IN-FLIGHT CAMERA CALIBRATION FOR DIRECT GEOREFERENCING

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ABSTRACT:

Direct georeferencing is increasingly applied in connection of the photogrammetric film cameras. The prerequisite for the use of this technique is an airborne system calibration. The calibration issue was investigated by analysing 10 calibration blocks obtained with four GPS/IMU/optics-combinations. The earlier studies already showed that in-flight interior orientation determination was highly relevant with the data. The objectives of this study were to investigate the further extension of the system calibration model with the typical image deformation parameters and to evaluate efficient calibration routines for daily use. The physical image deformation parameters appeared to be quite problematic due to their high correlations with other parameters. Mathematical image deformation model of Ebner appeared to have a consistent behaviour; with the examined data the maximum corrections for image coordinates were 4-12 μm depending on the optics. It appeared that the accuracy of the direct orientation observations was the limiting quality factor. A minimal block geometry with a single bi-directional flight line and no ground control points (GCPs) allowed the determination of the principal point and boresight unknowns; the calibration with this minimal block structure was clearly advantageous. Single GCP improved the reliability, but in order to obtain good accuracy, several GCPs were needed.

1. INTRODUCTION

The future of airborne image acquisition is direct georeferencing (DG) by combining direct image orientation with digital imaging. DG is also becoming an integral part of the image production based on film cameras. A central step in DG is the in-flight system calibration, which can be made by using permanent test-fields or by using a calibration block photographed in the mapping area. Different approach is self-calibration, which can be made if integrated sensor orientation approach is taken (see Heipke *et al.* 2001).

The boresight parameters are the central parameters in the system calibration. Practical results of DG have shown that the sole boresight calibration is not sufficient in applications with higher accuracy requirements. As the conclusion of the OEEPE test Heipke *et al.* (2001) recommended to include the interior orientation parameters to the system calibration whenever possible. Wegmann (2002) and Jacobsen (2003) have made similar conclusions based on the OEEPE data. Results of Cramer *et al.* (2001, 2002) have also shown the importance of the extension of the collinearity model by additional parameters. Honkavaara *et al.* (2003) reported results of 11 practical calibration blocks with 4 GPS/IMU/optics combinations. The determination of the interior orientations was a necessity; with all the systems appeared a significant (20-40 μm) correction in the direction perpendicular to the flying direction (y0) and with one optics appeared a significant (25-35 μm) correction in the principal distance. Due to the systematic errors and instabilities, Hansa Luftbild German Air Surveys performs routinely the airborne system calibration in the mapping area (Schroth 2003). Also ICC of Barcelona determines the system calibration frequently e.g. using a minimal block configuration (Baron *et al.* 2003).

National Land Survey of Finland (NLS) photographed a large number of calibration blocks with four GPS/IMU/optics-combinations in summer 2002. The first results of the datasets were reported by Honkavaara *et al.* (2003). In this study the NLS calibration data has been further processed. The first objective was to study the expansion of the above-mentioned parameters with other standard additional parameters modelling image deformations. The second objective concerned cost effective daily calibration routines.

2. CALIBRATION

2.1 Mathematical model of calibration

2.1.1 Grouping of the parameters. The in-flight calibration is performed by using standard bundle block adjustment techniques. Honkavaara *et al.* (2003) used the following grouping of feasible parameters:

1. Boresight misalignments (dω, dφ, dκ)
2. Flying direction dependent corrections
   a. Constant position shifts dependent on flying direction (e.g. lever arm $(dX, dY, dZ)_{lever}$)
   b. Camera interior orientation (dc, dx0, dy0)
3. Other image deformations: the available parameters model physical distortions (e.g. radial and tangential distortions) or try to compensate systematic image deformations using mathematical polynomials.
4. Datum transformation: a full or a partial 7-parameter similarity transformation $(dX, dY, dZ, \alpha, \beta, \gamma, scale)_{datum}$.

Modes of image and GPS/IMU-position and -attitude observations used in this study are discussed below. Burman (2000), Cramer *et al.* (2002), and Wegmann (2002) have reported related work.

2.1.2 Image observations. A common practice is to extend the collinearity equation with various parameters to acquire a model, which more accurately corresponds the imaging conditions (Brown (1976), Ebner (1976), Kilpelä (1981), Jacobsen (1982), Fraser (1997), Cramer *et al.* (2002), Jacobsen (2003)). Mathematical parameters used in this study were the well-known Ebner's parameters (Ebner 1976). The physical deformation model applied in this investigation was the following:

$$\Delta x = dx_0 - \frac{x}{c}dc + x(k_1 r^2 + k_2 r^4 + k_3 r^6) + p_1(r^2 + 2x^2) + 2p_2 xy + B_1 x + B_2 y \tag{1}$$

$$\Delta y = dy_0 - \frac{y}{c}dc + y(k_1 r^2 + k_2 r^4 + k_3 r^6) + 2p_1 xy + p_2(r^2 + 2y^2) \tag{2}$$

where $r^2 = x^2 + y^2$, k1, k2 and k3 model radial distortions, p1 and p2 model tangential distortions and B1 and B2 model affinity and shearing.

2.1.3 GPS/IMU-position observations. In the ideal situation, the model for the GPS/IMU position observations consists at most of the corrections for the datum and the lever arm. Linear zero- or first-order time dependent lever arm or shift corrections are sometimes necessary; especially they were indispensable with the traditional GPS-supported case. A general model for the GPS/IMU-position observations is the following:

$$\vec{X}^m_{GPS/IMU} = \underbrace{\lambda R_{datum}\vec{X}^m_0 + dX^m_{datum}}_{Datum} + \underbrace{R^m_p\left(\Delta X^p_{lever} + \sum \vec{a}_i t^i\right)}_{Leverarm} + \underbrace{\sum \vec{b}_i t^i}_{Remainingerrors} \tag{3}$$

2.1.4 GPS/IMU-attitude observations. The model for the GPS/IMU-attitude observations is the following:

$$\vec{r}^{\,p}_{GPS/IMU} = T(\vec{\omega}^p) + \vec{\alpha}_0 + \vec{\alpha}_1 t \tag{4}$$

T transforms the photogrammetric angles to the navigation angles. The transformation includes the boresight misalignment correction ($R^m_p = R^m_b R^b_p$, with rotation matrixes R^b_p from camera frame to IMU body frame, R^b_m from object frame to IMU body frame and R^m_p from camera frame to object frame). Additional corrections can be used to correct remaining zero or first order time dependent errors.

2.1.5 Selection of appropriate parameters. With typical block configurations a feasible parameter combination is 1, 2a or 2b, 3 and 4 (dX, dY). Due to correlations of the parameters, the appropriate parameters must be selected based on analysis of their correlations and quality (Jacobsen 2003).

The height correction is probably the most problematic unknown. Several causes result in need for the height correction; these include changes in the principal distance, lever arm inaccuracies, datum errors and inaccuracy of the GPS height determination. The camera dependent height corrections can be separated from the other mentioned sources, if two blocks with different flying heights are adjusted simultaneously (Jacobsen 2003, Tempelmann *et al.* 2003). In this article blocks with single flying height are used, and the height correction is modeled as the principal distance correction; this is an accurate approach, if height error components are the same in the calibration and the mapping sites (see also Jacobsen 2003).

2.2 Calibration block structures

An important factor affecting the cost of calibration is the calibration block structure. The important parameters are the flight lines and the ground control points (GCPs). Honkavaara (2003) evaluated theoretically the determinability of the boresight and interior orientation parameters with various block structures and GCP configurations.

Flight line configurations can be grouped, for instance, into three classes (see also Figure 1):

1. Comprehensive: several flight lines and crossing flight lines.
2. Cross: two perpendicular bi-directional flight lines.
3. I-block: single bi-directional flight line

The cross-shaped block appears to be a sufficient choice for the determination of the most important parameters (e.g. Honkavaara 2003, Tempelmann *et al.* 2003). The comprehensive block is the most accurate alternative, but its cost probably does not cover the benefits. Even the I-shaped block allows the determination of the boresight misalignments, interior orientations and many of the image deformation parameters.

Basically, in the GPS/IMU-supported case the GCPs are needed for determination of the datum parameters and the height corrections, and for the quality control. In addition, some of the image deformation parameters may require GCPs (Jacobsen 2003). In order to determine the datum and height correction accurately, several GCPs are needed, e.g. 10. However, even 1 reliable GCP improves reliability (Honkavaara 2003).

If the calibration is performed on a daily basis, the calibration block should be as cost effective as possible. For this purpose the most attractive block structure is the I-shaped block with minimal or no GCPs. The extra expense of this approach is an additional flying of a short part (e.g. 9 images) of one flight line in the opposite direction. If the flight mission is long, this procedure may be necessary both in the beginning and in the end of it (Scroth 2003).

3. MATERIALS AND METHODS

3.1 Calibration blocks

Empirical investigation was made using 10 calibration blocks photographed by the National Land Survey of Finland (NLS) over the FGI's Sjökulla calibration fields in summer 2002; the details of the blocks are shown in Table 1 and in Figure 2. The image scales were 1:8000 and 1:16000; calibrations were made using single flying height. The data have been thoroughly described by Honkavaara (2003). From the complete blocks reduced blocks were extracted, resulting in three different block structures:

- Full: the complete, comprehensive block with 8 flight lines (Figure 2) and all 12 GCPs.
- *2 GCP, I*: a single bi-directional flight line with 9 images, (total of 18 images), and a double GCP (2 XYZ-GCPs located close to each other) (Figure 1, I-block)
- *0 GCP, I*: a single bi-directional flight line with 9 images, (total of 18 images), and no GCPs (Figure 1, I-block)

The calibration task consisted of the calibration of four GPS/IMU/optics-combinations; NLS is operating two aircrafts (OH-ACN, OH-CGW), both having RC20 cameras with exchangeable wide-angle (153 mm) and normal-angle (214 mm) optics, and Applanix POSAV™ 510 systems (see Table 1). NLS performed all the preprocessing of the data (GPS/IMU-processing, photographic processing, scanning and image measurements), and delivered the observation data to the FGI for the further analysis.

Complete analysis of the direct exterior orientation data was reported by Honkavaara *et al.* (2003). The results were in accordance with the vendor's specifications (5.6 mgon in ω and φ, and 8.9 mgon in κ), excluding minor exceeding in two blocks. Evaluation of the direct position observations was disturbed by the poor quality of the reference values and the apparent systematic errors (interior orientation, datum).

3.2 Methods

The investigation was made by evaluating the calibration results of 10 test blocks (scales 1:8000 and 1:16000) using three different block-structures (see Chapter 3.1). Calibrations were performed using bundle block adjustment software FGIAT of FGI. The mathematical models of FGIAT were described in Chapter 2.1. FGIAT treats the image deformation parameters as weighted observations and GPS/IMU-parameters as free unknowns. The object coordinates were in a local tangential coordinate system.

The qualities of the parameters were evaluated after calibration. The significance of a certain parameter was evaluated by comparing the parameter value to its standard deviation; if the value was at least 2 times larger than the standard deviation, the parameter was considered as significant. Also the correlations of the calibration parameters were evaluated.

The DG accuracy was evaluated in the image space by calculating the image coordinates of the checkpoints using the calibration parameters and direct orientation observations and comparing the calculated values to the measured values. GCPs were used as checkpoints. The limitation of this approach was especially with the full blocks that the calibration and the quality analysis were made with the same data. However, the analysis gave understanding about the performance of various cases.

4. RESULTS

4.1 Determinability of parameters

Correlation of the radial distortion parameters (k1, k2, k3) was remarkable, as expected. When all the radial distortion parameters were used, their correlations with interior orientation parameters become significant. If only k1 was used, the correlation was low. Correlations were high also between principal point and tangential distortion parameters (x0 & p1, y0 & p2).

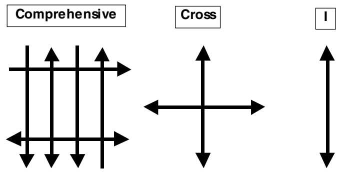

Figure 1. Comprehensive, cross and I-block structures.

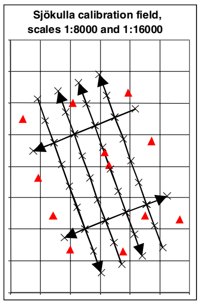

Figure 2. 1:8 000 and 1:16 000 scale calibration field of FGI. Size: 4 km x 5 km, 12 accurate GCPs.

Date 2002	Blo-ck	Optics			
		Plane: OH-CGW		Plane: OH-ACN	
		13026, 153.300	7163, 214.066	13153 153.030	7183, 214.108
24.4	2119 2120				1:16 000 1:8 000
25.4	2121 2122			1:8 000 1:4 000	
26.4	2124				1:8 000
3.5.	2128	1:8 000			
4.5.	2129		1:16 000		
14.7.	2134	1:16 000			
15.7.	2135		1:16 000		
3.9.	2137				1:16 000
4.9.	2136			1:16 000	

Table 1. Calibration flights of NLS. The block structure and the GCP distribution are shown in Figure 2.

An example of the correlations between the physical parameters and boresight parameters is shown in Table 2 for two different block structures. Tangential parameters had quite high correlation with the boresight parameters (p1 & dφ and p2 & dω). When tangential parameters were used, the correlations between boresight and principal point parameters got high (y0 & dω, x0 & dφ). When tangential parameters were not used correlation of these parameters was low.

The block structure had some effect on the determinability of the parameters. The affinity parameter (B1) could not be accurately determined with the I-block. In I-block appeared also high correlations between some Ebner's parameters and other parameters. Comprehensive and cross-shaped blocks did not have these problems.

The additional parameters were mostly significant; especially c (optics 7183), y0 (all optics), radial distortion (typically all the terms), tangential distortion (typically both terms) and Ebner's parameters (in general 1-3 insignificant parameters). The block adjustment results were consistent when Ebner's parameters were used. If the full set of physical parameters were included in the adjustment, high correlations appeared with many para-

Blo-ck		c	x0	y0	k1	k2	k3	p1	p2	B1	B2
1	do	0.03	0.00	0.44	-0.01	0.00	0.00	0.01	0.59	-0.01	0.00
	dp	0.02	-0.43	0.00	0.02	-0.02	0.02	-0.61	0.00	-0.02	0.02
	dk	-0.01	0.02	-0.02	0.00	0.00	0.00	0.00	0.00	0.01	-0.08
1	do	0.04	-0.01	0.16	-0.06						
	dp	0.06	-0.13	0.00	-0.02						
	dk	-0.01	0.02	-0.02	0.00						
2	do		0.02	0.46	0.02	-0.02	0.01	0.06	0.60		
	dp		-0.49	-0.06	0.05	-0.05	0.05	-0.60	-0.07		
	dk		0.00	-0.02	0.01	-0.02	0.02	-0.01	0.00		
2	do		-0.01	0.10	-0.04						
	dp		-0.10	0.01	-0.03						
	dk		0.02	-0.03	0.01						

Table 2. An example of correlations of boresight unknowns with physical image deformation parameters. Blocks: 1: the full block with full GCPs, 2: I-block with 0 GCPs.

meters, and the parameters got instable. The use of first order radial term and affinity parameters did not affect instability.

4.2 Comparison of various block structures

The results of the boresight calibration with various block structures are shown in Figure 3. In Figure 3a the differences of the boresight parameters of the reduced blocks and the full blocks are given. Differences in dκ were mostly 2-4 mgon. In dω and dφ the differences were smaller than 2 mgon. The apparent systematic difference is most likely caused by the small stripwise systematic errors of GPS/IMU-attitude observations. The standard deviations of the boresight parameters of 10 calibration blocks were similar, so only their averages are shown in Figure 3b. The average standard deviation in the full block was about 0.7 mgon in dω and dφ and 1.2 mgon in dκ, while in the I-block these values were almost doubled. The results of I-blocks with and without GCPs were practically the same.

The effect of the block structure on the interior orientation corrections is shown in Figure 4. In Figure 4b the averages of the standard deviations of interior orientation corrections for different principal distances, imaging scales and block structures are shown. The standard deviations were naturally higher with the reduced blocks. The standard deviation of the principal point was better than 3.5 µm in all the cases, which can be considered acceptable. The standard deviation of the principal distance with the I-block with 2 GCPs varied between 8-10 µm, which is quite poor accuracy. The block structure did not affect the values of x0 and y0 significantly (Figure 4a). The variability of the principal distance was larger, typically 10-20 µm, as could be expected based on high standard deviation values. The determination of principal distance was advantageous only with the optics 7183, which had >20 µm corrections.

In most of the blocks appeared about 10 cm global shift in X-direction, thus also a global shift was determined for the blocks with GCPs. It is noteworthy that with I-block with 2 GCPs standard deviations of the global shift parameters were in dX and dY 5-10 cm and in height 8-16 cm, so their determination was not very accurate. In the full blocks the standard deviations of the shift parameters were 2-3 cm.

4.3 Image deformations

The effects of the Ebner's parameters were evaluated for each optics. The maximum effects of the Ebner's parameters on the

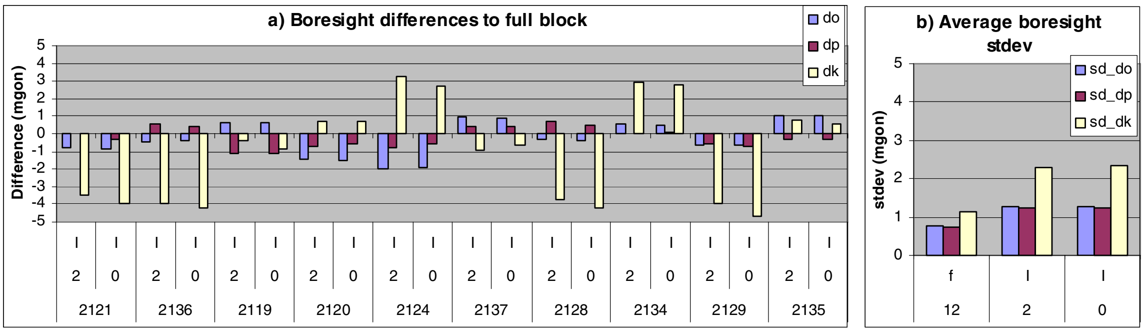

Figure 3. Effect of block structure on boresight parameters. a) differences between the full block and the reduced blocks, b) average boresight standard deviations of 10 calibration blocks. Symbols below the graphs indicate block structure (I), number of GCPs (12, 2, 0) and block name (2121, etc.).

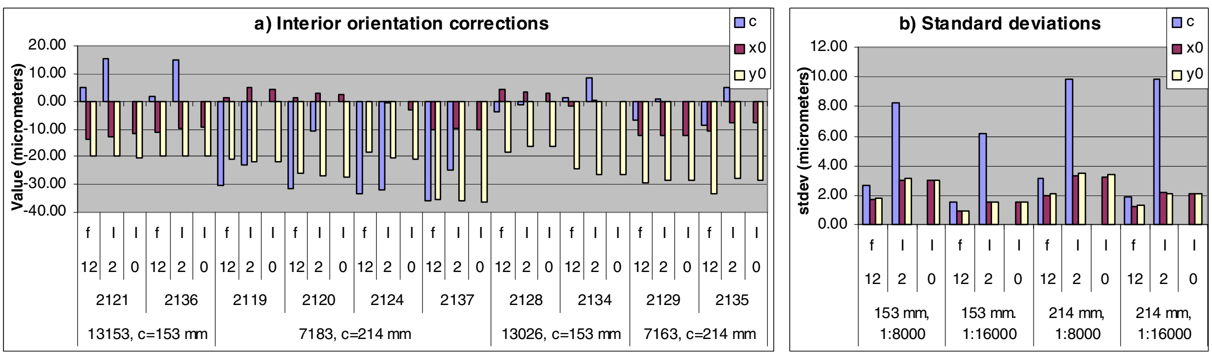

Figure 4. Effect of block structure on interior orientation corrections. a) Interior orientation corrections calculated using reduced and full blocks, b) average interior orientation standard deviations for each scale/principal distance-combination. Symbols below graphs indicate block structure (f=full, I), number of GCPs (12, 2, 0), block name (2121, etc.) and optics (13153, etc.).

image coordinates were 4-12 µm. In Figure 5 an example of the effects in a 5x5 point grid are shown as a line plot for optics 7183; blocks 2119 and 2120 were consecutive, block 2124 was flown 2 days after block 2120 and block 2137 4 months later than the others. Corrections of the two consecutive blocks were similar. Even the first and the last calibrations with 4 months difference had some similarity. Stability of the corrections was different for various optics. Further conclusions are not drawn from these results yet, because the analysis is unfinished.

4.4 Accuracy of DG

The main purpose of the DG accuracy evaluation was to compare different block structures. The boresight, interior orientation, k1 and global shift (if >0 GCPs) parameters were determined with the different block structures, and the obtained values were then applied in DG. Also a case with only boresight parameters was evaluated (I-block without GCPs). The RMSEs in image space are shown in Figure 6.

Based on the previous results, it could be expected that at least the effects of y0-correction and the principal distance correction with optics 7183 should be visible. The importance of y0-correction is clear, when comparing the results with and without y0-corrections (Figure 6).

An interesting observation was that the accuracy in x-direction was clearly better than in the y-direction. Various additional parameter models were tested, but they did not eliminate the difference. Feasible explanation for the difference in many cases is that the roll accuracy appeared to be worse than the pitch accuracy, especially in the blocks 2120, 2124 and 2137.

The accuracy of I-blocks with and without GCPs were quite similar. An exception is optics 7183 where GCPs were essential due to the large principal distance correction.

These results are consistent with the expected accuracy. 4 mgon accuracy of orientation angles indicates approximately 9 µm resection accuracy with the 150 mm optics and 13 µm resection accuracy with the 214 mm optics. With 153 mm optics and optics 7163 the accuracy in x and y coordinates was about 10-15 µm, if principal point error was corrected. In optics 7183 the height error deteriorated the results. The accuracy of block 2120 was poorer than the others; a good explanation for this is the worse attitude accuracy that has been detected in earlier studies.

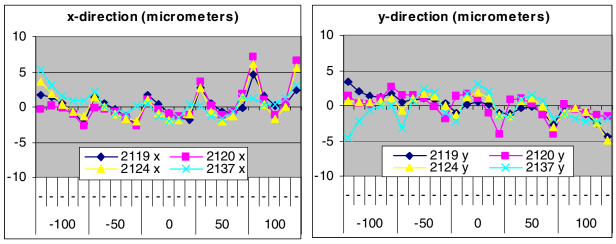

Figure 5. Image coordinate corrections in 5x5 grid caused by Ebner's parameters for four calibration flights of optics 7183.

5. ANALYSIS

The results of this investigation are consistent with the previously presented results of DG. The importance of the determination of interior orientation parameters along with the boresight parameters has been observed widely, e.g. Cramer *et al.* (2002), Heipke *et al.* (2001), Wegmann (2002), Jacobsen (2003) and Honkavaara *et al.* (2003).

Cramer *et al.* (2002) preferred the mathematical models for additional parameters instead of physical models. The above results are in accordance with Cramer's results. With Ebner's parameters the image corrections were less than 12 µm, and with most of the optics less than 5 µm. The use of the full set of physical parameters resulted in high correlations between various parameters (see also Jacobsen 2003), which in turn affected instability to the calibration parameters. The best approach is probably to use some central physical parameters and then use mathematical parameters to further extend this parameter set. It is still questionable, what are the best additional parameter models.

It appeared that the use of the additional parameters, other than interior orientation corrections, would probably not be essential in DG with the examined optics. The accuracy improvement due to more accurate imaging model did not become visible, because in the evaluated cases the quality of the orientation observations was the bottleneck. In order to verify this conclusion, additional tests have to be made and calibration results from a longer time period should be analysed. Accuracy of DG was consistent with the angular accuracy (10-15 µm in image if significant interior orientation corrections were made).

Many results of system calibration have been obtained using comprehensive block structures. As it seems that the calibration with film cameras have to be carried out frequently (Baron *et al.* 2003, Schroth 2003), procedures should be developed for minimal block structures. In the empirical study the principal

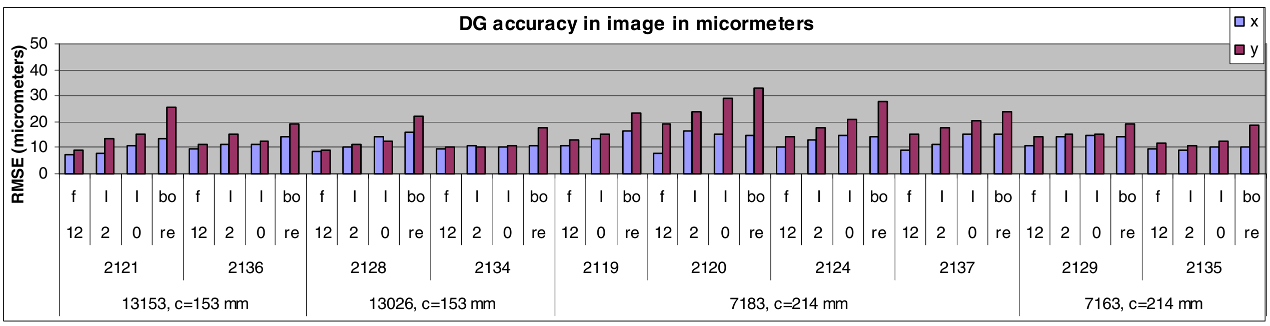

Figure 6. Accuracy of direct georeferencing for 10 blocks. Symbols below the graphs indicate block structure (f=full, I), number of GCPs (12, 2, 0), block name (2121, etc.) and optics (13153 etc.). Calibration parameters: full and I-block with 2GCPs: boresight, dc, dx0, dy0, k1 and global shift; I-block with 0 GCPs: boresight, dx0, dy0, k1, I-block with 0 GCPs: boresight (abbreviation bore).

point and boresight parameters could be accurately determined with blocks consisting of a single bi-directional flight line and no GCPs. With the I-block the determination of some image deformation parameters was not possible, so in accurate applications the use of the cross-shaped block is recommended. These results prove theoretical results of Honkavaara (2003).

Single GCP improves the reliability, but does not enable accurate determination of the principal distance or datum in the single scale calibration. In accurate applications about 10 GCPs are preferable, as suggested by Honkavaara (2003). Even a single GCP is advantageous, if the unknowns to be estimated are significantly larger than the obtainable standard deviations.

The standard deviations of the unknowns have been extensively used as quality indicators in this study. As well known, there are many limitations for the utilisation of these numbers (systematic errors, improper weighting, ignored correlations etc.), and they cannot be used as a sole quality indicator. It is recommendable to collect standard deviation data systematically, because this is valuable information for the quality control procedures.

6. CONCLUSIONS

In this article results of analysis of 10 calibration blocks of scales 1:8000 and 1:16000 were given. The block structures were a comprehensive block consisting of 8 flight lines and having 12 GCPs, a single bi-directional flight line having one double GCP and a single bi-directional flight line without GCPs. Calibrations were made in single scales.

The most significant calibration parameters were interior orientations and boresight. Also most of the physical and Ebner's mathematical deformation parameters were significant. Tests are still needed to conclude whether or not these additional image deformation parameters improve significantly the quality of DG; with the examined optics it appeared that rather the quality of the orientation observations was the bottleneck.

These results do not verify what are the best additional parameters to be used. Interior orientation parameters have a clear physical meaning, thus their use is well founded. Full sets of radial and tangential distortion parameters are difficult because they correlate with other parameters. It is important, that the treatment of the deformation parameters and the analysis of the correlations and accuracy are efficiently implemented to the commercial block adjustment software.

Principal point and boresight parameters could be determined accurately enough with a block having a single bi-directional flight line and no GCPs. The use of one double GCP was advantageous only if >20 cm datum corrections or >20 µm principal distance corrections were necessary.

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