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Integrated sensor orientation – ground control points for a large-block aerotriangulation

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Abstract. The article describes research on the number and distribution of ground control points (GCPs) for large blocks of aerotriangulation using Integrated Sensor Orientation Technology (ISO). The study was conducted through simulation of aerotriangulation. Simulations were performed for five common types of image blocks in Poland and for 2 levels of measurement precision established on the basis of previously performed studies of 19 large blocks constructed in 2008 – 2010.
The utility of the developed rules for designing GCPs distributions were checked in real aerotriangulations of 10 large blocks of images. In the study a reference is made to the accuracy required by Polish national standards, to homogeneity of the results, as well as to the reliability of measurements.
The test results define a sufficient number of GCPs for the aerotriangulation of large rectangular blocks and for the ribbon block (block of three strips). For rectangular blocks the required GCPs number defined as the number of photos per one control point is 40 to 150 and for a ribbon block is 24 to 45, a number that depends on the level of measurement precision and on the shape of the block.

Keywords: photogrammetry, aerotriangulation, simulations, ISO, GCPs distribution

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1. Introduction

The use of the measurements of projection centers and angles of orientation of the images obtained from devices GNSS/IMU in aerotriangulation is now common. Greater use of them was initiated by the research of OEEPE „Integrated Sensor Orientation", which took place in 2000/2001 (Heipke et al., 2002a, 2002b). The research related to the technology, integrated sensor orientation, whose main feature is the determination of systematic errors of equipment (calibration) during the production aerotriangulation, which allows for the omission of frequent calibration of equipment by means of photogrammetric flights over test fields.

The main purpose and advantage of the ISO is further reduction of the required number of ground control points in the block in aerotriangulation based on the measurements of the coordinates of projection centers only. The reduction of field surveys provides a new quality, since even for small-scale images it is feasible and cost-effective to target ground control points which gives a large increase in the accuracy of the results. Also, the ISO advantage is the ability to reduce the number of tie points which at today's high degree of automation of the measurement in the photos is important especially in difficult terrain or in case of insufficient overlap.

During the last ten years a large number of tests has been performed directly on the ISO technology. One can quote publications on subjects such as: performance of digital cameras, stability of systematic errors, the role of additional parameters in adjustment with the ISO technology, required number of ground control points in the ISO, limitation of the number of tie points in the ISO, increase of the level of measurement precision of the image orientation elements, new methods to develop results.

In the past few years, a comprehensive testing of photogrammetric technology using digital cameras has been conducted, with the participation of several institutions: in the years 2008–2010 the test known as „The DGPF-Test on Digital Airborne Camera Evaluation" (Cramer 2010; Jacobsen et al., 2010), and in the years 2008 – 2010 the test "Euro SDR project: Radiometric Aspects of Digital Photogrammetric Images" (Honkavaaraa et al., 2009). The results of the last few years, as well as from last year (Jacobsen, 2011) show the continuous development of photogrammetric technology.

The ISO Technology, in a larger, production scale, is used in Poland since 2008. The aerial photographs and the measurment of the orientation elements is performed by many companies with the use of equipment of significantly different parameters. It is worth noting that in the last few years the use of analogue cameras has been abandoned, and the large-format digital cameras became a photogrammetric standard.

An important factor in the Polish photogrammetric practice is the lack of clear requirements on the quality of aerotriangulation, being an intermediate product. Overview of requirements for contractors shows that they do not reflect the aim of the aerotriangulation. They neither relate directly to the accuracy of the assigned unknowns nor directly to the accuracy of the products they serve, i.e. the accuracy of the orthophoto and digital elevation model. They also do not include a possibility of reducing the required number of ground control points and checkpoints.

The research described in the literature do not undertake important issues encountered in the design and implementation of aerotriangulation. The problem significantly affecting the quality, which according to analysis showed to be a serious trouble to national contractors is the design of GCPs distributions. In most blocks, the number of ground control points exceeds the number sufficient for normal development even several times (Ziobro, 2011).

The problem of GCPs distribution should be considered in relation to other network parameters such as the size of the block of photos being developed, the precision of coordinates of the ground control points – targeted or untargeted, the reliability of coordinates of the ground control points in aerotriangulation, the increase in accuracy of the results of aerotriangulation with an increase in the number of ground control points. The research presented in the literature indicate that the sensor calibration is mathematically solvable with one GCP in the block, located at its center, but because of the minimum reliability of the coordinates of GCPs there should be no less than four GCPs, located on its outskirts (Kremer et al., 2003; Smith et al., 2010).

Also no references of increasing the accuracy of results with an increase in the number of GCPs are in the literature. The author's research on aerotriangulation with the measured projection centers (Ziobro, 2008a) shows that the increase in accuracy of results with an increase in the number of ground control points is asymptotic. The increase in accuracy quite rapidly slows down despite the steady increase in the number of ground control points, thus making further increasing the number of GCPs senseless.

An important objective in designing of aerotriangulation is to obtain possibly homogeneity of precision of object points. This is particularly important in calculating the elevation *Z*. This issue also is not reflected in the literature refering to ISO.

The effect of changes in the value of one of the network parameters on the elements of the network quality assessment, such as the accuracy of aerotriangulation, the homogeneity of the accuracy, and reliability of measurements, is highly nonlinear and it is not possible to be determined through a simple analogy to results from other aerotriangulations. The high nonlinearity of these relationships means that in some value ranges of the selected parameter, the effect of its changes is significant, and in other ranges is virtually unnoticed. The desired parameter value can be assigned through simulation of the aerotriangulation – a series of simulations with variable value of a selected parameter.

It should be noted that the usefulness of the conclusions of these simulations is strictly conditional on compliance of the parameters taken as constants in the simulations with the parameters used in photogrammetric practice, such as precision of measurements or network design. In practice, the constant simulation parameters can be assigned through analysis of the commercially made aerotriangulation. Such analysis was performed in previous studies, based on 19 commercial aerotriangulation performed in Poland in 2008–2010 (Ziobro, 2011). Photos of the analyzed blocks were performed with the large-format digital cameras, and 90% of the images had GNSS/IMU measurements. Commercial aerotriangulations were again developed using Bingo sofware, to remove the occasional obvious errors and to standardize the statistical evaluations.

The analysis allowed to:
- evaluate the ground control points design – their number and location in the block,
- determine the average precision of each group of measurements and the range of variation of these precisions,
- determine the average reliability of each group of measurements,
- determine the precision of object points.

2. Objective and methodology of the research

The purpose of the research was the determination of the number and distribution of ground control points for large blocks of photos with ISO technology. In the study, when determining the parameters the simulation of aerotriangulation was primarily directed towards the technical realities occurring in the production demands of the general design of surveying networks, including aerotriangulation. Here are the detailed rules for surveys to determine the adequate GCPs distribution for large blocks of images found in domestic practice.

2.1. Simulations of block adjustment

Number and location of ground control points were determined by successive approximation based on the sequence of aerotriangulation simulations of a selected block with variable number of ground control points. Sequences of such simulations were done for 5 types of blocks met in domestic production and for two levels of measurement precisions. Simulations were performed with the use of Bingo v.5.4 software for aerotriangulation, which has the function of simulation of the block adjustment, in particular calculating the standard deviations of unknowns and local redundancy numbers of the measurements. To start the function, the values of approximate measurement values, approximate values of the unknowns, standard deviation of observations, and parameters of cameras should be given.

Variants of the GCPs distributions were created by gradually increasing the number of ground control points on the edges of the block, where they were located symmetrically about the axis of the block. The last variants of the GCPs distributions for a selected block given in the tables of results (Tables 3 and 4), are the GCPs distributions of very large number of GCPs uniformly placed in the area of the block.

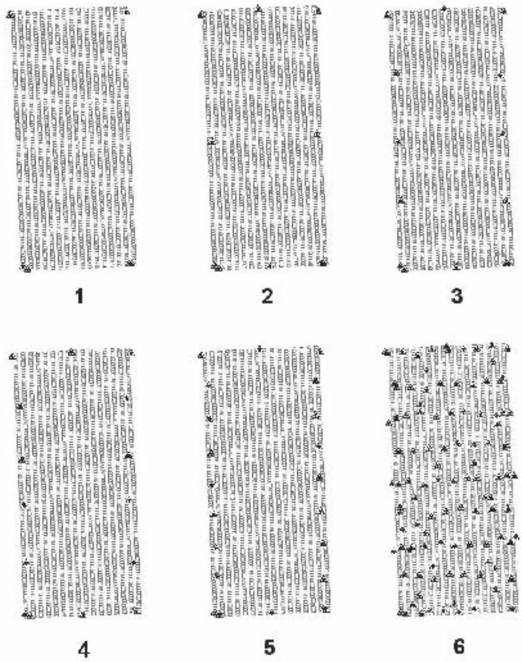

Fig. 1. Block A, variants of GCPs distribution

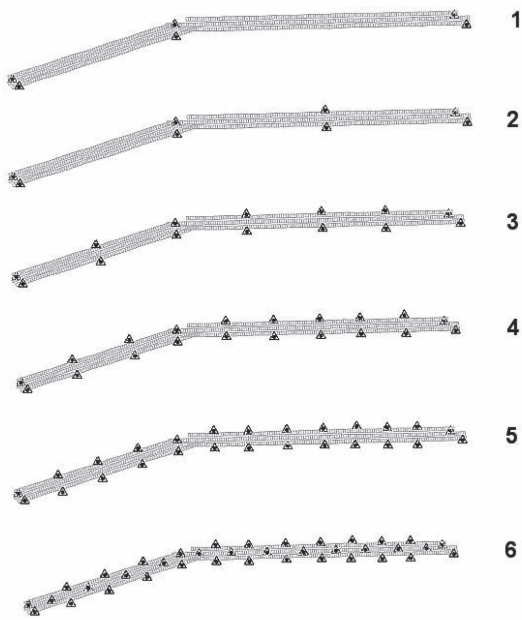

Fig. 2. Block E, variants of GCPs distribution

For each of the five types of blocks in two levels of the measurement precision, a sequence of 6 to 7 simulations was developed. Examples of the GCPs distribution of test blocks developed for a rectangular block and for a ribbon block are shown in Figures 1 and 2. Control points are generally located in the sidelap area so that they are measured at least on four photographs, which provides good reliability of photocoordinates. In rare cases, despite the rule they were located on only two images, in order to comply with the terms of occurrence in reality. Also for this reason, the rule of regular deployment of GCPs was sometimes departed from.

2.2. Types of simulated blocks

It was assumed that large blocks will be tested with sizes ranging from one to two thousand images having the parameters appearing in the photogrammetric practice in Poland. Geometric constructions of simulated blocks come directly from commercial blocks – they are their fragments. It meets the demand that fixed simulation parameters were as close as possible to real. For the study four rectangular blocks were selected with the number of images from 960 to 2342, differing in ground sample distance (GSD) and image scale. The ribbon block was also investigated. It is a three-strip construction of large-scale images consisting of 208 photos. This block is marked with the letter E.

The blocks of images were taken with multi-head digital cameras DMC (simulated block A) and UltraCam (blocks B ÷ E). Systematic errors of GNSS, shift and drift, were determined strip-wise. Calibration of IMU data was determined globally, separately for each camera. Test block parameters are given in Table 1.

2.3. Levels of measurement precision

Levels of measurement precision adopted in the research were determined on the basis of analysis of photogrammetric practice in Poland. It was assumed that the simulations are performed for two levels of measurement precision, that is:

- for negative low-precision measurements, but still acceptable in commercial practice,
- for the average precision obtained in the commercial measurements.

The first scenario assumes a low precision of the photocoordinates and the coordinates of the projection centres, low precision of orientation angles and the coordinate precision of ground control points corresponding to the natural ground control points. In the second variant, precisions of the measurement were assigned as the mean values of the precision obtained in 19 commercial blocks, and precisions of the targeted ground control points. For ribbon block simulation the precisions of the targeted ground control points were adopted in both levels because of the large-scale images. The measurement precisions used in each block of test simulations are summarized in Table 2.

2.4. Homogeneity of results

Homogeneity of the precision of the results is one of the requirements of the surveying network design, and it requires homogeneous precision of unknowns in the entire block. On the basis of tests described in the literature as well as the author's own research (Ziobro, 2008b) it can be concluded that the lowest accuracy in assigning coordinates of object points in the block is obtained, especially for the *Z* coordinate, distributed around the peri-

Table 1. Parameters of simulated blocks

Simulated block name	No. of photos	No. of strips	No. of photos in strip	Scale of photos	Ground sample distance [cm]	Endlap/ Sidelap [%]
A	1760	16	110	1:19 250	23	60/30
B	1767	10	177	1:36 200	22	60/30
C	960	12	80	1:38 100	34	60/30
D	2342	14	167	1:13 800	8	80/40
E	625	3	208	1:6 600	4	60/50

Table 2. Precision of group of measurements in simulated blocks represented by standard deviations

Simulated block name	Precision level of measurements	Image points	GCPs		Positions		Attitudes	
		σ_x/σ_y [μm]	σ_X/σ_Y [cm]	σ_Z [cm]	$\sigma_{X_0}/\sigma_{Y_0}$ [cm]	σ_{Z_0} [cm]	$\sigma_\omega/\sigma_\varphi$ [cc]	σ_κ [cc]
A	low	2.5	25.0	20.0	15.0	10.0	100	200
	average	1.4	11.5	6.0	6.0	3.0	45	125
B	low	2.5	22.0	15.0	15.0	10.0	90	200
	average	1.4	11.0	6.0	6.0	3.0	45	125
C	low	2.5	22.0	15.0	15.0	10.0	90	200
	average	1.4	11.0	6.0	6.0	3.0	45	125
D	low	2.5	8.0	5.0	15.0	10.0	90	200
	average	1.4	4.0	4.0	6.0	3.0	45	125
E	low	2.5	2.5	5.0	15.0	10.0	100	200
	average	1.4	2.5	5.0	6.0	3.0	45	125

meter of the block. This is the reason for locating GCPs as close as possible to the edge of the block.

Nevertheless, the accuracy obtainable at the edge of the block is significantly lower than the accuracy at its interior. This negative phenomenon is compensated by photogrammetric flight planning, so that images overlap bigger area than the strict area of the digital terrain model or orthophoto, namely: the two extra photos in a strip outside the area border, and in transverse direction, an extra half-width strip or full-width strip outside the area border.

In order to assess whether the GCPs distribution variant provides a homogeneous precision of the results, the distribution of standard deviations of coordinates of object points in the block were checked through the analysis of graphical spatial presentation of the files of standard deviation of object points coordinates, that is files of σ_X, σ_Y or σ_Z.

2.5. Internal reliability of ground control points

Reliability of measurements is another demand of the network design. In the design of aerotriangulation it is recommended that the network has provided a local redundancy numbers not less than 0.25 (Kruck, 2007). Four control points located at the corners of a rectangular block give too small reliability of their coordinates. In the aerotriangulation simulations performed on the basis of this number of ground control points (not presented in detail in this article), the average redundancy numbers for all three coordinates of a GCP happened to be less than 0.10, which indicates low reliability of the measurement (Foerstner, 1985). To meet the demand of reliability, it was assumed in the simulations that the minimum variant of the GCPs distribution is based on two control points located at each corner of a rectangular block. This GCPs distribution pattern provides the average redundancy numbers of GCP coordinates greater than 0.20.

For ribbon block, the minimum GCPs distribution are two control points located on the strip opposite edges, but assuming that there will be no less than six ground control points in the block.

2.6. Criteria for selecting the GCPs distribution variant

Within the developed simulations a GCPs distribution variant was chosen according to three criteria described below, which should ensure the usefulness of aerotriangulation with possibly a small number of ground control points.

The first criterion was the precision of the result arising from the requirements on the accuracy of orthophotos. It has been determined based on the relationship between GSD of photos, and the average precision of the object points coordinates. National standard for orthophoto (Dziennik Ustaw 253, 2011) require the position error on ortofotomap not greater than twice the size of the orthophoto pixel. It is worth noticing that GSD of photos is usually about 10% to 20% smaller than orthophoto pixel. From the above relationship it can be assumed that the average standard deviation of the horizontal coordinates of the object points if not greater than 0.6 GSD, ensures the required accuracy of orthophotos, because aerotriangulation has then about three times less impact on the accuracy of orthophoto than the impact of successive stages of its preparation.

Criterion based on the required accuracy of aerotriangulation to develop digital terrain model has not been formulated here since, as mentioned, national standard (Dziennik Ustaw 253, 2011) contains no such requirement. This standard includes only tolerances for differences in height obtained on the independent check points. For these values reference is made in section 5, when discussing the rules of distributing ground control points in real aerotriangulations.

The second criterion was based on the asymptotic nature of the decrease in the standard deviation of the coordinates of object points with an increase in the number of ground control points in the block. It was investigated whether there is a significant decrease in the standard deviation in another variant of GCPs distribution, i.e. in the variant with a larger number of ground control points.

On the basis of the simulation results (Tables 3 and 4), and graphs drawn on the basis of the relationship between the number of ground control points and a standard deviation of the coordinates of object points, a GCPs distribution variant was defined that meets the requirement under the first criterion, and can provide cost-effective increase in accuracy at the expense of some additional ground control points. Examples of graphs are shown in Figures 3 and 4.

The third selection criterion was the homogeneity of the precision of the results. The set of standard deviations of the object points coordinates obtained from the block adjustment was investigated in a 3D graph of individual standard deviations or with the aid of a surface approximating the set of deviations. On the graph the elevation coordinate represented the standard deviation of the object points coordinates, and the horizontal coordinates defined the position of the standard deviation in the space of the block. Visual assessment of homogeneity could be carried out at different perspective view of the errors space.

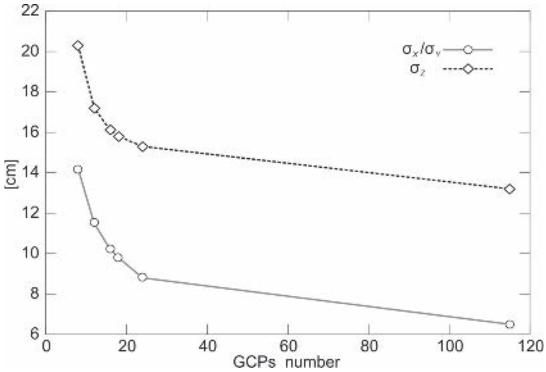

Figure 3. Block A, GCPs distribution variant No. 3, low level of measurement precision. Dependence between the GCPs number and RMS of standard deviation of object points coordinates

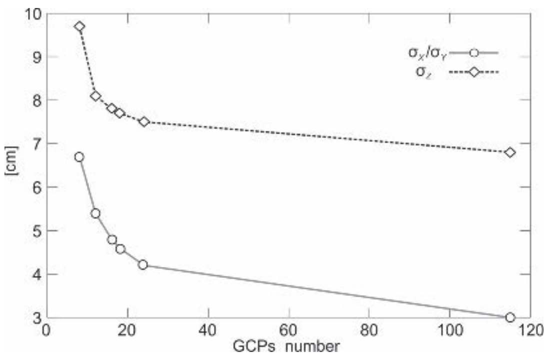

Figure 4. Block A, GCPs distribution variant No. 3, average level of measurement precision. Dependence between the GCPs number and RMS of standard deviation of object points coordinates

It should be noted that the impact on homogeneity, especially on *Z* precision, also has a number of individual measurements of tie points on the photos. Appearing in this respect lower level of homogeneity has, however, a local character, because in one photo there are tie points measured both on three and on six photos. Differentiation of the precision of ground coordinate due to different number of measurements of tie points on the photos is shown in Figures 6, 7 and 8. Approximation of a set of standard deviations by the interpolated surface has shown that these are the local variations of precision, which do not affect the overall distribution of the precision of the block. Figure 5 shows an example of approximation of a distribution of the standard deviation of *Z*.

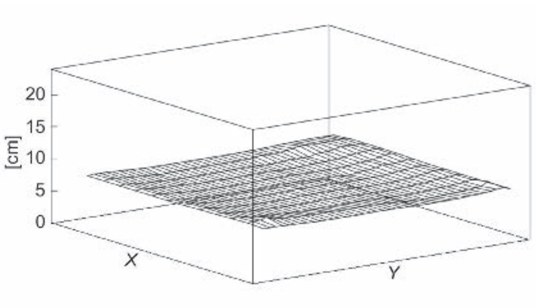

Figure 5. Block A, GCPs distribution variant No 3, average level of measurement precision. Precision distribution of *Z* coordinate of object points. Standard deviation surface was calculated from 20 091 object points

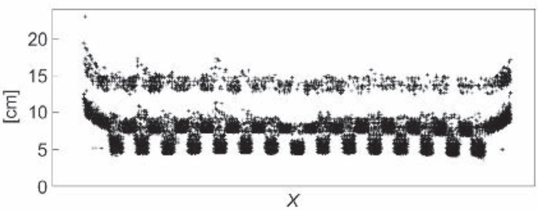

Figure 6. Block A, GCPs distribution variant No. 3, average level of measurement precision. Precision distribution of *Z* coordinate of object points. 3D view of 20 091 standard deviation of object points. View into the depths of 110 photos

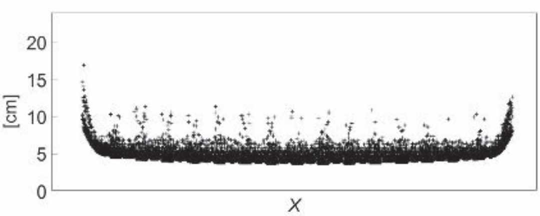

Figure 7. Block A, GCPs distribution variant No. 3, average level of measurement precision. Precision distribution of *X* coordinate of object points. 3D view of 20 091 standard deviation of object points. View into the depths of 110 photos

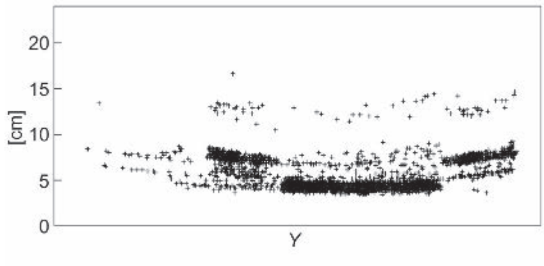

Figure 8. Block E, GCPs distribution variant No. 3, low level of measurement precision. Precision distribution of *Z* coordinate of object points. 3D view of 3 768 standard deviation of object points. View into the depths of 128 photos

2.7. Selection of a GCPs distribution variant

In the first stage of the selection procedure a GCPs distribution variant was indicated with an average standard deviation of the horizontal coordinate not greater than 0.6 GSD. In the second stage, the decline in the standard deviation of the coordinate in subsequent variants was examined. This stage of the selection was carried out only for the standard deviation of *X* and *Y*, because the precision of *Z* has a significantly lower variability. In the third stage, the homogeneity of the precision of the results for a selected GCPs distribution variant was examined.

3. The simulation results

The results of sequences of simulations for the studied test blocks are given in Table 3. In Table 4, results are given for GCPs distributions, which satisfy the criteria discussed above.

4. Analysis of results

The following is an analysis of the characteristics of GCPs distributions that meet established criteria.

4.1. Precision of object points

Shown in Table 4, the average standard deviations of the horizontal coordinates of the object points,

Table 3. Results from simulated aerotriangulation

Parameters of GCPs distribution variants					Precision of results			
Name of variant		No. of GCPs	No. of photos per one GCP	Distance between GCPs along block border [base length]	Low precision of measurements		Average precision of measurements	
					RMS of standard deviation of object points coordinates			
					σ_X/σ_Y [cm]	σ_Z [cm]	σ_X/σ_Y [cm]	σ_Z [cm]
1		*2*	*3*	*4*	*5*	*6*	*7*	*8*
A	1	8	220	110	14.2	20.3	6.7	9.7
	2	12	146	55	11.5	17.2	5.4	8.1
	3	16	110	27	10.2	16.1	4.8	7.8
	4	18	98	21	9.8	15.8	4.6	7.7
	5	24	73	13	8.8	15.3	4.2	7.5
	6	115	15	not apply	6.5	13.2	3.0	6.8
B	1	8	221	158	26.5	36.8	13.8	19.8
	2	10	177	79	18.0	34.0	9.3	18.5
	3	14	126	39	15.2	32.8	8.0	17.9
	4	16	110	31	14.4	32.5	7.6	17.7
	5	20	88	22	13.4	32.1	7.0	17.6
	6	28	63	16	12.3	31.6	6.5	17.3
	7	110	16	not apply	10.2	30.6	5.4	16.8
C	1	8	120	80	17.8	37.4	9.4	20.0
	2	10	96	40	17.0	36.8	8.8	19.8
	3	13	73	40	15.4	36.0	8.0	19.5
	4	17	56	20	14.5	35.7	7.6	19.3
	5	21	46	13	13.7	35.4	7.2	19.3
	6	24	40	11	13.4	35.3	7.0	19.2
	7	83	12	not apply	10.8	34.3	5.8	18.9
D	1	8	239	166	5.9	11.1	3.0	6.8
	2	10	234	84	5.0	10.6	2.6	6.1
	3	14	167	42	4.4	10.4	2.3	5.9
	4	18	130	33	4.0	10.4	2.2	5.9
	5	24	98	21	3.8	10.2	2.0	5.8
	6	65	36	not apply	3.3	10.0	1.8	5.7
E	1	6	104	104	3.8	6.5	2.3	4.1
	2	8	78	69	3.5	6.3	2.1	3.8
	3	14	45	35	3.0	5.9	1.8	3.5
	4	20	31	23	2.6	5.7	1.6	3.3
	5	26	24	17	2.4	5.5	1.6	3.2
	6	38	16	not apply	2.2	5.3	1.4	3.1

Table 4. Variants of GCPs distribution meeting the selection criteria

Name of variant		Scale of photos / GSD [cm]	Precision level of measurements	No. of GCPs	No. of photos per one GCP	Distance between GCPs along border of block [base length]	Precision of results: RMS of standard deviation of object points coordinates			
							σ_X/σ_Y		σ_Z	
							[cm]	[GSD]	[cm]	[GSD]
1		*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
A	3	1:19 250	low	16	110	27	10.2	0.4	16.1	0.7
	3	23	average	16	110	27	4.8	0.2	7.8	0.3
B	5	1:36 200	low	20	88	22	13.4	0.6	32.1	1.5
	3	22	average	14	126	39	8.0	0.4	17.9	0.8
C	3	1:38 100	low	13	73	40	15.4	0.5	36.0	1.1
	3	34	average	13	73	40	8.0	0.2	19.5	0.6
D	3	1:13 800	low	14	167	42	4.4	0.6	10.4	1.3
	3	8	average	14	167	42	2.3	0.3	5.9	0.7
E	5	1:6 600	low	26	24	17	2.4	0.6	5.5	1.4
	3	4	average	14	45	35	1.8	0.5	3.5	0.9

for low precision of measurement are not greater than 0.6 GSD and for average precision of the measurements are not greater than 0.5 GSD, (column 8), which meets the precision criterion.

The standard deviation of elevation for low precision measurements is in the range of 0.7 ÷ 1.5 GSD and in the range of 0.3 ÷ 0.9 GSD for average precision of measurement, (column 10).

4.2. Number of ground control points in the block

In GCPs distributions for rectangular blocks the number of images per one GCP (Table 4, column 5) is within the range of 73 ÷ 167. The number of ground control points in the distribution variant with low precision of measurements and in the distribution variant with average precision in the three rectangular blocks does not differ. This is because of the highly nonlinear relationships between parameters and the results of aerotriangulation, and because of the second criterion, telling about the profitability of a small increase in the number of ground control points to obtain significantly more accurate result.

For ribbon block with low and average precision of measurements of 1 GCP per 24 photos and 1 GCP per 45 photos are required, respectively.

Distribution of ground control points along the edges of the block in the direction of the axis of the strip (column 6 in Table 4), for rectangular and ribbon blocks (block E) shows that the GCPs should be placed with spacing of 22 ÷ 42 and 17 or 35 bases, respectively, corresponding to the precision level of measurement.

4.3. Internal reliability of measurements

Reliability of measurements in rectangular blocks in all four groups of measurements is sufficient. The lowest rate of local redundancy numbers is measured for *Z* coordinate of targeted ground control points, with the average measurement precisions. The rate of local redundancy numbers for these coordinates, depending on the type of block, is ranging from 0.23 ÷ 0.41.

In the ribbon block the measurement reliability is also sufficient. For such block the photogrammetric measurement of ground control points is represented by the lowest rate of local redundancy number (0.42).

4.4. The homogeneity of the precision of results

The homogeneity of the precision of object points in GCPs distributions given in Table 4 is sufficient.

Visual assessment of the precision distribution in the block, shows that the average standard deviation of a coordinate in GCPs distribution variants that meet the criteria posed, represents well a set of standard deviations in the entire block (except for the edge of the block, as already mentioned in section 2.4.). Examples of visualization of the precision distribution in the block are shown in Figures 5, 6, 7, and 8.

Clustering of the standard deviations of *Z* coordinate, whose source is the different number of measurements of tie point on the photos is observed in Figures 6 and 8. The highest precision of *Z* coordinate of object points was obtained from the sidelap area, where the points were measured on multiple images. The lowest precision received the coordinates of points measured on only two photos.

Large concentration of standard deviations in such groups indicates that the precision of *Z* coordinate is independent of the position of the point in the block and only depends on the number of its measurements on the photos.

5. Testing the design rules for ground control points distribution in real aerotriangulations

In order to verify the effectiveness of the design rules for ground control points distribution developed with the aid of aerotriangulation simulations, tests in real aerotriangulations were conducted. Tests were performed for 10 blocks from the years 2008–2010, having a large number of ground control points, which allowed an independent assessment of the correctness of design rules. Archival nature of the blocks restricted freedom of design, which resulted in using the same GCPs distribution as the one used in studies based on commercial data. These blocks were irregular in shape, in most cases with multiple corners of the block boundaries. These blocks have been developed again with the GCPs distributions according to the following rules:

– control points were located at the edges of the block,
– in the corners of the block two control points were located,
– along the edge of the block, in a direction consistent with the strip axis, control points were placed every 15 to 25 photographing bases,
– in a direction transverse to the axis of the strip, control points were located at a density of 4 to 8 strip,
– in some blocks, because of their shape and large size, the GCPs distribution was increased by a few control points inside the block,
– control points, which were not used in a GCPs distribution served as the checkpoints, not involved in the adjustment.

Basic parameters of the actual blocks are provided in Table 5, and the results of testing GCPs distributions are given in Table 6.

Table 6 shows RMS of checkpoint coordinate differences and is expressed in the size of the GSD, (columns 5, 6 and 7). The table shows also RMS of standard deviation of object points coordinates (column 8, 9 and 10), which was also expressed in the GSD.

Results show that the average standard deviation of the horizontal coordinates of the object points is not greater than 0.6 GSD (columns 8 and 9). This confirms the correctness of the rules of locating ground control points. Number of photos per one control point in the original studies based on commercial data was on average 20.0, and in studies of the tested GCPs distributions the ratio was 75.3 photos per one control point, which indicates possible significant benefits from the application of principles of the GCPs distribution design developed here.

The average horizontal coordinate differences at checkpoints (*DX* and *DY*) does not exceed 1.3 GSD (columns 5 and 6), and for differences in elevation (*DZ*) are not greater than 1.9 GSD (column 7). For listed in Table 5 scales of aerial photographs and GSD, standard allows for differences in coordinates of checkpoints of the size 0.75 m, (Dziennik Ustaw 253, 2011). At 1038 control points in these blocks, in 19 points, i.e. 1.8% of all points, the differences of coordinates were of the size 0.75 ÷ 1.08 m.

Most of these differences occurred in the last three blocks listed in Table 6, which are of small-scale images and GSD less than 25 cm. The reason for exceeding the tolerance may be the impact of systematic errors not entirely removed, but also too high standard of requirement for such a scale of images and GSD.

Table 5. Parameters of real blocks

Name of block	No. of photos	GSD [cm]	Scale of photos
OB3_2A	1760	23	1:19 200
OB4_1	1955	23	1:32 200
OB4_2	2724	23	1:31 600
OB1_1	960	34	1:38 100
87_OB4_1	1659	30	1:41 500
OB_7_1	3175	20	1:29 100
OB_7_2	2757	20	1:29 600
OB_9_1	1581	22	1:36 200
OB_9_2	1881	22	1:36 200
OB_9_3	3526	22	1:36 600

6. Conclusions

Developed rules for location of ground control points for aerotriangulation fulfill the requirements effective in Poland. It is worth noting that the use of GCPs distributions with significantly greater number of ground control points than those specified in the presented studies is not viable due to the slow growth of the accuracy of the unknowns with the number of ground control points. In the case of higher requirements on the accuracy of aerotriangulation, another parameter should be changed, for example, the scale of images.

Recently published requirements for performing aerotriangulation continue commanding to design the GCPs distributions with large numbers of ground control points, several times exceeding the needs of good orientation of the block, which strongly limits the profit from the use of new technologies.

The recommended GCPs distributions are important for blocks with similar characteristics, such as those outlined here. For blocks of images with different accuracy requirements, or which are substantially different in design or measurement precisions, examination should be performed by methodology similar to that developed by this study.

Table 6. Results from real aerotriangulation

Name of block	No. of control points	No. of photos per one GCP	No. of check points	RMS of checkpoint coordinate differences			RMS of standard deviation of object points coordinates		
				DX [GSD]	*DY* [GSD]	*DZ* [GSD]	σ_X [GSD]	σ_Y [GSD]	σ_Z [GSD]
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
OB3_2A	17	103	73	0.8	0.5	1.0	0.4	0.3	0.6
OB4_1	21	93	113	0.4	0.5	0.8	0.3	0.3	0.4
OB4_2	18	151	113	0.6	0.7	0.9	0.2	0.2	0.4
OB1_1	21	46	37	0.8	1.0	1.3	0.4	0.5	0.9
87_OB4_1	30	55	44	0.5	0.8	1.2	0.3	0.3	0.5
OB_7_1	38	84	185	0.9	0.9	1.2	0.3	0.4	0.6
OB_7_2	45	61	153	0.8	0.9	1.6	0.3	0.4	0.8
OB_9_1	27	58	51	0.5	0.6	1.9	0.3	0.3	0.7
OB_9_2	30	63	73	0.8	0.7	1.9	0.3	0.4	0.8
OB_9_3	45	78	196	1.0	1.3	1.3	0.5	0.6	1.2

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Zintegrowana orientacja sensorów — fotopunkty dla dużych bloków aerotriangulacji

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Streszczenie. W artykule opisano badania dotyczące liczby i rozmieszczenia fotopunktów dla dużych bloków aerotriangulacji z wykorzystaniem technologii zintegrowanej orientacji sensorów *Integrated Sensor Orientation* (ISO). Badania przeprowadzono na drodze symulacji aerotriangulacji. Symulacje wykonano dla 5 typów bloków zdjęć spotykanych w kraju oraz dla dwóch poziomów precyzji pomiarów wyznaczonych na podstawie wcześniej wykonanych badań 19 dużych bloków wykonanych w kraju w latach 2008–2010.
Użyteczność opracowanych reguł projektowania fotopunktów sprawdzono w rzeczywistych aerotriangulacjach 10 dużych bloków zdjęć. W badaniach odniesiono się do dokładności wymaganych przez krajowe instrukcje, do homogeniczności uzyskiwanych wyników, jak również do niezawodności pomiarów.
Wyniki badań określają wystarczającą osnowę dla aerotriangulacji dużych prostokątnych bloków i trójszeregowego bloku wstęgowego. Wymagana liczba fotopunktów dla bloków prostokątnych określona liczbą zdjęć przypadających na jeden fotopunkt wynosi 40÷150, a dla bloku wstęgowego 24÷45, przy czym liczba ta jest zależna od poziomu precyzji pomiarów i od kształtu bloku.

Słowa kluczowe: fotogrametria, aerotriangulacja, symulacja, ISO, projektowanie fotopunktów