DEVELOPMENT OF DIGITAL AERIAL CAMERAS

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Commission I, WG I/4

KEY WORDS: digital aerial cameras, block adjustment, development of CCDs, geometric performance

ABSTRACT

Digital aerial cameras have replaced analogue aerial cameras in several countries. The development for operational aerial photogrammetry started with the line scan camera ADS40, followed by Z/I Imaging DMC and Vexcel Imaging UltraCam. Recently the line scan camera Jena Optronik JAS-150 was introduced. The capacity of the UltraCam was enlarged by replacing the used CCDs with 9µm pixels over 7.2µm to 6µm for the UltraCamXp, having 196 Mpix. The DMC and the UltraCam are system cameras, reaching the large number of pixels by a combination of 4, respectively 9 CCDs. Even if the large format line scan cameras have demonstrated their geometric potential, the major replacement of analogue cameras came by the digital large frame cameras, while the line scan cameras found their major field with orthoimages.
In the meantime digital mid-format cameras, equipped with a single CCD-array, with approximately 39 Mpix took also a share by the replacement of the analogue aerial cameras. Their combination with GPS and inertial measurement units (IMU) compensates partially the disadvantage of handling a high number of images. The mid-format cameras are equipped with Bayer pattern, limited to 3 spectral bands opposite to the 4 spectral bands offered by the large format frame and line scan cameras. This changed by the introduction of mid-format system cameras RMK D from Z/I Imaging and UltraCamL from Vexcel Imaging. In addition now camera systems equipped with 4 mid-format cameras as the IGI Quattro DigiCAM and the Trimble Aerial Camera (TAC) (former Rolleimetric) AIC-x4 are available. These cameras are not offering homogenous virtual images as the DMC and UltraCam.
Just recently a new situation came with the development of large format monolithic CCDs by DALSA. Based on this Z/I Imaging introduced now the DMC II 140, having 11712 x 11200 pixels on one CCD with 2 sec frame rate. In the fall the DMC II 230 (230 Mpix) and in the spring 2011 the DMC II 250 with 17216 x 14656 pixels with 1.7 sec frame rate will follow. This corresponds to the dream of photogrammetrists replacing the film just by one CCD.
The geometric performance of the large format digital cameras and the mid-format camera TAC and Quattro DigiCAM have been analyzed in a test of the German Society of Photogrammetry and Remote Sensing (DGPF), showing an advantage of the large format digital cameras against scanned analog photos. The monolithic DMC II 140 was analyzed separately, demonstrating an excellent geometric performance better as other cameras before.

1. INTRODUCTION

The discussion if digital or analog aerial cameras should be used came to an end. The advantage of digital cameras is so obvious, that in several countries new analog aerial photos are not anymore accepted. In addition the production of analogue aerial cameras came to an end. Nevertheless there is a lack of knowledge about the geometric and radiometric property of digital cameras. The old relation of the image scale to the map scale cannot be transferred to digital cameras. For digital cameras the image scale is not important, only the ground sampling distance (GSD) - the distance of one projected pixel center to the neighbored on the ground – is important because of varying pixel size. In fact not only the GSD is important, the effective GSD should be used, which takes the different quality of digital images into account. In addition for the handling of digital cameras the selected f-stop is important because the image quality also may degrade with growing f-stop (smaller diameter of the diaphragm) if the diffraction limited resolution is not respected.

2. NUMBER OF PIXELS IN RELATION TO PHOTO

It is the question, how many pixels are required for the information contents included in a 230 mm x 230 mm film. The first simple estimations were based on the operational resolution of 40 line pairs per mm and that one line pair should be presented by 2 pixels, leading to 18 400² pixels. Very fast it was recognized that this was not the correct manner for the comparison of the information contents because of the quite better contrast and lower noise of digital images. A comparison of details which could be extracted for topographic mapping from DMC, UltraCam and ADS40 images as well as scanned aerial photos having different ground sampling distance (GSD), was leading to the result, that just 8520² pixels are required for the information contents of scanned aerial photos in relation to digital images (Jacobsen 2009a)
Not only the numerical size of the GSD should be used, the effective ground resolution is required. This may be affected by the lens quality, diffraction limited resolution (fig. 1), but also the atmosphere. The influence of the atmosphere may be reduced by a filter because the haze depends upon the wavelength. The diffraction limited resolution (Jacobsen 2009b) is caused by the wave nature of the light, leading to a reduced

resolution (modulation transfer function (MTF)) if the diaphragm is getting too small. The diameter of an infinitive small object point is getting in the image a shape of a circle, the so called airy, with a diameter corresponding to table 1.

f-number	λ=0.55µm (green)	λ=0.65µm (red)
5.6	3.1 µm	3.7 µm
8	4.5 µm	5.3 µm
11	6.1 µm	7.2 µm
16	8.9 µm	10.5 µm
22	12.2 µm	14.4 µm

Table 1: diffraction limited resolution for f=100mm up to f=120mm

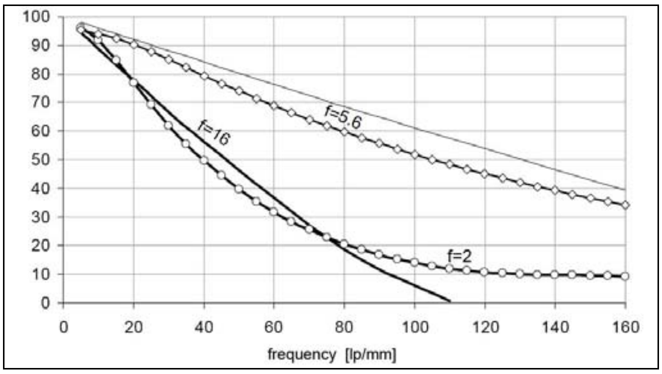

Fig. 1: effect of the diffraction limited resolution to the MTF (Nasse, H.H. 2009), vertical direction = modulation

camera	Sun elevation	Image type	Factor for effective pixel size
DMC	43°	pan	0.92
UltraCamD	27°	pan-sharpened	1.16
UltraCamX	27°	pan-sharpened	1.23
UltraCamX centre	27°	panchromatic	1.03
UltraCamX corner	27°	panchromatic	1.24
RC30	46°	RGB colour	1.43
ADS40	46°	pan forward 2°	0.99
ADS40	46°	pan after 14°	0.95
ADS40	46°	pan forward 27°	1.11

Table 2: factor for effective pixel size, test area Franklin Mills - corresponding to information contents (Passini, Jacobsen 2008)

The factor for effective pixel size, determined by edge analysis with the point spread function, has to be multiplied with the nominal GSD to get the effective GSD. An extreme case of reduced image quality was found at a small digital camera having 1.9µm pixel size. Here the diaphragm limited resolution caused a factor for the effective pixel size of 2.2, corresponding to an effective pixel size of 1.9µm x 2.2 = 4.2µm.

3. DIGITAL CAMERAS USED IN PHOTOGRAMMETRY

Digital cameras usable for photogrammetric purposes must have a well defined and stable inner orientation, this requires a fixed focus. Beside the well established large format system cameras and line san cameras, also more and more mid-format cameras are in use. In addition these mid-format cameras partially can be arranged as a group of 2 up to 5 sub-cameras. As a new development the Z/I Imaging DMC II 140 has been released, operating the high resolution panchromatic band just with one very large CCD-array. In the fall 2010 the DMC II 230 and in spring 2011 the DMC II 250 will follow.

camera	pixels	pixel size	f [mm]	frame rate	Pan / MS
DMC	7680 13824	12µm	120	2.1sec	4.6:1
UltraCamD	7500 11500	9.0µm	100	1sec	2.9:1
UltraCamX	9420 11310	7.2µm	100	1.6sec	2.9:1
UltraCamXp	14430 17310	6.0µm	100	2sec	3.0:1
UltraCamXpW	14430 17310	6.0µm	70	2sec	3.0:1
ADS80	12000	6.5µm	62	~1000 lines/sec	1:1
JAS 150S	12000	6.5µm	150	800 l/s	1:1
DMC II 140	11200 12096	7.2µm	92	2 sec	2.0:1
DMC II 230	14400 15104	5.6µm	92	1.7sec	2.5:1
DMC II 250	14656 17216	5.6µm	110	1.7sec	3.2:1

Table 3: large format digital cameras

camera	pixels	pixel size	f [mm]	frame rate	Pan / MS
RMK D	5800 6500	6µm	45	1sec	1:1
UltraCam L	9735 6588	7.2µm	70	2.5sec	1.8:1
DigiCam	7216 5412	6.8µm	82	1.9sec	Bayer pattern
Trimble Aerial C.	7160 5420	6.8µm	80	2.0sec	Bayer pattern
DIMAC	7216 5412	6.8µm	55 - 120	1.9sec	Bayer pattern

Table 4: mid format digital cameras

The large format and the mid format cameras RMK D and UltraCamL are system cameras with color sub-cameras or color CCD-lines separate to the panchromatic information. This enables blue, green, red and infrared channels in the same camera, while standard mid-format cameras are equipped with Bayer pattern. In Bayer pattern 50% of the pixels are sensible to green and 25% to blue and red, or shifted to the configuration green, red and near infrared. If all 4 color channels are required, a combination of 2 cameras equipped with Bayer pattern has to be used. There are several standard mid-format digital cameras on the market, most of them equipped with the Kodak CCD having 7216 x 5416 pixels and Bayer pattern. The focal length – also of the DigiCam and the Trimble Aerial Camera (former Rolleimetric) is not fixed, there is a selection of different optics available. The DigiCam is also available as Quattro DigiCam as well as the Trimble Aerial Camera as a combination of 4 slightly convergent sub-cameras, corresponding to the DMC, but not with such a rigorous mount.

In Unmanned Aerial Vehicles (UAV) also very small format digital cameras are in use as the camera for the 1.1kg UAV Personal Mapping System (PAMS) from BLOM equipped with a CCD of 5.7mm x 4.3mm, a focal length of 5.9mm and a pixel size of 1.9µm. Of course with such small pixels the image quality cannot be optimal as mentioned above.

4. GEOMETRIC POTENTIAL

4.1 Test of the DGPF

The geometry of digital cameras has been analyzed and compared by Passini and Jacobsen (2008) and the German Society of Photogrammetry, Remote Sensing and Geoinformation (DGPF) (Jacobsen et al 2010). The results of both tests agree to each other, why only the latest test results are shown. This test of the DGPF includes following airborne cameras: as reference the analog RMK Top 15, the large format frame cameras Z/I Imaging DMC, Vexcel Imaging UltraCamX, 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 (now Trimble Aerial Camera) and the combination of four mid-format cameras Quattro-DigiCAM. The presented results 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. Here only the results based just on control points, without direct sensor orientation is shown.

The block adjustments for the geometric tests are based on tie points determined by automatic aerial triangulation. Nevertheless the control and check points have to be measured manually in the images. The precision of the manual measurements of course depends on the human operators, but also on the image quality. The point identification in the digitized analogue images of the RMK, especially with 20cm GSD, is quite more difficult as with other images, which reflects the lower radiometric quality of scanned analogue images compared to digital imaging..

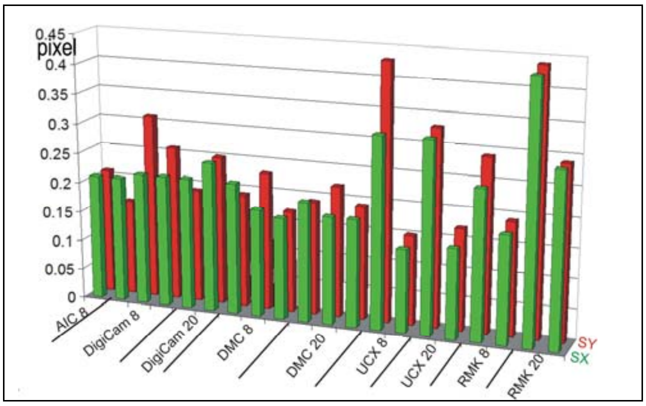

Fig. 2: Standard deviation of manual control and check point measurements [pixels] computed by differences of independent measurements (the number following the camera names indicates the GSD).

The image geometry can be determined by bundle block adjustment with self calibration by additional parameters. The systematic image errors, will show only the geometric effects which can be expressed by the used set of additional parameters, by this reason also the residuals of the bundle block adjustment have to be analyzed. If all residuals – the remaining image coordinate discrepancies – are overlaid corresponding to their image position and averaged in image sub-areas, this indicates the systematic image errors which have not been covered by the used additional parameters.

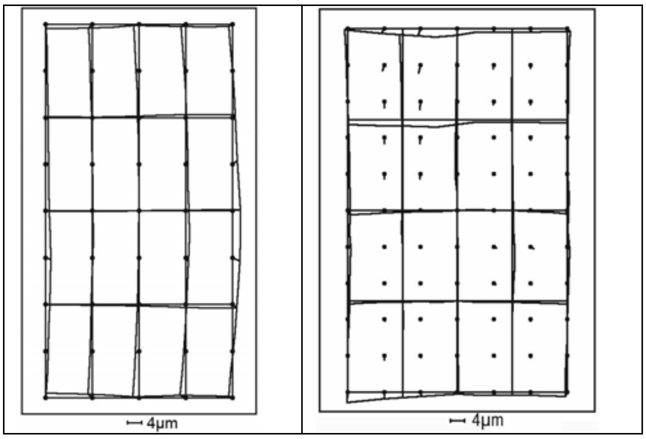

Fig. 3: systematic image errors, blocks with 8cm GSD
left: DMC right: UltraCamX

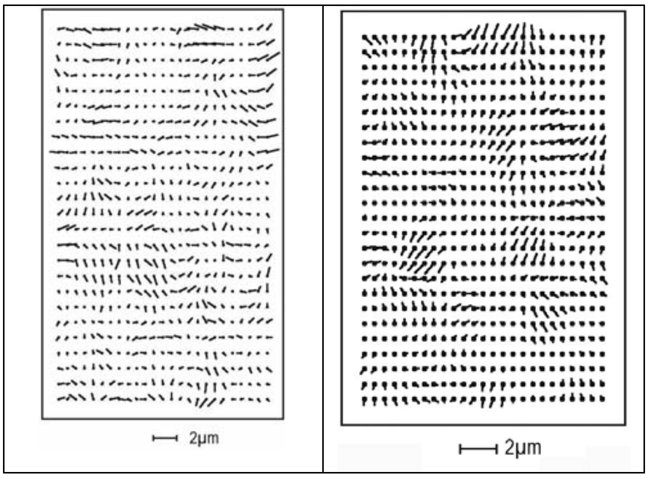

Fig. 4: remaining systematic image errors, 8cm GSD
left: DMC right: UltraCamX

The systematic image errors determined by bundle block adjustment with self calibration of the DMC and UltraCamX are small (fig. 3), especially for the UltraCamX this is different as with other datasets before. But it has to be mentioned, that the camera manufacturer got the data sets before investigation and they had the possibility to optimize the images, what is not realistic for operational handling. Also the remaining systematic image errors (fig. 4) in the root mean square are below 1µm that means, the systematic image errors have been determined in a satisfying manner by the used additional parameters.

The convergent arrangement of the 4 DMC panchromatic sub-cameras allows a three-dimensional stitching by bundle solution. The stitching of the 4 in the same plane arranged sub-cameras with in total 9 sub-images of the UltraCam is quite more complex and as recent solution by the so called “monolithic stitching” the 9 panchromatic sub-images are stitched to the homogenous geometry of the lower resolution green channel, solving some existing problems (Ladstädter et al 2010). Even if improved and more reliable, the stitching to a lower resolution reference image is not the optimal solution and is contradict to the syntopic mode because of the offset of the optics of the green channel across the flight direction. With syntopic mode the time delayed exposure of the UltraCam is named for having the same projection center for the 4 panchromatic sub-cameras, which are arranged in flight direction. But in reality the offset of the projection centers from the synthetic projection center never plaid a remarkable role. Reverse it happened with the syntopic mode that under rough flight conditions the stitching failed and a re-flight was required.

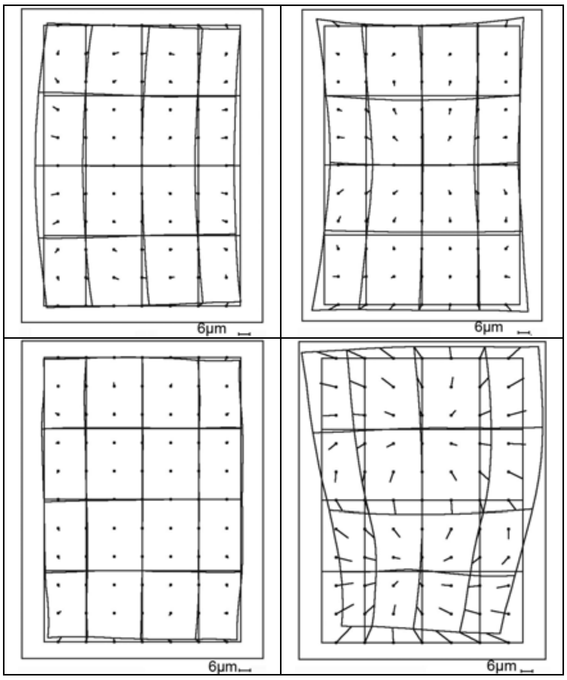

Fig. 5: systematic image errors of Quattro DigiCam sub-cameras

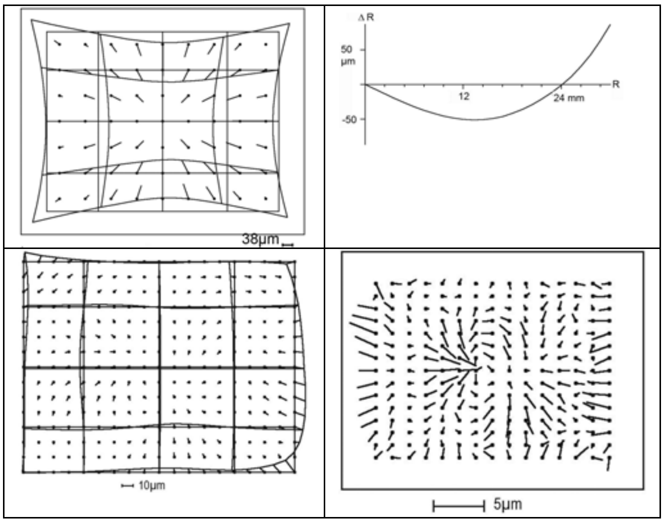

Fig. 6: Trimble Aerial Camera (Rolleimetric) f=47mm
Upper left: systematic image errors, upper right: radial symmetric distortion, lower left: systematic image errors without influence of radial symmetric distortion, lower right: remaining systematic image errors (RMS=3.1µm)

As expected the systematic image errors of the mid-format cameras IGI DigiCam and Trimble Aerial Camera are larger as for the large format cameras. Especially the 47mm optics of the Trimble Aerial Camera has a very large radial symmetric distortion with up to 98µm in the image corner (fig. 6), but the correction by radial symmetric lens distortion is standard and not causing problems. More difficult are the distortions after respecting the radial symmetric component, here the DigiCam and the Trimble Camera are reaching values up to 10µm and this has to be respected in the model handling. So a software package for the model handling, able to respect systematic image errors is required. Only for ortho images such a distortion is not important. In addition the not respected systematic image errors (fig. 6, lower right) for the handled mid-format cameras are in the range of 2µm up to 3µm in the root mean square, reducing the accuracy potential.

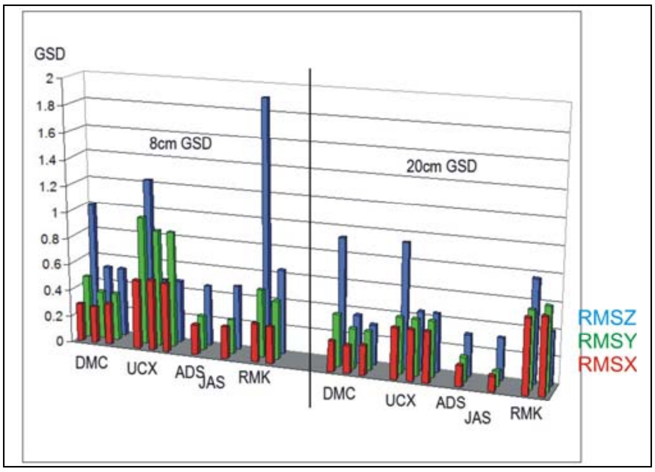

Fig. 7: overview over root mean square differences at check points [GSD] left columns: without self calibration (not ADS40 and JAS150s), center columns: additional parameters 1-12, right columns: additional parameters 1-12 + camera specific parameters (only DMC and UCX)

The data acquisition for bundle block adjustment is based on different teams; in addition the flight conditions for the different cameras have been different making a direct comparison of the data sets difficult. Only trends can be determined by the analysis. The object point accuracy by bundle block adjustment, computed with independent check points, shown in fig. 7, is based on 8 to 9 ground control points. Only the results of the ADS40 and the JAS 150s are supported by direct sensor orientation (GPS-coordinates of the projection centers and attitude information from IMU). Of course the results achieved with the digital and analog frame cameras can be supported also by direct sensor orientation – especially the use of the GPS-projection centers improves the ground coordinates (Jacobsen et al 2010), but the block size is limited and the blocks have at least 60% side lap and crossing flight lines, so the advantage of direct sensor orientation in this case is small and so the camera geometry can be compared in a better manner.

It is obvious that self calibration is required especially for the vertical component. For the ADS40 and the JAS150s only the results of block adjustment with self calibration are shown. For the analog RMK Top 15 no camera specific parameters exist. The advantage of the camera specific additional parameters for the DMC and the UltraCamX are limited.

The images of the UltraCamX, opposite to DMC and RMK, have 80% end lap instead of 60%, but this does not show any advantage for the achieved accuracy at check points. The over all result of the object point coordinates determined with the scanned analog photos of the RMK is on a lower level as for the digital cameras, confirming some earlier comparisons (Passini, Jacobsen 2008). The geometric quality of the line scan cameras ADS40 and JAS150s is very good, the standard deviation for the height is on the same level as for the DMC, in X and Y even a little better.

The mid format cameras are not included in figure 7. The images taken by the Quattro DigiCam system have also 60% end and 60% side lap, supported by 2 crossing flight lines, but no stitched synthetic perspective images as with the DMC and UltraCamX have been available. If no joint projection center of the image configuration taken at the same instant and/or no direct sensor orientation are used in the block adjustment, the geometric configuration of this camera configuration corresponds to a block with 20% side lap, requiring a high number of control points. In general the object point accuracy achieved with the DigiCam is slightly below the accuracy achieved with the RMK Top 15. The photo flight for the Trimble Aerial Camera (TAC) was influenced by poor weather conditions, so only images with 8cm GSD, not supported by crossing flight lines, having in the average 60% end and 60% side lap have been taken. In addition the photo flight was made with a small and unstable aircraft, causing a variation of the roll angle up to 7° in both directions, leading partially to poor side lap. So a high number of control points are required. The reached root mean square differences at check points in X and Y is in the range of 0.5 GSD for the Z-component in the range of 1.3 GSD.

4.2 DMC II 140

The new developed DMC II 140 with one large CCD-array of 11200 x 12096 panchromatic pixels was investigated over the test field Aalen, Germany with 5cm, 9cm and 20cm GSD with flights of 60% end and 60% side lap together with crossing flight lines with same overlap. The DMC II 140 has the advantage of not requiring a stitching of sub-camera images.

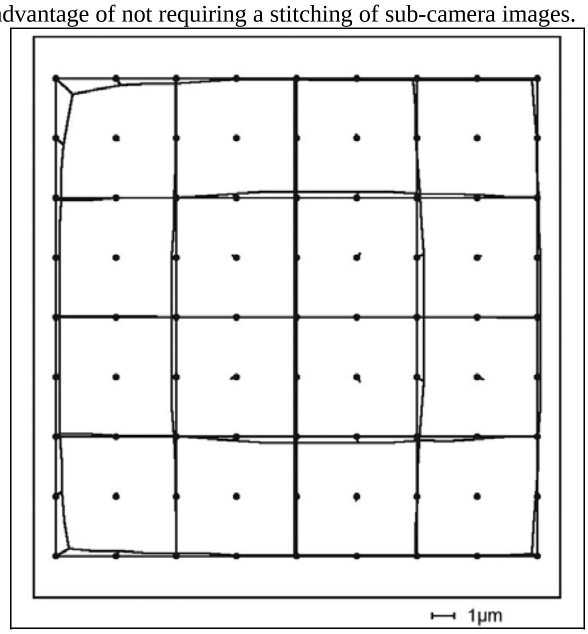

Fig. 8: systematic image errors of the DMC II 140 (9cm GSD)

The monolithic CCD has a size of 80.6mm x 87.1mm. The sigma0 of the bundle block adjustment is below 1 μm and the remaining systematic image errors, determined by the residuals, are clearly below 0.5μm. In the image corner the view direction is 32.8°, requiring a flatness or knowledge of the flatness of the CCD below 1μm. This is nearly impossible, but it can be determined and respected by the camera calibration used during the image generation process. For the user this is not visible and only improved images are generated. Standard mid-format and even small format CCDs are not guaranteeing a satisfying flatness, requiring for the determination of the influence to the image corners special additional parameters as 81 up to 88 of program system BLUH (Jacobsen et al 2010). The systematic image errors of the DMC II 140, shown in fig. 8 with the example of the block with 9cm GSD, astonish small. Only a radial symmetric component, slightly changing with the flying height, but not exceeding 2 μm in the extreme case, exist. The root mean square of systematic image errors is 0.2μm, 0.3μm respectively 0.6μm for the three different ground resolutions and 0.1μm, 0.1μm respectively 0.2μm without the effect of the radial symmetric component. Such a small value of systematic image errors is absolutely remarkable. The remaining systematic image errors are in the rot mean square 0.14μm, 0.17μm respectively 0.25μm for the three different flying elevations, indicating that there is no effect not covered by self calibration.

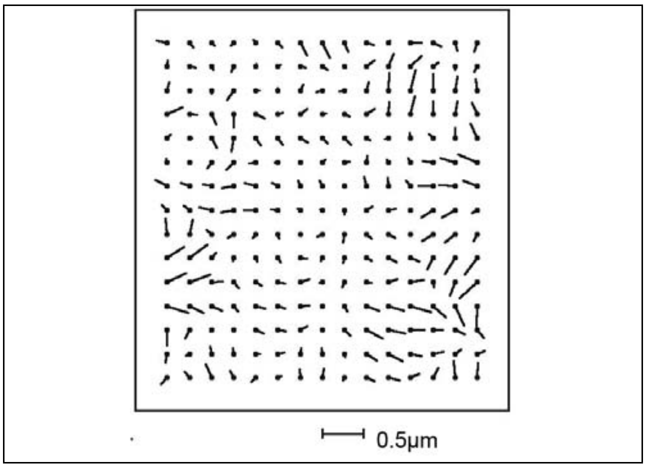

Fig. 9: remaining systematic image errors for DMC II 140, 20cm GSD

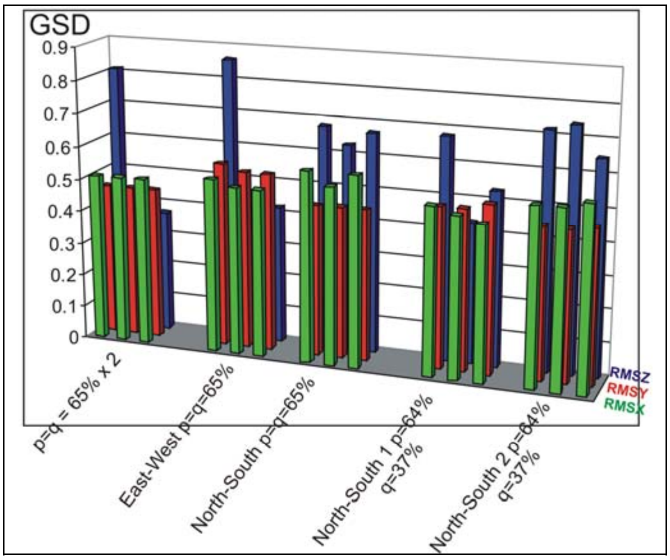

Fig. 10: Bundle block adjustments with 5.7cm GSD, root mean square differences at check points, left columns: without

additional parameters, center column: additional parameters 1 – 12, right hand column, additional parameters 1 – 12, 81 – 88

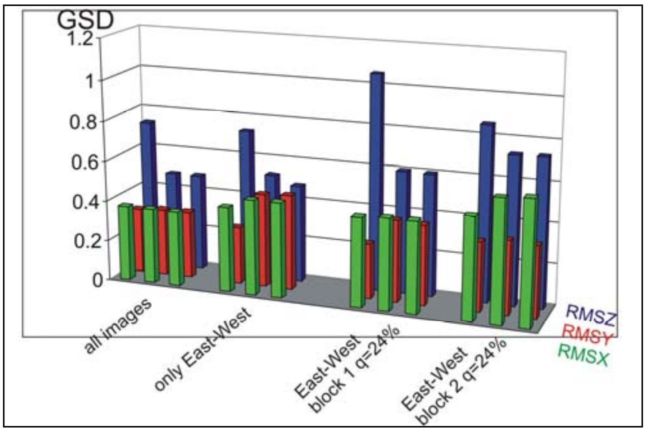

Fig. 11: Bundle block adjustments with 9.5cm GSD, root mean square differences at check points, left columns: without additional parameters, center column: additional parameters 1 – 12, right hand column, additional parameters 1 – 12, 81 - 88

Bundle block adjustments using the Hannover program system BLUH with 6 to 8 GCPs have been made with all block configurations. Depending upon the data set of the test field Aalen between 48 and 19 check points could be used for the quality check. For being more realistic, also blocks only with flight lines in one direction (double blocks) and blocks only with flight lines in one direction and 24% up to 37% side lap (single blocks) have been handled. The bundle block adjustments of the test blocks flown with the DMC II 140 with 5.7cm, 9.5cm and 20.2cm GSD show very good results, but some limitations are caused by the test field. The a priori standard deviation of the control and check point coordinate components are in the range of 2cm up to 3cm and this is the accuracy achieved for the X- and Y-coordinates of the flight with 5.7cm GSD. It is explaining why for this resolution the number of images used for the block adjustments do not have any influence to the X- and Y-component (fig. 10). As usual, the vertical accuracy is below the horizontal, by this reason the influence of the self calibration and the number of used images can be seen for the height values of the 5.7cm-GSD-blocks and the blocks with 9.5cm GSD. There is no advantage of the special additional parameters for improving the image corners and the reached accuracy can be achieved just with the radial symmetric additional parameters.

The 9cm-GSD-block shows more clear the dependencies of the root mean square discrepancies at independent check points (fig. 11). The self calibration, at least with the radial symmetric parameters, is required for the height, but because of the very small systematic image errors it has no influence to the horizontal components. Of course the results achieved with all images are better as with just a subset of images, but as usual for blocks with changing control point combinations, it is not exactly as corresponding to simple theory.

The ground resolution of 20cm is too large for the available targets in the test area Aalen, causing problems of exact point identification and a reduction of the accuracy in relation to the GSD. By this reason the accuracy achieved with the 20cm-GSD-block cannot be used for quality estimation, nevertheless this is not influencing the analysis of the systematic image errors. By simple theory the accuracy determined at check points should be independent upon the ground resolution, but fig. 10 and 11 demonstrate the dependency of the results upon the test field itself, caused by the accuracy of the check point coordinates. A comparison of the results achieved with the DMC II 140 with the results based on the DGPF-test demonstrates that the DMC II 140 is in the highest accuracy class.

5. CONCLUSION AND OUTLOOK

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 of the DGPF-test not the same vertical accuracy has been reached as with the large format digital frame and line scan cameras. In addition the not so good image quality of scanned analogue images became obvious at the manual identification of the control and check points in images with 20cm GSD.

The large format digital frame cameras DMC and UltraCamX as well as the line scan cameras ADS40 and JAS150s confirmed their potential. Of course the limited test site does not allow a direct extrapolation to large blocks. The mid-format and system of mid-format digital cameras show larger systematic image errors, what can be handled with the used updated set of additional parameters, but requires also their use during model handling.

The advantage of a single monolithic CCD of the DMC II 140 to the image geometry is obvious. With the exception of very small radial symmetric image errors, slightly changing with the flying height, the systematic image errors are negligible and quite smaller as shown by other cameras before. Together with the high image quality this leads to a very good accuracy level of the block adjustments. With the announced DMC II 230 and DMC II 250 more economic solutions for digital aerial photogrammetry will come.

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