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Article

DGPF-Project: Evaluation of Digital Photogrammetric Camera Systems – Geometric Performance

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Summary: The geometric performance of digital airborne cameras also including the impact of direct sensor orientation has been evaluated by a test of the German Society of Photogrammetry, Remote Sensing and Geoinformation (DGPF). This test includes following airborne photogrammetric cameras: the large format frame cameras Z/I Imaging DMC, Vexcel Imaging UltraCamX and the line scanning camera system Leica Geosystems ADS40 (2nd generation) and Jena Optronik JAS-150 as well as the mid-format camera Rolleimetric AIC-x1 and the combination of four mid-format cameras Quattro-DigiCAM. The results presented in this paper were achieved by a group of researchers from different institutions, working independently from each other and with different programs for data acquisition and bundle block adjustment. Moreover, different adjustment configurations (i. e. with/without use of perspective centre coordinates and/or attitude information from GPS/inertial systems), and also different control point configurations have been used in the test; this results in a wide range of solutions and accuracy results which are not easy to compare, on the other hand this just shows the spectrum of possible solutions in operational applications.

Zusammenfassung: *DGPF-Projekt: Evaluierung digitaler Kamerasysteme – geometrisches Potential*. Das geometrische Potential digitaler Luftbildkameras, auch unter Berücksichtigung der direkten Sensororientierung, wurde im Rahmen eines Tests der Deutschen Gesellschaft für Photogrammetrie, Fernerkundung und Geoinformation (DGPF) untersucht. Dieser Test schließt folgende Kameras ein: die großformatigen Kameras Z/I Imaging DMC, Vexcel Imaging UltraCamX und Zeilenkameras Leica Geosystems ADS40 (2. Generation) und Jena Optronik JAS-150, sowie die Mittelformatkamera Rolleimetric AIC-x1 und die Kombination von vier Mittelformatkameras Quattro-DigiCAM. Die in diesem Bericht präsentierten Ergebnisse wurden von einer Gruppe wissenschaftlicher Mitarbeiter verschiedener Universitäten mit unterschiedlichen Datenerfassungsprogrammen, unterschiedlichen Bündelblockausgleichungsprogrammen, unterschiedlichen Konfigurationen der Ausgleichungen (z. B. mit/ohne Verwendung von Projektionszentrumskoordinaten und Richtungsinformation aus GPS/inertial Systemen) und unterschiedlicher Passpunktkonfiguration erzeugt. Diese Ergebnisse geben einen Überblick über die Variation der Lösungen und Genauigkeiten, die auch in operationeller Anwendung gegeben ist.

1 Introduction

Digital cameras are replacing more and more the analogue. The first large format photogrammetric cameras introduced into market were the line scanning camera Leica Geosystems ADS40 and the frame cameras Z/I Imaging DMC and Vexcel Imaging UltraCam, where current systems have already been modified compared to the market introduction. Recently the line scanning camera Jena Optronik JAS-150 has been introduced. Mid-format cameras are growing with the pixel numbers and multi-head configuration of mid-format cameras are available, which in terms of terrain coverage now can compete or are even superior to the large format systems. For the evaluation of the geometric performance

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not only the images itself, but also their combination with direct sensor orientation, leading to integrated sensor orientation (ISO), has to be considered. The selection of a camera type will not only be based on the geometric property and system size, depending upon the project definition, the selection has to be economic in relation to the varying project conditions. This paper only focuses on the geometric performance analysis; economical aspects have to be considered from later potential system users.

Up to now several tests for the geometric performance of digital cameras have been made, but only very few comparisons of different systems with images taken under similar conditions have been published. In (Passini & Jacobsen 2008) the accuracy potential of block adjustments with DMC-, UltraCamD-, UltraCamX-, ADS40- and RC30-images with approximately 5 cm GSD have been analyzed, but the test of the DGPF includes two different ground resolutions, mid-format cameras and a second line scan camera. Up to now it is the most comprehensive test of digital aerial cameras.

Within the next section the participating institutions and data acquisition is presented, and then some general investigations on the use of self-calibration are made. This also includes some discussions on the stability and validity of additional parameter models. Finally the overall geometric accuracy is outlined, obtained from independent check point analyses after bundle adjustment.

2 Aerial Triangulation – Data Acquisition

The geometric performance of a camera system depends on the correct mathematical modelling, the multiple coverage of the project area, the block configuration, the quality of the input data, the automatic aerial triangulation (AAT) including number and distribution of tie points, manual measurement of control and check points as well as the direct sensor orientation (projection centres determined by relative cinematic GNSS and inertial measurement units (IMU)). Besides, the quality of the images itself is of importance, which also might be influenced by the environmental conditions during image data acquisition.

In the frame of the DGPF-project for the camera evaluation different strategies have been used by the participants. Different programs for AAT, individual measurements of the control and tie points, different bundle block adjustment programs and block adjustments without direct sensor orientation and integrated sensor orientation (ISO) have been used. This does not allow direct comparison of the results achieved by the participants, but it opens the view to the wide range of possible solutions in photogrammetric projects. This also reflects the situation of later operational processing where each evaluation is based on the available process chain and maybe even more important the expertise of each user. In addition, not all image flights have been done in the planned configuration and the actual weather conditions for individual flights have been different, but this can be seen as more realistic conditions.

All camera manufacturers had access to 19 ground control points to check that their data sets are consistent and comparable to other flights. This was done before the data was sent to the pilot centre for further dissemination. The manufacturers had the possibility to optimize the post processing of sensor data, i. e. generation of the virtual images for the large format digital frame cameras or the optimum for the integrated sensor orientation. This may not be realistic for usual operational handling, so it has to be taken into account for the transfer of the achieved results to commercial projects.

2.1 *Participating Institutions and Analyzed Data Sets*

The results presented in this paper are mainly based on the investigations done by the photogrammetric institutes at Leibniz University Hannover (UH), University of Stuttgart (US), Graz University of Technology (TUG), Vienna University of Technology (TUV) and the RAG Deutsche Steinkohle (RAG) company in Herne (JAS-150 bundle adjustment) (cf. Tab. 1). This includes data sets (typically image coordinate measurements) generated by

Tab. 1: Analyzed sensor data sets from participating institutions.

Camera system	University of Hannover (UH)	University of Stuttgart (US)	TU Graz (TUG)	TU Vienna (TUV)	RAG Herne (RAG)
RMK	X	X	X	X	
DMC	X	X		X	
UltraCamX	X	X		X	
Quattro-DigiCAM	X	X	X		
ADS40	X	X			
JAS-150					X
AIC-x1	X	X			

University of Duesseldorf (Uni D), survey administration LVG Munich (LVG M) and the private company CuB Technik.

2.2 *Manual Measurement of Image Coordinates*

Image coordinates of control and check points usually are measured manually because of the strong variety of the shape of object points and varying background. The manual measurements partially dominate the determination of the object point coordinates. Centres of signalized points shown in the images are not independent upon the background in the object space. If the background is not homogenous, the imaged centres may be slightly shifted, leading to systematic pointing errors. Simple error propagation for such point locations cannot be used. In the case of this camera test especially for the data sets with 20 cm GSD the identification of corresponding image points was sometimes difficult. All signalized points were marked with 60 × 60 cm² white colour markings, in the central part of the Vaihingen/Enz site. Where the 8 cm GSD flights were done, these white targets were additionally provided with 30 × 30 cm² black squares in the centre of the white target. Fig. 1 shows with

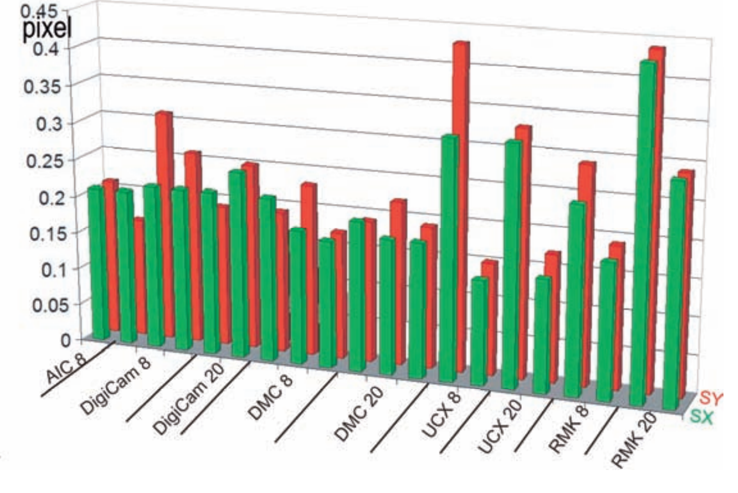


Fig. 1: Standard deviation of manual control and check point measurements [pixels] computed by differences of independent measurements (the number following the camera names indicates the GSD).

Tab. 2: Source of manual image point measurements of control and check points.

Camera	Image coordinates measured by
RMK	US, LVG M, TUV
DMC	US, LVG M, TUV, CuB Technik
UC-X	US, LVG M, TUV
DigiCAM	UH, US, TUV, CuB-Technik
AIC-x1	UH, US, Uni D

any pair of columns (SX and SY) typical root mean square differences (RMS) of the manual measurements of always two organizations (see also Tab. 2) divided by 1.414 to reduce it to the standard deviation of single manual pointing – what is correct if both of the compared measurements have the same accuracy. This may give a realistic view on the variations in manual image coordinate measurements and to some of the limitations of such a test with accurate reference.

The precision of the manual control and check point image coordinate measurements of course depends on the qualification and precision of the human operators, but also on the image quality. The point identification in the digitized analogue images of the RMK, especially with 20 cm GSD, is quite more difficult as with other images, which already reflects the lower radiometric quality of scanned analogue images compared to digital imaging. The slightly higher values for the Quattro-DigiCAM are concentrated to the same operator, while for the UltraCamX no clear explanation can be seen – the same operators got better pointing values with other cameras, so this may be caused by a learning process of the operators, measuring the same points in images taken with different cameras. Such a variation of the manual pointing is influencing the finally reached results of the block adjustments. The differences between the cameras may reflect also the impact of different environmental conditions during sensor flights, also influencing the radiometric performance of the image data.

3 Self-Calibration

3.1 *Systematic Image Errors*

The geometry of photogrammetric cameras is approximated by the mathematical model of perspective geometry. The real image geometry does not correspond exactly to this model. Discrepancies can be caused by the optics, the planarity of the sensor plane and in case of the large format multi-head frame sensors the mosaicing of sub-images to homogenous virtual images. The discrepancies within the CCD usually can be neglected.

Geometric differences between the real image geometry and the perspective geometry, named systematic image errors, usually are determined and respected by self-calibration with additional parameters. This requires a systematic characteristic of the discrepancies, being constant within the used group of images. The number of used additional parameters should be limited to avoid weakening of the block geometry. On the other hand the parameters must be able to model the main part of the systematic image errors. Remaining systematic image errors after self-calibration with additional parameters can be analyzed through residuals at the image coordinates after bundle adjustment. By superimposing all image residuals in one image plane the residuals can be averaged in small image sub areas.

This grid can also be used as a correction grid for improving the image coordinates in a second block adjustment. The correction grids can be combined with self calibration, but also used without. Correction grids determined without self-calibration do not need any hypothesis about geometry of systematic image errors. The high number of sub areas of a correction grid may weaken the block adjustment and requires a high number and good distribution of image points. The following results are based on at least 100 residuals in average, minimizing random errors. The constant characteristic of the systematic image errors has been analyzed by subdividing the images of a block into two groups as function of the flight time to determine changes of the geometry between both sub-blocks, which can only be caused by a time depending change of the image geometry.

3.2 *Additional Parameters*

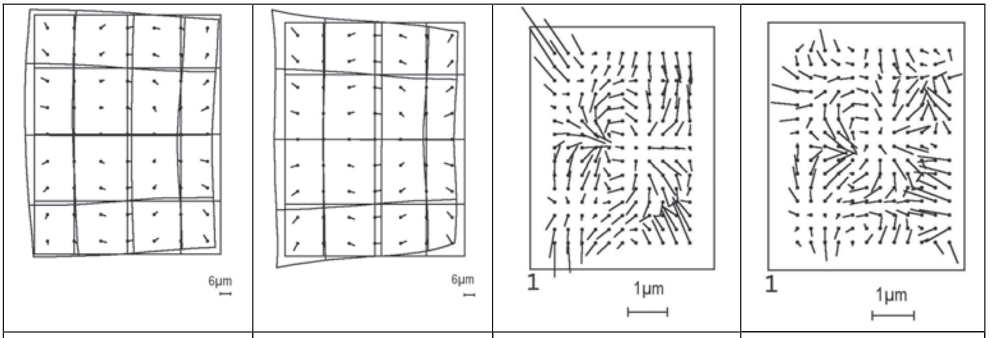
Different sets of additional parameters are in use. They may be based on a pure mathematical justification, as the 12 Ebner parameters (Ebner 1976), eliminating the systematic effects in a grid of 3 × 3 points (Gruber points) or the 44 Grün parameters (Grün 1976) based on 5 × 5 points. Such sets of additional parameters were justified at the time when tie points have been measured manually in just 9 Gruber-points, later also raised to a grid of 5 × 5 points in the photos, but today equal distributed tie points are preferred. The Ebner set of 12 additional parameters has been shown as not satisfying for digital images (Wu 2007), but also for analogue photos with distributed tie points distributed equally in the images. In Fig. 8, right hand side, it can be seen that the adjustment US(3), based on the Grün-parameters drastically improved the accuracy against the same data set adjusted with the Ebner-parameters (case US(2)). Despite the fact that these mathematical polynomials are implemented in many commercial software packages, they are not allowing a satisfying description of the actual image deformation, especially of modern multi-head digital frame cameras. The Vienna University of Technology by this reason has extended the Ebner parameters by two radial symmetric and two tangential parameters (using a balanced version of Brown's formulation), named as Ebner+4 in Tab. 4.

Another possibility is the use of parameter sets which can model physical justified effects like radial symmetric and tangential lens distortion, principal point offset or focal length refinement by a reduced number of additional parameters. The most common known parameter set of this type is the one introduced by Brown (Brown 1971). The bundle adjustment program BLUH (Jacobsen 2007) uses a standard set of 12 parameters composed of mainly physical parameters. Physical parameter sets are also defined in the bundle adjustment software packages BINGO (Kruck 1983), DGAP (University of Stuttgart), Orient (TU Vienna) and PhoBA (TU Graz). In addition to the standard parameter sets, specially designed parameters have to be used for the large format digital cameras DMC and UltraCam. They are able to handle small geometric deformations caused by the stitching process by operating on well defined image regions covered by the individual sensor units. Such parameter sets are implemented e.g. in the bundle adjustment programs BLUH and BINGO.

Still there is the need to know how well this modified parameter sets fit the true sensor geometry, which only may be analyzed through extensive empirical testing. Thus modifications to refine existing self-calibration models or to take care of new sensor designs have already been made or are under development. The BLUH bundle adjustment may serve as one example. There the physical parameters have to be added by some mathematical parameters for effects which are not properly covered. The 12 general additional parameters of the program system BLUH (typically used for the traditional block adjustment of analogue imagery) (Jacobsen 2007) just recently have been complemented by the special parameters 81 up to 88 (cf. Tab. 3), modelling geometric effects of the image corners of digital mid-format cameras, which may be caused by non flatness and deformation of the sensor CCD array. For the large format digital cameras DMC and UltraCam special additional parameters are included to be able to cover

Tab. 3: Additional parameters of program system BLUH covering corner effects of digital mid-format cameras (AP81 – AP88 = numeric values of the additional parameters).

81. $x' = x + AP81*ABS(x^3 * y^3) * 10^{-9}$	$y' = y - AP81*ABS(x^3 * y^3) * 10^{-9}$	for lower right quarter
82. $x' = x + AP82*ABS(x^3 * y^3) * 10^{-9}$	$y' = y + AP82*ABS(x^3 * y^3) * 10^{-9}$	for lower left quarter
83. $x' = x + AP83*ABS(x^3 * y^3) * 10^{-9}$	$y' = y - AP83*ABS(x^3 * y^3) * 10^{-9}$	for upper left quarter
84. $x' = x + AP84*ABS(x^3 * y^3) * 10^{-9}$	$y' = y + AP84*ABS(x^3 * y^3) * 10^{-9}$	for upper right quarter
85. $x' = x + AP85*x^2 * y^2 * 10^{-6}$	$y' = y + AP85*x2 * y^2 * 10^{-6}$	for lower right quarter
86. $x' = x + AP86*x^2 * y^2 * 10^{-6}$	$y' = y + AP86*x2 * y^2 * 10^{-6}$	for lower left quarter
87. $x' = x + AP87*x^2 * y^2 * 10^{-6}$	$y' = y + AP87*x2 * y^2 * 10^{-6}$	for upper left quarter
88. $x' = x + AP88*x^2 * y^2 * 10^{-6}$	$y' = y + AP88*x2 * y^2 * 10^{-6}$	for upper right quarter



Systematic image errors, a.p. 1 – 12	Systematic image errors, a.p. 1 – 12 + 81 – 88	Remaining systematic image errors, a.p. 1 – 12	Remaining syst. image errors, a.p. 1 – 12 + 81 – 88

Fig. 2: Systematic image errors and remaining systematic image errors (Quattro-DigiCAM, camera 1, 20 cm GSD) based on adjustment with different sets of additional parameters (a.p.).

geometric effects of the image mosaicing (details in Jacobsen 2007).

The positive impact of the recently introduced new BLUH parameters 81 up to 88 should exemplarily be illustrated by one of the 4 cameras of the Quattro-DigiCAM configuration (camera 1), shown in Fig. 2. The differences of the systematic image errors determined by the additional parameters 1–12 (standard 12 BLUH parameters) and 1–12 + 81–88 are limited to the image corners. Without use of additional parameters 81–88 the averaged and overlaid residuals, shown as remaining systematic image errors, show larger values at the image corners. The root mean square of the remaining systematic image errors for the Quattro-DigiCAM is reduced by the parameters 81–88 in the x- and y-component by 15 % to 25 % to ± 0.4 µm and ± 0.7 µm, respectively. Even though this improvement is well within in the sub-µm level it is of influence for the later bundle adjustment, as long as no additional support from direct sensor orientation is available. A bundle block adjustment of the Quattro-DigiCAM configuration just based on 15 control points, not using direct observations for the positions of projection centres, leads to improved coordinates of independent check points of approximately 15 % in all 3 coordinate components. In general, non modelled systematic image errors are causing a block deformation especially in the height component if the block is not stabilized by a higher number of well distributed control points or GPS-coordinates of the projection centres. The positive impact of these BLUH additional parameters 81–88 is similar for the Rolleimetric AIC-x1.

Instead of self-calibration with additional parameters also an iterative block adjustment with improvement of the image coordinates by correction grids, based on the overlaid and averaged residuals, is possible. This for example is implemented and used by BLUH, BINGO and PhoBA adjustment software and also used by the Intergraph/ZI software (Dörstel 2007). But this method includes a high number of additional unknowns corresponding to the number of image sub-areas for averaging. In the example of Fig. 2, 12 × 15 = 180 sub-areas are used. To avoid a too strong influence of random errors, the correction grids should be improved by weighted average filter. Block adjustments using correction grids are leading to approximately the same accuracy determined at independent check points in the case of the camera test, having a high number of image points. But only very limited possibilities of statistical tests of the justification of the correction grids within the bundle block adjustment are possible. The program system BLUH includes statistical tests of the additional parameters – not justified and too strong correlated additional parameters are removed automatically from the adjustment, so the final adjustment will be made with a reduced set of additional parameters. Corresponding reduction of unknowns is not possible with correction grids. So correction grids should only be used for tests with data sets having a satisfying number and equal distributed image points. Even though such correction grids may have certain relevance for photogrammetric bundle adjustment their use for operational purposes may be dangerous, since they may handle random errors as systematic errors, leading to smaller σ0, which not necessarily corresponds to better object coordinates.

4 Sensor Stability

The self-calibration requires constant systematic image errors for the group of images handled as one unit. If the image geometry is changing within the data set caused by thermal or other influences, only the average systematic image errors can be determined and respected. In addition it is important to know, if systematic image errors are constant or if they are depending for example on the time and the flying height. Such dependencies are also limiting pre-corrections based on calibration sites. For the investigation of the geometric sensor stability, the images of the 8 cm GSD data sets have been separated into two groups corresponding to the flight time, i. e. the first half of the 8 cm GSD flight forms the first sub-block, the second half the second sub-block. The self-calibration has been computed with two sets of additional parameters, each limited to one group of images. The comparison of the so determined systematic image errors is answering the question if the image

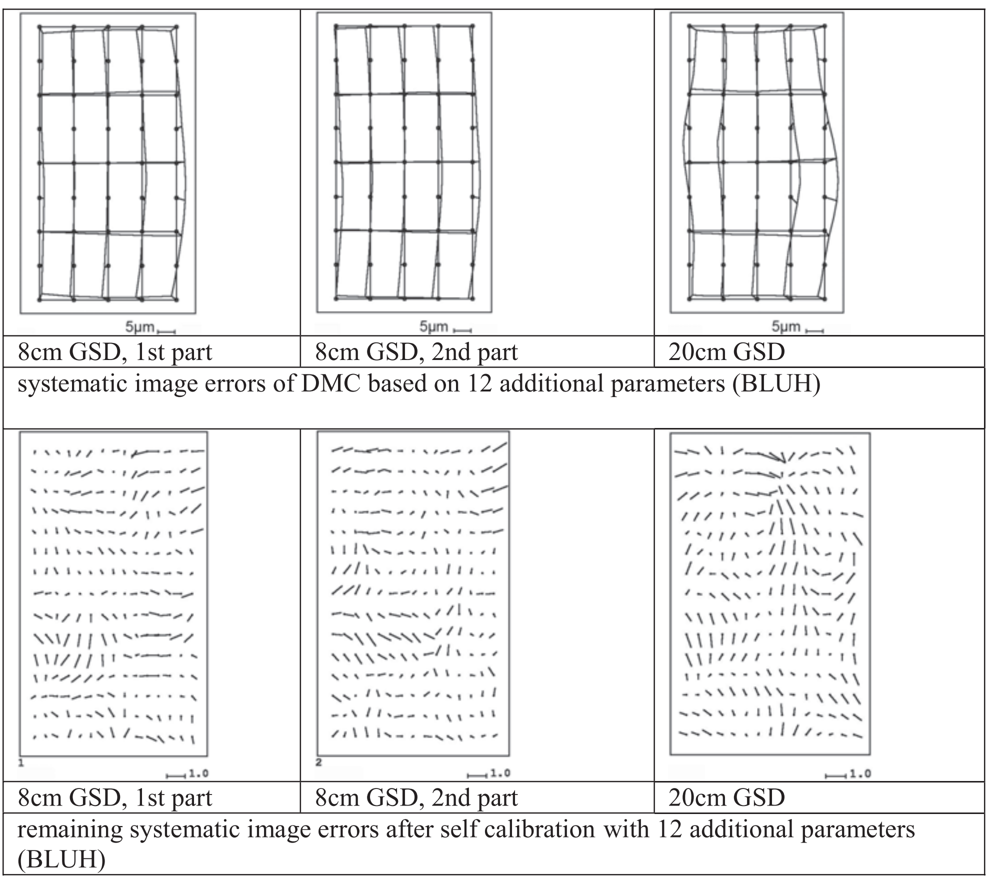


Fig. 3: Systematic image errors and remaining image errors of DMC based on 12 additional parameters (separately estimated for two 8 cm GSD sub-blocks and 20 cm GSD flight).

geometry is the same within the whole block. A comparison with the systematic image errors determined for the blocks with 20 cm GSD is showing the dependency on the flying height or the time.

The large format frame camera images DMC and UltraCamX are virtual images based on the merging of the smaller sub-images. So as additional source for systematic image errors the effect of mosaicing may exist. Program system BLUH includes special additional parameters for the DMC and also the UltraCam. The data of the DGPF-camera test show only limited improvements of the bundle block adjustments using in addition to the basic 12 additional parameters the camera specific parameters. Because of this fact, following only the results based on the basic 12 BLUH parameters is shown.

The systematic image errors of the DMC are limited (cf. Fig. 3 upper part). For the lower flying height (8 cm GSD) in the mean square just 0.8 µm or 0.07 pixels are reached, while it is a little more with 1.3 µm or 0.11 pixels for the upper flying height. A small change of the systematic image errors between the first and the second block part of the lower flying height can be seen, but with 0.5 µm or 0.04 pixels in the mean square it can be neglected in the bundle block adjustment. Thus need for 2 different sets of parameters for the first and second block part of the lower flying height is not proven, which indicates the stability of the camera system.

The remaining systematic image errors (cf. Fig. 3 lower part) of the block adjustments with the 12 basic additional parameters are limited. For the lower flying height it is similar, for the upper flying height it is different, but some similarities can be seen. With sub-block specific additional parameters the results of the block adjustment with DMC images have been slightly improved, even if the effect to the systematic image errors is limited for the case of the DGPF test and can hardly be seen in later check point differences in object space. Thus, division of blocks and the use of different sets of self-calibration parameters for those smaller sub-blocks or groups of images are not applied in later adjustments presented in section 5.

Within the test similar investigations have been made with the other cameras, leading to similar results. The systematic image errors and the remaining systematic effects show only small differences between the first and the second block part. In no case it was justified to handle the block parts with different sets of additional parameters. In other words: a significant change of the systematic image errors within the blocks cannot be seen. Independent upon earth curvature and refraction correction the image geometry is changing more between the lower and the upper flight level. So a system calibration in one flight level cannot lead to the full accuracy potential if it will be used as a pre-correction for the other flight level if no self-calibration is used again.

5 Bundle Block Adjustments

Tab. 4 and 5 give an overview over the different strategies used by the participants for evaluation of the camera systems. Note that for several camera systems different parameter sets, GCP configurations and integration methods for GPS/IMU data have been tested by the participants. They are tagged by a version number which is also given in the graphical presentation of the various results (see Figs. 4–9).

As mentioned above, different strategies have been used by the participants for the evaluation of the camera data sets. In order to illustrate the performance of area based cameras, not overlaid by effects from direct sensor orientation, block adjustments without GPS/IMU data have been made by the Leibniz University Hannover (UH). This is also the case for systems which are used without GPS/IMU-sensors. Nevertheless, even though additional GPS/IMU sensors are only optional for large format frame based sensors DMC and UltraCamX in principle, almost all of the systems are equipped with such devices. These integrated systems are mandatory part of the line scanning sensors and also advantageous for multi-head medium format sensors, where the images are not merged to form a large format virtual image (see later discussion on the Quattro-DigiCAM data analysis).

Tab. 4: Configurations of bundle block adjustments of CCD-array cameras.

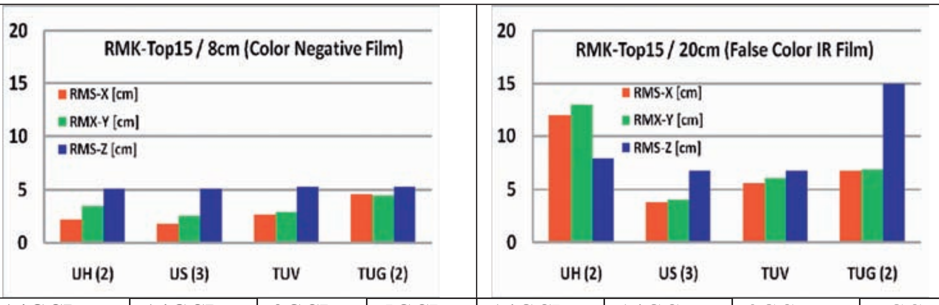
Cam. System	**Insti-tution**	**Tie Point**	**Bundle Adjustm.**	**#ADPA**	**GPS / ISO**	**#GCP 8 cm/20 cm**	**#ChP 8 cm/20 cm**
DMC	UH	Match-AT (LVG M)	BLUH	12	no	9/9	45/95
	US	Match-AT	Match-AT	44 (Grün)	ISO	4/4	113/180
	TUV	Match-AT	Orient	Ebner+4	GPS	8/8	52/99
UCX	UH	Match-AT (LVG M)	BLUH	12	no	9/9	99/99
	US	Match-AT	PAT-B DGAP	44 (Grün)	ISO	4/4	111/180
	TUV	Match-AT	Orient	Ebner+4	GPS	8/8	52/99
RMK-Top15	UH	Match-AT (LVG M)	BLUH	1: 0 2: 12	no	14/14	40/82
	US	Match-AT	Match-AT	1: 0 2: 12 (Eb.) 3: 44 (Gr.)	no	14/14	107/172
	TUV	Match-AT	Orient	Ebner+4	GPS	8/8	49/93
	TUG	ISAT	PhoBA	5 (Brown subset)	1+2: GPS 3: no	59/82 5/5 5/5	56/67 110/77 110/77
Quattro-Digi-CAM	UH	ERDAS	BLUH	1: 4x12 2: 4x20	no	10/15	28/91
	US	Match-AT	Match-AT	4x12 (Ebner)	ISO	4/4	114/161
	TUG	Match-AT (IGI)	PhoBA	5 (Brown subset)	1+2: ISO 3: no	57/104 5/5 5/5	56/69 108/168 108/168
AICx1	UH	Uni Düsseldorf	BLUH	1: 0 2: 12 3: 20	not av.	47/-	10/-
	US	Match-AT	Match-AT	44 (Grün)		60/-	50/-

Tab. 5: Configurations of bundle block adjustments of CCD-line scan cameras.

Camera System	Institution	Tie Point Generation	Bundle Adjustm.	#ADPA	ISO	#GCP 8 cm/20 cm	#ChP 8 cm/20 cm
ADS40	UH	GPRo	ORIMA	0	ISO	9/-	52/-
	US	GPRo	ORIMA	6	ISO	4/4	121/182
JAS-150	RAG	Jena Optronik Software	BINGO	12	ISO	1: 0/0 2: 4/4 3: 19/19	75/105 71/101 56/85

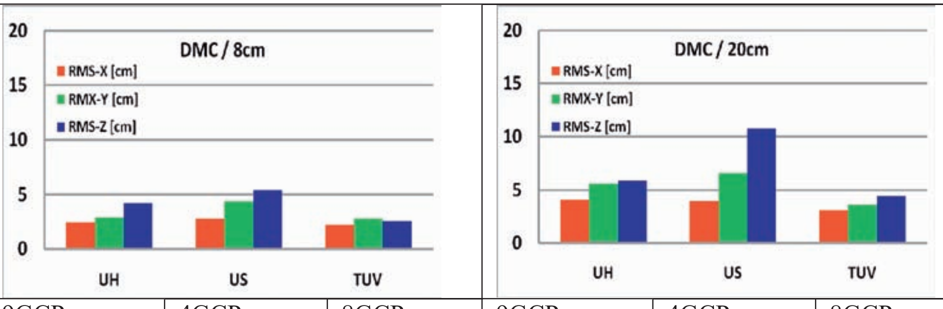
Tab. 6: Abbreviations used in the graphical presentations.

p60 / p80	60% / 80% end lap		apE12	12 additional param. (Ebner)
q20	20% side lap		apE16	12 Ebner + 2 radial + 2 tang.
cr0 / cr2	0 / 2 crossing strips		apG44	44 additional parameters (Grün)
nDS	No direct sensor orientation		apB12	12 additional param. (BLUH)
GPS	Combined adjustment with GPS		apB20	apB12+parameters 81–88
ISO	Integrated sensor orientation		apBN12	12 additional param. (BINGO)
0ap	No self calibration		apBRs	Brown subset with 5 parameters



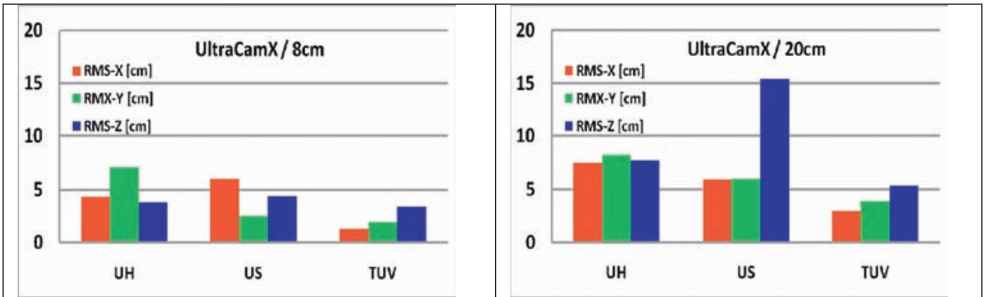
14GCP nDS apB12	14GCP nDS apG44	8GCP GPS apE16	5GCP ISO apBRs	14GCP nDS apB12	14GCP nDS apG44	8GCP GPS apE16	5GCP ISO apBRs

Fig. 4: RMS values from check point analyses RMK-TOP15 (overlap by camera system: p60, cr2).



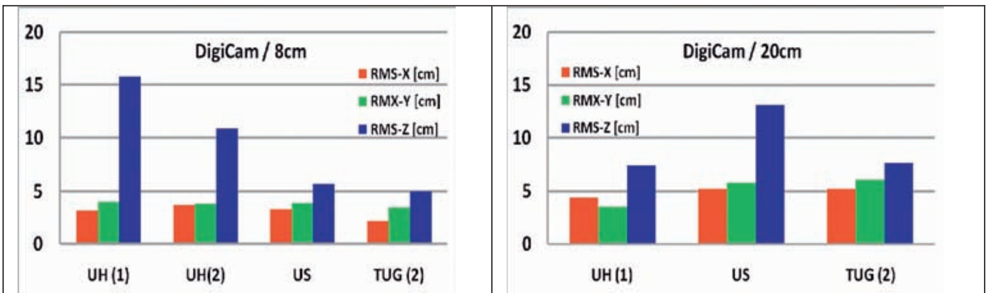
9GCP nDS apB12	4GCP ISO apG44, cr0	8GCP GPS apE16	9GCP nDS apB12	4GCP ISO apG44, cr0	8GCP GPS apE16

Fig. 5: RMS values from check point analyses DMC (overlap by camera system: p60, cr2).



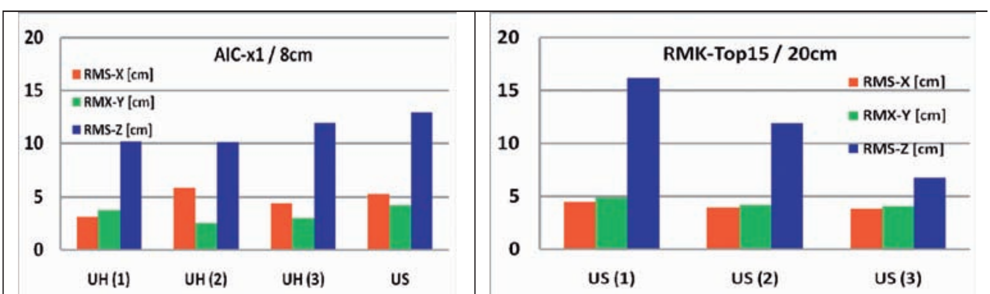
9GCP nDS apB12	4GCP ISO apG44, cr0	8GCP GPS apE16	9GCP nDS apB12	4GCP ISO apG44, cr0	8GCP GPS apE16

Fig. 6: RMS values from check point analyses UltraCamX (overlap by camera system: p80, cr2).



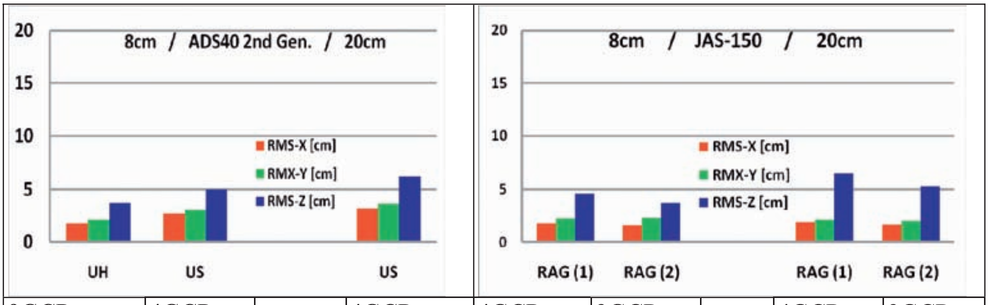
10GCP apB12x4 nDS	10GCP apB20x 4 nDS	4GCP apE12X 4	5GCP apBRs ISO	15GCP apB12x4 nDS	4GCP apE12X4 ISO, cr0	5GCP apBRs ISO

Fig. 7: RMS values from check point analyses Quattro-DigiCAM (overlap by camera system: p60, q60).



47GCP 0ap nDS	47GCP apB12 nDS	47GCP apB20 nDS	60GCP apG44 nDS	14GCP 0ap nDS	14GCP apE12 nDS	14GCP apG44 nDS

Fig. 8: RMS values from check point analyses AIC-x1 (left, cr0) and RMK-TOP15 (with the use of different additional parameter sets).



9GCP 0ap ISO	4GCP apO6 ISO		4GCP apO6 ISO, cr0	4GCP apBN12 ISO	9GCP apBN12 ISO		4GCP apBN12 ISO	9GCP apBN12 ISO

Fig. 9: RMS values from check point analyses ADS40 (left) and JAS-150 (right).

The Vienna University of Technology (TUV) preferred combined block adjustments with GPS-coordinates of the projection centres. From their investigation results from that were more accurate than using GPS/IMU data in integrated sensor orientation. The block adjustments of the University of Stuttgart (US) and Graz University of Technology (TUG) in most cases have been performed as integrated sensor orientation. Note that different direct sensor orientation equipment was used and this may dominate the results based on it more as the camera geometry itself.

For adjustments of University of Stuttgart no cross-strips (even though mostly available for all the flights) were introduced, in order to simulate a more operational like environment where often no cross-strips are flown, especially when integrated GPS/inertial systems are available.

Integrated sensor orientation causes an advantage for blocks with less strong image connections. In case of blocks having a limited size and good image connections, a non optimal modeling of systematic errors can cause a negative influence because proper weighting and separation of systematic errors from random errors are more difficult.

In the following figures, the RMS values at independent check points are presented with the dimension [cm]. The information 8 cm corresponds to the data sets based on 8 cm GSD, while 20 cm corresponds to 20 cm GSD. For better interpretation, some key information about the evaluation strategy used is given below each graph. The exact meaning for each abbreviation is given in the following table. The results of the different block adjustments shown in Figs. 4 up to 9 show the large varieties of the solutions. It's not possible to directly compare the results of the different camera systems because the flight conditions have been different and also the end lap is varying between 60 % and 80 %. Even more, for one camera system results depend upon the different configurations used, as just based on GCPs, use of combined adjustment with relative cinematic GPS-positions of the projection centres or integrated sensor orientation, using the integrated GPS/inertial trajectory information for exterior orientation plus image and ground control points. In addition different sets of additional parameters have been used.

The influence of the sets of parameters to the block adjustment becomes very clear in Fig. 8 right hand side (exemplarily shown for the traditional RMK data set, but also similar for the other systems). Especially the height is strongly influenced by the radial component of systematic image errors as it is obvious at the Ebner parameters having problems to compensate radial symmetric and tangential image errors. With the 44 Grün parameters such effects can be compensated more efficiently, reducing the root mean square differences at independent check points drastically. The results from University of Stuttgart, shown above, are (mostly) based on the Grün parameter set (except for Quattro-DigiCAM). Vienna University of Technology extended the Ebner parameters by two radial symmetric and two tangential additional parameters. Such parameters are included in the program system BLUH, so such problems did not appear. The Graz University of Technology even with just a subset of 5 Brown additional parameters was able to avoid such a problem of the Ebner parameters as shown in Fig. 8, right hand side.

The influence of exterior sensor orientation parameters is quite depending upon the block configuration and the number of GCPs, which can be seen from the Quattro-DigiCAM (see Fig. 7). The four images of the Quattro-DigiCam, taken at the same time, are not stitched together to a virtual image; they are handled as individual images during adjustment and later product generation. The 60 % side lap of the system of 4 images corresponds only to a block with 20 % side lap regarding to virtual images (see Fig. 10). This leads to a very strong influence of systematic image errors to the achieved results, which has to be compensated by additional parameters. If self-calibration is done properly, quite reasonable results can be obtained even without using directly measured exterior orientation elements. Still GPS/IMU components are an inherent part of the Quattro-DigiCAM product and use of directly measured exterior orientations is standard approach for processing such data sets. Thus, results shown in Fig. 7 not using direct sensor information are not corresponding to the recommended operational scenario, even if the accuracy has been strongly improved by self-calibration. For 20 cm GSD on the first view it seems to be different, but the different number of GCPs has to be taken into account. It should be mentioned that IGI now also offers merged large format virtual images as an optional product from Quattro-DigiCAM. This type of image product was not considered in the DGPF test evaluations.

The standard deviation of the manual measurements of control and check points shown in Fig. 1 also demonstrate the strong influence of the point identification in the images. Especially in the RMK Top15 images with 20 cm GSD the exact identification of the points in the images is very difficult – here the operators of the University of Stuttgart benefited by quite better knowledge of the exact point location. In the other data sets some manually measured image positions had to be excluded from the block adjustment because of exceeding the tolerance limit. In general the results reached by the Vienna University of Technology does not correspond very well with the results coming from the other participants, while the range of the results by the other participants can be explained by the different handling parameters.

Because of weather conditions during photo flight for the Rolleimetric AIC-x1 only images with 8 cm GSD and 60 % side lap and no crossing flight lines exist. It was the explicit wish of the system provider to do the flight test with a "low-cost data acquisition scenario", i. e., using a very small aircraft without additional GPS/inertial components and effective camera stabilization. This finally leads to very strong variations of the orientation elements with up to +/– 4.0 grads in phi, +/– 11 grads in omega and +/– 5 grads in kappa. As example

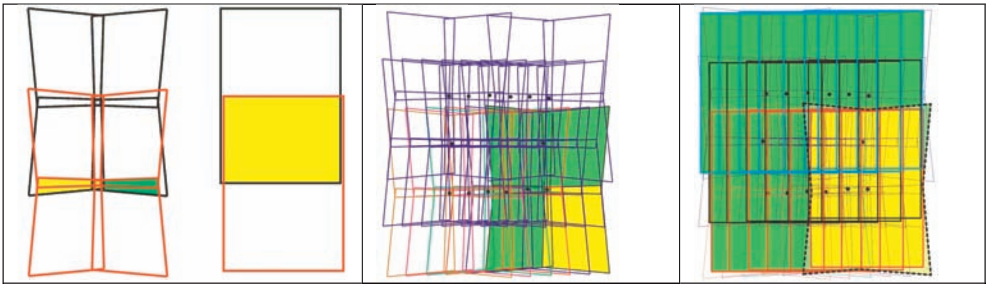


Fig. 10: Overlap and image tie – left: connection of images of a 4-image combination in relation to virtual images – both with 60 % side lap, centre: connection of one image of a 4-image combination in a block with 60 % side lap of the camera system, right: connection of images joined together to virtual images in a block with 60 % side lap of the camera system.

the most north located flight line has partially only 40 % instead of 60 % side lap. No direct sensor orientation was available, requiring a high number of GCPs. The large size of systematic image errors is not influencing the block adjustment itself, it only has to be considered for the handling of the models. For the not optimal conditions of the block the achieved results are still satisfying (see Fig. 8), but they cannot be compared with the results based on the other cameras. Still, for operational projects more regular flights and use of directly measured exterior orientations (at least GPS perspective centre coordinates) should be recommended.

The point determination from the line scanning cameras ADS40 and JAS150 are on a very good accuracy level (cf. Fig. 9). The obtained accuracy of both systems is very similar and is fully comparable maybe also superior to the results obtained from frame based sensors. It is also interesting to see that results from GSD 20 cm and GSD 8 cm blocks from JAS-150 are almost of same accuracy, which should not be expected. Similar to all other data sets these results are based on these test flight evaluations only, and have to be verified from other data sets.

6 Conclusions

There is no more reason to use analogue photos instead of original digital images. Even with the wide angle RMK Top15 under approximately comparable conditions not the same vertical accuracy has been reached as with the large format digital aerial cameras. In addition the less optimal image quality from analogue scanned images became obvious at the manual identification of the control and check points in the images with 20 cm GSD. This also will be of importance for later DSM generation.

The line scanning cameras ADS40 and JAS-150 are providing quite good results. Of course the available test sites are limited in size, so an extrapolation to larger areas may be difficult. The handling for data acquisition following the orientation process still requires special software, which is not available in several locations.

The large format digital frame cameras DMC and UltraCamX confirmed their potential. The image geometry itself is somehow mixed with the influence of integrated sensor orientation or by combined block adjustment with GPS-coordinates of the projection centres, but this is realistic for operational application. Of course the limited test site does not allow a direct extrapolation to large blocks.

Using direct sensor orientation based on the results of the integrated GPS/IMU system, the Quattro-DigiCAM shows results that are comparable to results of the large format systems. This is different when larger blocks using individual images from camera heads are processed without GPS/IMU support and limited number of control points. Also the single midformat camera Rolleimetric AIC-x1 can cover some important applications.

In general sub-GSD-accuracy can be reached especially for the horizontal component, but also in most cases for the vertical component of ground coordinates determined by block adjustment. This should not be mixed with the accuracy of photogrammetric data acquisition in stereo models which is just based on two images, while the block adjustment is using several images per object point. Depending upon the end and side lap the number of images per point for the block adjustment varies between 3.2 (Rolleimetric AIC-x1) over approximately 6 for blocks with 60 % end and side lap up to 10.6 for the block with 80 % end lap and 60 % side lap. In addition not all software packages for model handling are able to respect systematic image errors, leading to model deformation especially in the vertical component.

References

Brown, D.C., 1971: Close-range camera calibration. – Photogrammetric Engineering **37** (8): 855–866.

Dörstel, C., 2007: DMC – (r)evolution on geometric accuracy. – Photogrammetric Week '07, Wichmann Verlag, 81–88.

Ebner, H., 1976: Self Calibration Block Adjustment. – Bildmessung und Luftbild: 128–139.

Grün, A., 1976: Die simultane Kompensation systematischer Fehler mit dem Münchener Bündelprogramm MBOP. – ISP Congress Helsinki.

Jacobsen, K., 2007: Geometric handling of large size digital airborne frame camera images. – Optical 3D Measurement Techniques **VIII:** 164–171.

Kruck, E., 1983: Lösung großer Gleichungssysteme für photogrammetrische Blockausgleichungen mit erweitertem funktionalen Modell. – Wiss. Arbeiten d. Univ. Hannover **128**.

Passini, R. & Jacobsen, K., 2008: Accuracy analysis of large size digital aerial cameras. – International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences **37** (B1): 507–51.

Wu, D., 2007: Geometric aspects of large size digital frame cameras and their use for photogrammetric data acquisition. – Diploma thesis, Leibniz University Hannover.

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