3.0	4.0
	15	2.0	4.0	5.0
	16	5.0	3.0	5.0
	17	5.0	5.0	3.0
	18	4.0	6.0	5.0
4	19	6.0	4.0	4.0
	20	6.0	5.0	6.0
	21	1.0	5.0	6.0
	22	4.0	4.0	3.0
	23	3.0	4.0	6.0
	24	5.0	6.0	5.0
	25	5.0	2.0	4.0
	26	4.0	4.0	6.0

$$m_x = 4.4\text{ cm}, m_y = 4.4\text{ cm}, m_z = 5.0\text{ cm}$$

$$\delta_x = 0.9\text{ cm}, \delta_y = 0.9\text{ cm}, \delta_z = 1.0\text{ cm}$$

The obtained average quadratic errors m_x, m_y, m_z and their confidence intervals σ_x, σ_y, σ_z coordinate with project values very well.

Another object number 2 is the track with the small angles of rotation with length of 12 km. It is taken with one aerial photography route at 1 : 3000 scale. Strong points have been situated in pairs in 600 m (Figure 2).

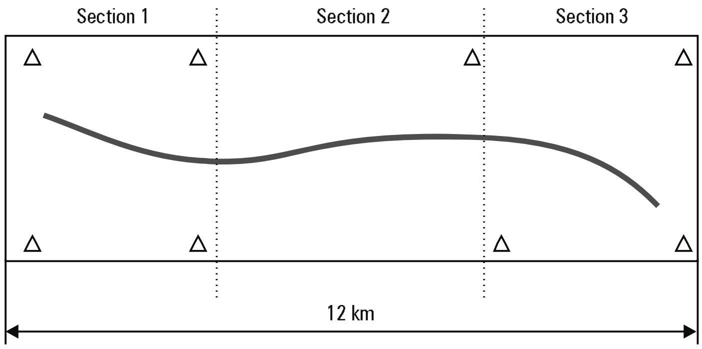

Fig. 2. Scheme of strong points, object number 2

Construction of the phototriangulation network has been conducted with two different options. In the first option the network was built separately in each of the sections 1, 2, 3. In the second option network was built simultaneously for three sections. For the assessment of accuracy in each sections there were 7, 8, 10 strong points respectively. The calculated average quadratic errors are given in the Table 5.

Table 5. Assessment of phototriangulation accuracy for sections 1, 2, 3 and for object number 2

Av. Quadr. Err [cm]	Section 1	Section 2	Section 3	Object no. 2
m_x	5.0	4.8	5.2	6.0
m_y	4.3	4.6	5.0	5.5
m_z	5.5	6.0	5.8	6.3

These results suggest that in the case of one route phototriangulation the better results are on short sections rather than on all of the sections, i.e. for the whole area.

The next experiment dealt with processing of two parallel routes of photo shooting that covered the railroad and created phototriangulation unit (Figure 3).

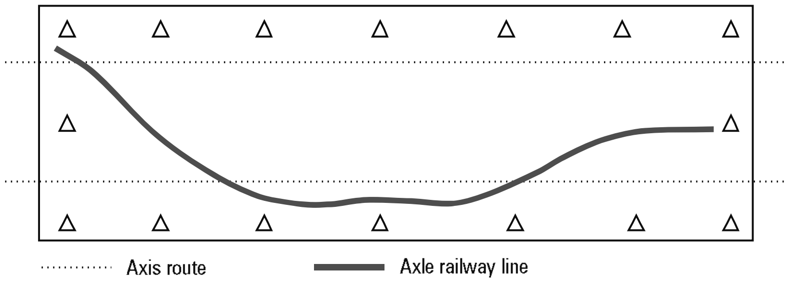

Fig. 3. Unit oft he images from two aerial shooting routes

The length of the road is 14 km, and there are 16 strong points on the area. 14 strong points are situated uniformly across the axis of the road. Block phototriangulation has been built without self calibration.

The results are:

$$m_x = 4.4 \text{ cm}, m_y = 4.2 \text{ cm}, m_z = 4.4 \text{ cm}$$

As objects number 1 and 3 are identical in length, even object number 3 is longer at 2 km, then a comparative analysis and a conclusion can be made. The conclusion is: block phototriangulation gives better results of defining the horizontal coordinates ca in 1,3 times and in altitude in ca1, 4 times. At the same time road number 3 is longer than the road number 2. The number of strong points has been 16 and 80. Therefore two route aerial photography and block triangulation deserve absolute preference.

3. Conclusions

1. It has been proved that the main source of information for cartographic supply for inventory of land and property fund is a digital picture.
2. To increase the accuracy of photogrammetry works it is necessary to take into account the effect of atmospheric refraction under condition of shooting from the altitude of 1500–3000 m. In modern software absent modules for consideration of refraction effect are supplied. Therefore in the software it is necessary to provide modules for calculation the atmospheric refraction effect.
3. It has been established that the accuracy of angular elements registration at the railroad with the help of INS is insufficient. Since GPS/INS systems in the majority of cases do not fix elements of external orientation with sufficient accuracy then it is necessary to use phototriangulation, better with self-calibration.
4. The performed works that concern thickening of supporting network have shown high accuracy of photogrammetry thickening (with an accuracy of 4–5 cm). In the future such materials will allow to create orthophotoplans and other final products for projecting and planning the reconstruction of the railroad.

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