GEOMETRY OF DIGITAL FRAME CAMERAS

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ABSTRACT

Digital aerial frame cameras like Intergraph DMC and Vexcel UltraCamD are becoming standard for mapping application. The virtual or synthetic images of these cameras are based on individual sub-cameras. The calibration of the sub-cameras is respected for the matching of the sub-images to a large virtual image. So by theory, the virtual images should have perfect perspective geometry without any systematic image error. In reality this is not the case and for reaching the possible accuracy potential, block adjustment with self calibration by additional parameters is required. So also under operational conditions quite better accuracy can be reached like with analog photos. Standard deviation of unit weight (sigma0) up to 0.15 pixels is possible by automatic aero triangulation.

Usual commercial digital photogrammetric workstations are not able to respect systematic image errors determined by block adjustment. This causes model deformations, acceptable for the horizontal coordinate components, but in the height, deformations exceeding the accuracy potential may occur. A program for a posteriori correction of digital elevation models has been generated, so the full accuracy potential can be reached. The photo flights have been made not with the latest versions of generating DMC- and UltraCamD images. In the meantime Intergraph and Vexcel modified the cameras and the data handling. The described geometric problems exist also for analog cameras, but they are usually ignored.

INTRODUCTION

The photogrammetric data handling today is done by digital photogrammetric workstations. Analog photos have to be scanned, causing a loss of accuracy and information contents. The degrading of the quality can be avoided in using directly digital sensors. Because of the better signal to noise relation, CCD- and not CMOS-sensors are used. It is not so simple to compare the information contents of a standard analog photogrammetric photo with a digital image. In the frame of a diploma thesis, intensive tests of mapping with analog photos and digital images with different image scales and different ground sampling distance (GSD) have been made in the same area (Oswald 2006). The result was quite clear - the same information contents, that means the identification of details, has been achieved in original digital images having approximately 1.5 times larger GSD than analog photos scanned with 20µm pixel size. So analog photos with a side length of 230mm, have comparable information contents like digital images, having 7700 x 7700 pixels. This is still less than expected few years ago, but CCD-arrays with such a dimension are not available for affordable price, fast read-out time and suitable image quality. By this reason the Intergraph DMC and the Vexcel UltraCam are based on a combination of smaller CCD-arrays which have to be merged to a virtual image. Another alternative solution is the use of CCD-line cameras like the Leica ADS-40, but with the disadvantage of scene accuracy dependency from the direct sensor orientation, based on relative kinematic GPS-positioning and inertial measurement units (IMU). Under operational conditions the direct sensor orientation is limited to a standard deviation of approximately 15cm. The handling of CCD-line scanner images also requires special software for the photogrammetric workstation. For mapping purposes usually CCD-array cameras are preferred, while for large size ortho images the CCD-line scanner is used more often.

The Intergraph DMC is based on 4 convergent arranged sub-cameras (Dörstel et al 2003) (figure 1) while the Vexcel UltraCam is using 4 parallel cameras with 1 up to 4 CCD-arrays (Leberl et al 2002) (figure 2). The sub-images are overlapping, allowing a merging to the homogenous virtual images. Especially the DMC has very solid sub-cameras, having quite better stability like the usual analog film cameras, but geometric changes caused by thermal

influences cannot be avoided totally. In addition theoretically synchronization errors may occur, causing second order effects. Also an influence of the projection center offset may cause geometric effects, if the settings are not handled in the correct manner.



SELF CALIBRATION BY ADDITIONAL PARAMETERS

The geometric problems of the cameras are not changing from image to image; usually they are similar for the whole block of images, allowing a determination by self calibration with additional parameters. General additional parameters, like common for standard bundle block adjustment, can be used for the determination of the general image geometry, but for the special arrangement of the sub-images at least additional parameters fitted to the geometry of the used digital frame cameras should be tested. Not all sets of additional parameters can be used for the handling of the digital cameras, polynomial sets should be avoided.

x, y = image coordinates normalized to r	maximal radial distance 162.6m	m (scale factor: 162.6 /	
maximal radial distance) $r^2 = x^2 + y^2$	$b = \arctan(y/x)$		Table 1.
1. $x' = x - y \cdot P1$	$\mathbf{y}' = \mathbf{y} - \mathbf{x} \bullet \mathbf{P} 1$	angular affinity	general
2. $x' = x - x \cdot P2$	$y' = y + y \bullet P2$	affinity	additional
3. $x' = x - x \cdot \cos 2b \cdot P3$	$y' = y - y \cdot \cos 2b \cdot P3$		parameters
4. $x' = x - x \cdot \sin 2b \cdot P4$	$y' = y - y \cdot sin 2b \cdot P4$		of program
5. $x' = x - x \cdot \cos b \cdot P5$	$y' = y - y \cdot \cos b \cdot P5$		system BLUH
6. x' = x - x•sinb • P6	$y' = y - y \cdot sin b \cdot P6$		-
7. $x' = x + y \cdot r \cdot \cos b \cdot P7$	$y' = y - x \bullet r \bullet \cos b \bullet P7$	tangential distortion	
1			
8. $x' = x + y \cdot r \cdot sin b \cdot P8$	y' = y - x•r•sin b • P8	tangential distortion 2	
9. $x' = x - x \cdot (r^2 - 16384) \cdot P9$	$y' = y - y \cdot (r^2 - 16384) \cdot P9$	radial symmetric	
r ³		-	
10. $x' = x - x \cdot sin(r \cdot 0.049087) \cdot P10$	$y' = y - y \cdot sin(r \cdot 0.049087) \cdot 1$	P10 radial symmetric	
11. $x' = x - x \cdot sin(r \cdot 0.098174) \cdot P11$	$y' = y - y^* \sin(r \cdot 0.0000000000000000000000000000000000$	P11 radial symmetric	
12. $x' = x - x \cdot \sin 4b \cdot P12$	$\mathbf{y}' = \mathbf{y} - \mathbf{y} \cdot \sin 4\mathbf{b} \cdot \mathbf{P} 12$	·	

The analysis of the DMC and UltraCamD-data has been made with the Hannover program system for bundle block adjustment BLUH. BLUH has its own set of additional parameters (table 1) which is a combination of parameters with physical background completed by general parameters to allow a compensation of any general type of image deformation. The actually used parameters are selected by program based on Student-test and check of correlation (Jacobsen 1982). In addition to the additional parameters, listed in table 1, the inner orientation parameters – focal length and principal point, parameters for the combined adjustment with GPS-positions of the projection centers and

parameters for special image geometry like for panoramic cameras are included. For the exact handling of possible problems caused by the matching of the DMC and UltraCamD sub-images, special parameters, listed in table 2, are introduced. With parameter 29 the incorrect handling of the individual DMC projection center offset, caused by wrongly defined flying height above ground, can be fitted. A synchronization error partially is compensated by the sub-image matching based on the tie points between the individual images (see also Dörstel et al 2003), so only second order effects are remaining and can be fitted by parameters 30 up to 33. Similar effects are caused by orientation errors (parameters 34 up to 41). Remaining radial symmetric effects of the sub-cameras are compensated for the DMC with parameters 74 up to 77. With parameter 79 the influence of a change of the field of view to the matching and with 80 a common change of the radial distortion of all 4 sub-cameras with the same size can be respected. The mathematical formulation of the UltraCamD problems is simpler because of parallel view direction of the individual sub-cameras, but the UltraCamD requires 8 parameters for any type of error of the 9 sub-images. The center image is not modified because of exterior orientation unknowns.

29. DMC projection center offs					
$30-33. x' = x + P32*(x^2-32x)$	Table 2.				
34. $x' = x - x^*y^*P34$	y' = y	orientation error	DMC X 1	special	
35. x' = x	$y' = y - x^*y^*P35$	orientation error	DMC Y 1	additional	
36-41 corresponding to $34-3$	5 for other sub-images			parameters for	
42-49 scale parameters for Ult	LiltroComD				
50 – 57 shift X parameters for U	JltraCamD			UltraCalliD	
58 – 65 shift Y parameters for UltraCamD					
66 - 73 rotation parameters for					
74 – 77 radial symmetric param					
butterfly shape (caused by focal length of sub cameras)					
80 same radial symmetric parameter for all DMC sub-images togehter					

EMPERICAL ANALYSIS OF DIGITAL FRAME CAMERA IMAGES

Indication of systematic image errors

Different blocks of digital frame camera images have been analyzed for its geometric behavior. Only the main important results are shown, but the characteristics have been the same for the DMC results and corresponding also for the UltraCamD results. All blocks have been handled by automatic block adjustment; that means, the tie points are determined by image matching and only the image coordinates of the control and check points have been measured manually. Often the manual measurements and the point definition in the image geometry could be analyzed.

Figure 3. overlay of all	Figure 4a. averaged image	Figure 4b. averaged image	Figure 4c. averaged
image points, block Rubi	residuals, Rubi North, 9 x	residuals, Rubi South, 9 x	image residuals, Rubi,
with overlay of sub-areas	9 sub-areas	9 sub-areas	25 x 25 sub-areas
for averaging results	vector scale [mm]	vector scale [mm]	vector scale [µm]

The expression "systematic image error" is common, even if the precise definition means the difference between the existing image geometry and the used mathematical model of perspective geometry. The systematic image errors are influencing the image coordinate residuals of the bundle block adjustment. These residuals are based on the systematic errors, random errors and influenced by the over determination of the orientation and object point unknowns. If all residuals are overlaid corresponding to the position of the image point location, they are showing the tendency of the systematic errors if the overlaid residuals are averaged in image position sub-areas. Figure 3 shows the overlaid 45464 image points of the block Rubi from the ICC Barcelona. A block adjustment without self calibration of the northern sub-block resulted in the averaged image residuals shown in figure 4a. Each vector is representing the average of 280 residuals located in the sub-area of the overlay image. The result of the southern sub-block is similar. More details can be seen in figure 4c, based on the whole block of 426 images, for 25 times 25 image sub-areas. Neighbored vectors are strongly correlated, indicating the structure, but not the size of the systematic image errors are larger. If the vector distribution is random, no systematic image errors or in the case of a block adjustment with self calibration, no remaining systematic error exists.

Intergraph DMC

The block Rubi of the Cartographic Institute of Catalonia (ICC), Spain, has been analyzed in detail. The block with 426 photos having 80% end lap, approximately 40% side lap and 3 crossing flight lines, 7763 object and 45464 image points, has been matched with the Intergraph software. The image scale 1:8180 leads with the pixel size of 12μ m in the image to 9.8cm GSD. 17 control points with distances up to 12 base length, in relation to 60% end lap, are used and 21 independent check points. The control and check points are announced with a standard deviation of 2cm for X and Y and 4cm for Z.

additional parameters	sigma0	cont	rol points [c	check points [cm]				
	[µm]	RMSX	RMSY	RMSZ	RMSX	RMSY	RMSZ	
None	1.89	2.1	3.0	7.7	3.2	2.9	7.6	
9 (r ³)	1.84	1.9	3.2	4.6	2.5	3.2	6.3	
1 - 12 (basic set of BLUH)	1.81	1.9	2.2	2.4	2.3	3.1	5.9	
1 - 12, 29 - 41	1.81	1.8	2.1	1.8	2.5	3.1	5.6	
1 - 12, 29 - 41, 74 - 77	1.74	1.8	2.1	1.9	2.5	3.3	5.3	
1 - 12, 79, 80	1.75	1.9	2.1	1.7	2.5	3.2	4.6	
Table 3. DMC block Rubi, results of block adjustment with self calibration, 9.8cm GSD 1cm = 0.10pixels								

10μm			and a stand of the
Figure 5a. systematic	Figure 5b. averaged	Figure 6a. systematic	Figure 6b. averaged
image errors, parameters	residuals, parameters	image errors, parameters	residuals, parameters
1 – 12, block Rubi	1 – 12, block Rubi	1-12, 79-80, block Rubi	1-12, 79-80, block Rubi

The high internal accuracy of the block adjustment is indicated by the root mean square discrepancies against

the averaged residuals in the image sub-areas (figure 4c) of RMSX= $1.5\mu m$ and RMSY= $1.3\mu m$ corresponding to RMSX=0.14 pixels and RMSY=0.11 pixels. This was also confirmed by the sigma0 value of the bundle block adjustment with values, depending upon the used additional parameters, between $1.89\mu m$ and $1.74\mu m$. To avoid any influence of the earth curvature correction, the adjustment was handled in a tangential coordinate system. Such a strict orthogonal coordinate system corresponds to the mathematical model.

The block adjustment without self calibration shows some discrepancies for the height values of the independent check points. For control point distances up to 12 base length (p=60%), this is not unusual and in relation to analog photos still good. With just the radial symmetric additional parameter 9, the root mean square discrepancies at the check points are reduced to 6.3cm in Z. The standard additional parameters (1 - 12) are improving the accuracy of the check points to RMSX=2.3cm = 0.23pixels, RMSY=3.1cm = 0.31pixels and RMSZ=5.9cm = 0.59pixels corresponding to a root mean square x-parallax of 0.19pixels for the hypothetical end lap of 60%. With standard size analog photos such accuracy in the range of 3μ m in the image cannot be reached. With the special additional parameters for the DMC computed individually for each sub-image, no real improvement can be seen. Better is the result just with the basic 12 parameters of BLUH plus the parameters 79 and 80 handling the change of the field of view and the radial distortion together for all sub-images, that means with just 14 additional parameters. This is improving the height accuracy at independent check points to 46mm, corresponding to a standard deviation of the x-parallax of 0.15pixels. The parameters 79 and 80 for fitting the influence a change of the focal length and the radial symmetric distortions are important. It is not necessary to use corrections individually for each sub-camera. The parameter 29 for compensating of a not correct handling of the projection center offset is not significant corresponding to the theoretical estimation.

The averaged residuals of the block adjustment with the standard additional parameters 1 up to 12 (figure 5b) are still indicating remaining systematic image errors. They are a little smaller like the values from adjustment without self calibration (figure 4c), but the mayor structure is the same. Only with the special additional parameters for the DMC 79 and 80 in addition to the standard additional parameters, the averaged residuals (figure 6b) are nearly free from remaining systematic effects and the root mean square size is reduced to 0.3μ m. Because of this, it is a surprise, that there is more or less no further improvement by the special DMC additional parameters. But the finally achieved results in X and Y are still in the range of the estimated accuracy of the given control and check points. In Z it is 25% above the estimated accuracy, but we do have large distances between the control points and the reached accuracy is excellent and could not be reached under similar conditions with analog photos.

The EuroSDR, an European organization working in the field of Geographic Information by collaborative research of mapping organizations, universities and industry, has made test flights over the test field Frederiksstad, Norway with the DMC and the UltraCamD. The lower level flight level taken with the DMC includes 115 images with image scale 1:7666 or 9.2cm GSD. An automatic aero triangulation with LPS generated 22134 image points and 7028 object points. The quality of this block is limited by the difficult identification of the control and check points in the images. A higher percentage of the area is covered by forest. This caused a limited accuracy of the block, but nevertheless it is usable for the investigation of the DMC image geometry.

			8.8	
Figure 6a.	Figure 6b.	Figure 6c. averaged	Figure 6d.	Figure 6e.
averaged residuals	averaged residuals,	residuals, parameters	systematic image	systematic image
without self	parameters 1-12	1-12,	errors,	errors, parameters
calibration		30-41, 74-77	parameters 1-12	1-12, 79-80
DMC block Frederiks	stad, 9.2cm GSD			

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The general shape of the systematic image errors of block Frederiksstad and also the averaged residuals are
similar to block Rubi, even if a different DMC has been used. The averaged residuals only can be reduced with the
combination of the general BLUH-parameters $1 - 12$ together with the special DMC parameters (see figure 6).

additional parameters	sigma0	control points			check points		
	[µm]	[cm]			[cm]		
none	4.23	7.7	4.2	13.3	6.8	6.0	13.8
1 -12	4.19	4.2	2.3	5.2	3.6	3.9	9.2
1-12,30-36,74-77	4.13	4.0	2.5	5.6	3.4	4.0	8.8
1-12, 79-80	4.14	4,5	2.3	5.4	3.6	3.9	9.2
Table 4. DMC block Frederiksstad, block adjustment with self calibration. 9.2cm GSD 1cm = 0.11 pixels							

As expected, the results of the DMC block Frederiksstad are not so accurate like for block Rubi, having a similar GSD. But the general tendency is the same – self calibration is required and with the special additional DMC parameters the accuracy at the independent check points is more or less not improved. The same tendency exists for most of the handled DMC blocks. The adjustment with the 12 standard parameters plus parameters 79 and 80 in this case is not leading to the optimal result, but it is very close to it. Even if the parameters 79 and 80 are significant – the parameter 80 has a T-test value of 20.3, they are not improving the accuracy determined with check points.

The systematic image errors determined with block Rubi have been used as pre-correction for the block AMPOSTA, flown with the same DMC. This was leading to improved results in relation to a block adjustment without self calibration, but it did not reach the accuracy of a block adjustment with self calibration.

Vexcel UltraCamD

A photo flight with the Vexcel UltraCamD version 2.1.3, number 8 was made for the German Coal Mining Company 'Deutsche Steinkohle AG'(DSK) in the area of a mine site. This camera did not include the improved temperature handling, which is available since UltraCamD version 2.2. A subset of 2282 images has been analyzed. The images do have an end lap of 80% and a side lap of approximately 40%. With the flying height of 1271m and the average ground height of 252m, the image scale is 1:10046; or more important, the GSD is 9cm. The block is stabilized with crossing flight lines. The automatic image matching has been made with the Leica software, while the detailed analysis was made with the Hannover program system BLUH. 46245 object points are available with in total 298533 image points or the object points in the average are given in 6.5 images. The image points are equally distributed in the images with 130 points per image. The control point distance is in the range of 10 base length for 60% end lap.



The averaged residuals (figure 7), indicating the shape of the systematic image errors. Also for the UltraCamD-data systematic image errors only can be reduced with the general additional parameters together with special additional parameters for the used camera. With the general additional parameters, the size of the averaged residuals is reduced, but the shape remains (figure 7b). The averaged residuals for the UltraCamD are approximately 3 times larger like for the DMC and a more detailed fine structure exists – caused by the combination of 9 sub-images to one virtual image. In addition also the combination of all additional parameters does not totally eliminate the systematic effects.



Also the systematic image errors of the UltraCamD are stable - at least within the block. A handling of two sets of images together in one block adjustment was leading to negligible differences of the systematic image errors between both sub-blocks.

additional	sigma0	control points				check points			
parameters	[µm]	RMSX	RMSY	RMSZ	RMSX	RMSY	RMSZ		
		[cm]	[cm]	[cm]	[cm]	[cm]	[cm]		
without	2.66	3.6	3.4	2.9	3.8	3.7	7.6		
1 - 12	2.44	3.3	3.1	2.5	3.5	3.4	5.6		
1-12,42-73	2.26	3.0	2.8	2.3	3.2	3.0	5.4		
Table 5. UltraCamD block mine site, block adjustment with self calibration, 9.0cm GSD 1cm = 0.11pixels									
results of bundle block adjustment – root mean square discrepancies at 117 control points, 40 check									

Like with the DMC-data a block adjustment with self calibration is required. Also for the UltraCamD-block mine site only a very limited improvement of the results at the check points is reached with the additional special UltraCamD-parameters, even if the averaged residuals (figure 7) are indicating remaining systematic image errors if only the standard additional parameters 1 - 12 are used. 3.1cm at the check points are corresponding to 0.34pixels and 5.4cm in Z to hypothetical 0.16pixels for the x-parallax.

The EurSDR also with the UltraCamD number 2 made a test flight over the test field Frederiksstad. Also this camera did not include the improved temperature handling. 132 images with 80% end lap and 60% side lap, including a crossing flight line have been taken with an image scale 1 : 18 909 or 17cm GSD. An automatic aero

triangulation has been made with LPS, leading to 13601 image points for 1774 object points or 103 points per image and 7.7 images per point. The control point distance is in the range of 5 base length for 60% end lap.



Like before, the averaged residuals (figure 9), indicating the shape of the systematic image errors, only can be reduced with special additional parameters for the used camera together with the general additional parameters. With the general additional parameters, the size of the averaged residuals is reduced, but the shape remains (figure 9b). Also here small remaining systematic image errors exist after block adjustment with the general additional parameters 1-12 together with the special UltraCamD-parameters 42-73.



The systematic image errors (figure 10) of block Frederiksstad have a little different shape like the block mine site, but also here a curvature on the left hand side can be seen.

additional parameters	sigma0	control points			check points		
	[µm]	SX	SY	SZ	SX	SY	SZ
		[cm]	[cm]	[cm]	[cm]	[cm]	[cm]
without	2.46	6.1	5.5	24.6	7.8	5.3	15.7
parameters 1-12	2.34	5.4	4.8	14.4	5.3	5.7	12.6
parameters 1-12, 42-72	2.22	5.6	4.8	13.3	4.8	5.7	12.4
Table 6. UltraCamD-block Frederiksstad: discrepancies at check and control points 17cm GSD 1cm=							
0.06pixels							

Like before, a bundle adjustment with self calibration is required, but against a block adjustment with the general additional parameters 1-12 only a small improvement can be seen even if the remaining averaged residuals (figure 9) indicate the requirement of the special DMC parameters. The root mean square differences at the check point X- and Y-coordinates correspond to 0.31 pixels and the 12.4cm in Z correspond to the hypothetical x-parallax of 0.20 pixels for 60% end lap.

Model Deformation

Systematic image errors are causing model deformations. The main effect is in the vertical component, but also the horizontal changes have to be checked. For most precise ground coordinates the bundle block adjustment is used while for mapping usually the horizontal accuracy is not a problem. This may be different for the height, especially for digital elevation models (DEMs) generated by automatic image matching.

	RMSX	RMSY	RMSZ	relative F point d	RMSZ for istances		
				up to	630m –		
				630m	1260m		
comparison of bundle block adjustments – whole block [cm] used additional parameters of adjustments for comparison							
no self calibration - parameters 1-12	2.0	2.0	10.3	4.0	6.5		
no self calibration – parameters 1-12, 79-80	1.7	2.2	11.0	4.4	7.0		
parameters 1-12 - parameters 1-12, 79-80	0.6	0.8	1.9	1.1	1.3		
comparison of model 142/144 with end lap 53% = height to base relation 2.3 image coordinates improved by corresponding systematic image errors							
no self calibration – parameters 1-12	0.4	0.3	9.2				
no self calibration – parameters 1-12, 29-41, 74-77	0.8	0.6	9.3				
parameters 1-12 - parameters 1-12, 29-41, 74-77 0.5 0.6 0.8							
Table 7. influence of model deformation DMC-bloc	k Rubi, 9.80	em GSD, 1cr	n = 0.10 pix	kel			

The check points are measured in the average in 4 images, so a better ground accuracy can be expected from block adjustment like from an individual model. Caused by the higher number of images per point also the effect of the systematic image errors to the ground position is reduced. Nevertheless in the first view (table 7) this seems to be different, but the main influence to the height is caused by the large distance of the control points up to 12 base length in relation to 60% end lap and the used model is just located close to the block center, far away from control points. The relative accuracy of the Z-component for object point distances between 630m and 1260m shows this effect. 1260m is a little more than the model size; that means the main effect is caused by a block deformation and not a deformation of the model itself. If only a single model is investigated (table 7, lower part), based on image coordinates corrected by the corresponding systematic image errors and corresponding orientation, only the relative effects play a roll. It is interesting in both cases, that the special additional parameters for the DMC have only a limited influence to the object coordinates – the results based on the standard parameters 1-12 and the results based on the standard parameters plus the special DMC parameters are not too different. Within the model the effect to the horizontal coordinate components is nearly negligible.

	RMSX	RMSY	RMSZ	relative F	RMSZ for			
				up to	630m –			
				630m	1260m			
comparison of bundle block adjustment – whole block [cm]								
no self calibration – parameters 1-12	3.8	2.7	25.4	8.5	12.2			
no self calibration – parameters 1-12, 42-73	3.1	2.8	21.4	8.1	11.1			
parameters 1-12 - parameters 1-12, 42-73	2.8	2.5	9.2	4.6	5.5			
comparison of model 80833/80835 wi image coordinates improved by c	comparison of model 80833/80835 with end lap 66% = height to base relation 4.1 image coordinates improved by corresponding systematic image errors							
no self calibration – parameters 1-12	0.5	0.3	4.3					
no self calibration – parameters 1-12, 79-80	0.5	0.6	4.2					
parameters 1-12 - parameters 1-12, 79-80 0.1 0.3 0.3								
Table 8. influence of model deformation UltraCamE	Table 8. influence of model deformation UltraCamD-block mine site, 9.0cm GSD, 1cm = 0.11pixel							

The root mean square differences in Z (RMSZ) of the whole block adjustment of the UltraCamD-block mine site (table 8, upper part) cannot be compared directly with the DMC-block Rubi (table 7) because of the larger distance of control points in the DMC-block, the different block size and configuration. In general there is a stronger influence of the UltraCamD image deformation to the X- and Y-coordinates and a larger difference of the results with self calibration just with the standard parameters 1-12 to the standard parameters plus the special UltraCamD-parameters 42 - 73.

The shown discrepancies are based on the points used in the block adjustment; they are not equally distributed in the models. One reason for the investigations have been problems by the coal mining DSK with discrepancies in digital elevation models determined by automatic image matching of UltraCamD-images. The block mine site has been flown with 83% end lap and DEMs based on the even and separately the odd image numbers have been generated in the photogrammetric work station not respecting systematic image errors. The comparison of the overlapping DEMs showed a structure of systematic height differences with averaged discrepancies in the range of 25cm. With the scale of 1:10046, the end lap of 66% and the operational x-parallax accuracy of 0.25pixels, a standard deviation of the height values of 9.2cm is expected – quite less than the achieved values. This inconsistency can be explained by the model deformation caused by systematic image errors.

p ^{10cm} 5cm	5 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	-20cm) 2cm	-8 cm -12 cm -12 cm -12 cm -23 cm -5cm -5cm	
Figure 11a. model	Figure 11b. model	Figure 11c. model	Figure 11d. model	
deformation,	deformation, parameters	deformation, parameters	deformation, parameters	
parameters 1-12	1-12, 79-80	1-12	1-12, 42-73	
model deformation in Z: DMC-block Rubi,		model deformation in Z: UltraCamD-block mine site,		
9.8cm GSD, end lap 63%	5cm contour interval	9.0cm GSD, end lap 66% 5cm contour interval		

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range of DZ	-5cm up to 10cm	-9cm up to 10cm	-20cm up to12cm	-27cm up to 37cm		
RMSZ in model	9.1cm	10.4cm	6.3cm	11.3cm		
parameter configuration	1-12	1-12, 79-80	1 - 12	1-12, 42-73		
	DMC-block Rubi		UltraCamD-block mine site			
Table 9. model deformation in Z caused by systematic image errors						

The influence of the model deformation shown in figure 11 is not negligible in relation to the expected vertical accuracy of 7.6cm for the DMC-block Rubi and 9.2cm for the UltraCamD-block mine site. The influence to the height is more complex and local for the UltraCamD, while it is more smooth for the DMC. Usual commercial Digital Photogrammetric Workstation cannot respect the systematic image errors, so the generated object coordinates are influenced by the model deformation. The influence of the model deformation cannot be accepted for DEMs, by this reason the program DEMCOR for a posterior height correction of DEMs has been developed by the Leibniz University Hannover solving the problem of the model deformation.



Model deformation are not a special problem of digital cameras, also models based on analog cameras are influenced by it. Figure 12a shows the systematic image errors of a RMK TOP 15, used in the test area Frederiksstad and figure 12b shows the corresponding model deformation for the image scale 1:10600, corresponding to 1620m flying height above ground. The model deformation of normal angle cameras is twice as large for the same image scale. The systematic image errors of the RMK TOP 15 in Frederiksstad are moderate; more old cameras may show larger values.

CONCLUSION

The high accuracy potential of digital aerial frame cameras has been confirmed with standard deviations of unit weight sigma0 in the range of 0.15pixels for the Intergraph DMC and 0.25pixels for the Vexcel UltraCamD. For check points standard deviations for X and Y of 0.25 GSD with the DMC and 0.33 GSD with the UltraCamD have been reached under operational conditions. Not negligible systematic image errors are present. Even if this

does not agree with the investigated remaining systematic image effects, at independent check points nearly the same accuracy has been achieved by bundle block adjustment with self calibration just with the basic set of additional parameters. The camera specific additional parameters for the DMC and the UltraCamD reduce the remaining systematic image errors, but have only a very limited advantage for the accuracy achieved with check points. For the DMC the special additional parameter covering the effect of the offset of the sub-camera projection centers was not required, showing that this effect does not exist. In general all handled blocks show a typical DMC respectively UltraCamD type of systematic image errors. The reported results are not just based on the listed blocks; it is confirmed by more blocks. The high accuracy potential of the digital frame cameras and the more stable systematic image errors allow a larger distance of the control points for block adjustments with original digital images like for digitized analog photos. For the highest accuracy requirement the control point distance within the flight lines can be extended from 4 base length to 8 base length in relation to 60% end lap.

The systematic image errors are causing not negligible model deformations in the vertical coordinate component. The influence to X and Y are negligible for the DMC and tolerable small for the UltraCamD caused by the more local character of the systematic image errors for the UltraCamD. Since most commercial photogrammetric workstations are not able to respect systematic image errors, digital elevation models based on automatic image matching have to be improved a posterior by the effect of the systematic image errors like with the Hannover program DEMCOR. Of course a quite better and more flexible solution would be the on-line use of systematic image errors in photogrammetric work stations. Also a program for the geometric change of the images based on the systematic image errors has been created solving the problems in the photogrammetric workstations.

It has to be mentioned, that Intergraph and Vexcel made some modifications at the software for the generation of the virtual images to reduce the systematic image errors. The used data are processed with the more old versions. Also analog images are influenced by systematic image errors, causing model deformations. Such model deformations are usually ignored. The existence of model deformation is not a new thing just connected with the digital cameras.

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REFERENCES

- Baz, I., Jacobsen, K., Büyüksalih, G.: Analysis of a bundle block adjustment with UltraCam_D images over Istanbul, Turkish-German Geodetic Days, Berlin 2006 + http://www.ipi.uni-hannover.de/ (publication, 2006)
- Dörstel, C., Jacobsen, K., Stallmann, D.: DMC Photogrammetric Accuracy Calibration Aspects and Generation of Synthetic DMC Images, Optical 3-D Measurement Techniques, Zürich Sept. 2003 in: Grün A., Kahmen H. (Eds.), Optical 3-D Measurement Techniques VI, Vol. I, Institute for Geodesy and Photogrammetry, ETH Zürich, 74-82 + http://www.ipi.uni-hannover.de/ (publication, 2003)
- Kornus, W., Alamús, R., Talaya, J, 2006: Tests and performance analysis of the DMC at the Cartographic Institute of Catalonia (ICC), EuroCOW 2006, EuroSDR Commission I, ISPRS Working Group I/3, Castelldefels

Jacobsen, K.: Selection of Additional Parameters by Program, ISPRS Com III Helsinki 1982, Int. Archives of Photogrammetry and Remote Sensing, Vol 24-3, 266 - 275

Leberl, F., Perko, M., Gruber, M., Ponticelli, M., 2002: Novel Concepts for Aerial Digital cameras, ISPRS Com I, Denver 2002, ISPRS Archive Vol. 34 Part 1

Oswald, H. C.: Potential digitaler photogrammetrischer Luftbildkameras, Diploma thesis, University of Hannover, 2006