# – MODEL DEFORMATION – ACCURACY OF DIGITAL FRAME CAMERAS

V. Spreckels [a], A. Schlienkamp [a], K. Jacobsen [b]

[a] Deutsche Steinkohle AG (DSK), Dept. Geoinformation/Engineering Survey BG G, Shamrockring 1, D-44623 Herne, Germany - (volker.spreckels, andreas.schlienkamp)@dsk.de
[b] Inst. of Photogrammetry and GeoInformation, Leibniz University Hannover, Nienburger Str. 1, D-30167 Hannover, Germany - jacobsen@ipi.uni-hannover.de

**KEY WORDS:** digital aerial cameras, geometry, model deformation, stereo plotting

**ABSTRACT:**

Due to legal restrictions, the German hard coal mining company Deutsche Steinkohle AG (DSK) is obliged to conduct a monitoring on surface changes (subsidence) caused by mining activity (e.g. topographic surface, groundwater, water, flora and fauna, soil). To fulfill legal demands and to do this effectively, process chains by use of Photogrammetry, Remote Sensing and Geo Information Systems (GIS) have been established. Photogrammetric methods are used to generate high resolution Digital Elevation Models (DEM) from which in combination with subsidence data geometric changes at the topographic surface are deduced. For mine site areas from about 100 km² to 200 km² DEMs have to be handled on digital photogrammetric stereo workstations with a height standard deviation of ±10cm. This accuracy up to now could be obtained with analogue wide angle cameras at an image scale of 1:4000 and 80% end lap together with a high number of ground control points (GCP).

More and more digital aerial frame cameras like Intergraph DMC and Vexcel UltraCamD are available for mapping application. DSK decided to order photo flights with the Vexcel UltraCamD because only this camera is able to take images at 80% end lap with a ground sampling distance (GSD) of 10cm. A vertical accuracy of about ± 8 to 9cm should be reached. Since 2004 three digital photo flights have been made for DSK with the same camera, no. 8. In December 2004 for the stereo plotting of a site plan for a coking plant, in August 2005 a test flight covering 20 km² has been made to evaluate the potential of color-infrared images for environmental monitoring purposes and in March 2006 an aerial photo flight for DEM generation of a mine site followed.

The stereo plotting showed differences in height of about 25cm for neighbored 60% stereo models based on systematic effects in the digital aerial images. DSK noticed that usual commercial digital photogrammetric workstations were not able to handle systematic image errors determined by bundle block adjustment. The model deformations were acceptable for the horizontal coordinate components, but in the height, deformations exceeded the accuracy limit. The program DEMCOR has been generated at the Institute of Photogrammetry and Geoinformation, Leibniz University Hannover, for a posteriori correction of DEM and the program IMGEO for the resampling of the images for accurate stereo-measurements. So the full accuracy potential can be reached.

This paper presents the comparison of UltraCamD and analogue RMK TOP 15 DEM as well as the systematic image errors of a DMC (photo flight Frederiksstad).

The photo flights have **not** been made with the now available latest versions of DMC and UltraCamD processing software. In the meantime Intergraph and Vexcel modified the cameras and the data handling. The described geometric problems still exist for analogue cameras, but they are usually ignored.

## 1. INTRODUCTION

Already in the 2004 flight campaign for the coking plant “Prosper” near the city of Bottrop, Germany (Spreckels, Schlienkamp, Syrek, 2005), DSK noticed that the stereo-measurements in neighboring models having 60% end lap did not fit very well to each other in height. For this reason the stereo plotting was mostly done in the center parts of models with 40% end lap. Due to production and project deadline constraints these effects could not clearly be checked. For the measurements of the 2006 flight campaign these effects recurred.

## 2. FLIGHT CAMPAIGN

In 2006 the flight campaign “DSK-Saar” covering 120 km² of a mine site in the German federal state Saarland was performed using the UltraCamD camera no. 8. The flight took place at two days in March 2006 with 80% end lap and 35% side lap. The image orientation was recorded using dGPS-IMU. In total 31 flight strips with 2.800 images were flown with a ground sampling distance of 8cm to 11cm, depending on the flying height above ground in this low mountainous range area.

As ground reference 185 ground control points (GCP) were signalized (fig. 1) and measured by dGPS with an accuracy of better than ± 3cm in position and height. The requirements for the accuracy of the resulting DEM are ± 10cm.

## 3. DATA PREPARATION

DSK processed the images with Vexcel OPC-2.3.1 and performed the aerotriangulation (AT), DEM matching, DEM measurements and the stereo plotting of DEM-relevant break lines.

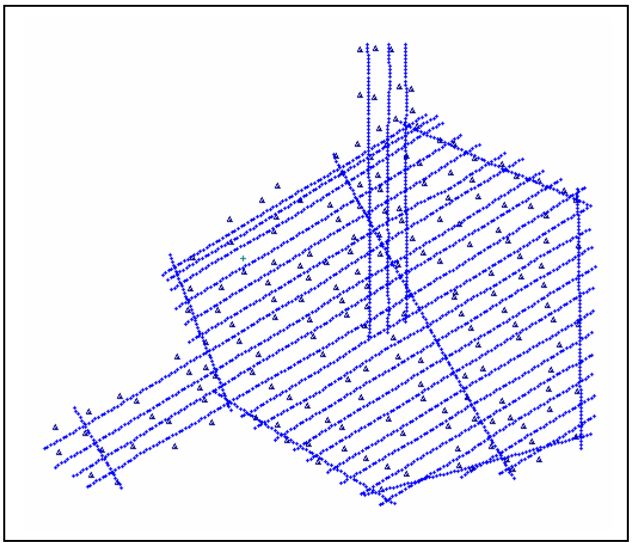

Figure 1: UltraCamD flight campaign “DSK-Saar”, 2006: configuration of projection centers and ground control points

Even terrestrial measurements for slopes and ditches were imported. The photogrammetric stereo-measurements showed differences between the models up to 25cm in height for neighbored models with 60% end lap and to terrestrial reference. Like in 2004, the differences in the center parts of 40% end lap models were within the required limit for height. Due to production and project deadline constraints the stereo plotting was completely performed in the center parts of 40% end lap models.

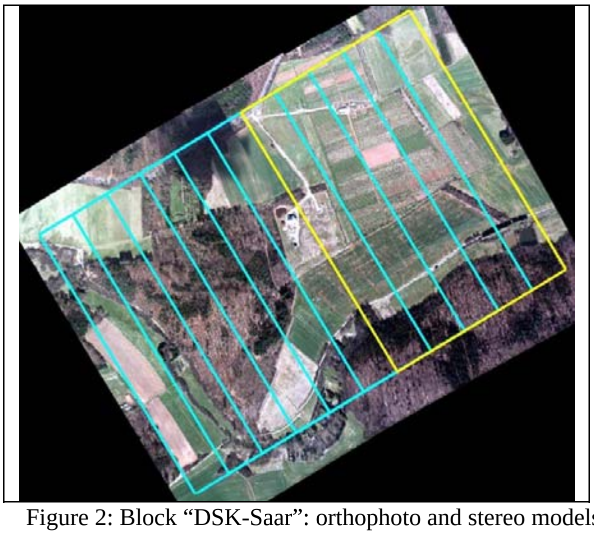

Figure 2: Block “DSK-Saar”: orthophoto and stereo models with 80% end lap

With hindsight DSK deepened the DEM control of the image data. For this project flown with 80% end lap it was possible to calculate two DEMs from 60% models covering the same area - one DEM with the even and one with the odd image numbers (fig. 2).

One year before, in March 2005, a shaft of the DSK-Saar mine site was flown using an analogue camera (RMK TOP 15) with a single flight strip, 80% end lap and at an image scale of 1:4000 (fig 3).

Figure 3: Orthophoto “DSK-Shaft”, analogue flight 2005

## 4. DEM COMPARISON

The UltraCamD DEMs could be compared to each other and to the DEM from analogue photos having the same theoretical height accuracy (fig. 4).

The comparison of these DEMs resulted in height differences up to ± 30cm, three times more than the expected ± 8cm to ± 9cm.

The DEM matching was performed based on orientation computed with and without IMU data. The results showed that this influence is negligible.

The aerotriangulation used for the image orientation as base for the DEM has been inspected. A sigma0 of 2.6µm has been reached. The distributor of the aerotriangulation-software was confronted with the results and the DEM differences and performed an own aerotriangulation. These “final” results showed a sigma0 of 1.9µm but the systematic DEM height differences stayed and in fact raised about 10cm. Figures 5 and 6 show the differences of the DEMs based on both block adjustments for the even and the odd image number combination leading to 60% end lap. The software did not include self calibration. Due to 80% end lap of the photo flight, the GCPs could be measured in up to 36. In the average the GCPs are included in 15 images. Unfortunately no internal check for the image coordinates to the reference coordinate is performed for the resulting point coordinates and all measurements are averaged, even those within areas with large x- and y-parallax.

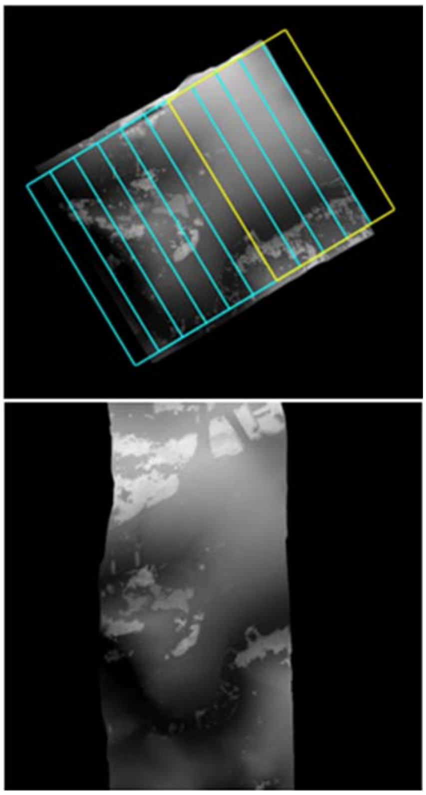

Figure 4: DEM-overview: UltraCamD DEM (upper image) and RMK TOP 15 DEM (bottom)

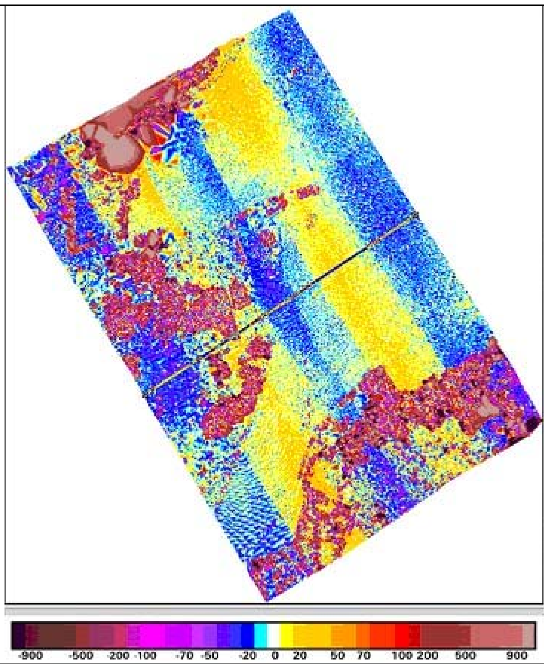


Figure 5: UltraCamD: colour coded DEM height differences [cm], of DEM based on even against DEM based on odd image numbers – of DEMs based on the block adjustment handled by DSK– block adjustments without self calibration, end lap 60%

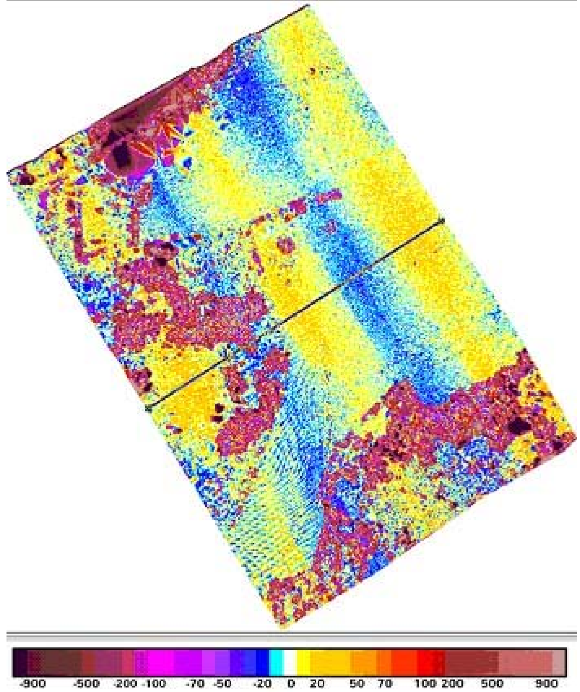


Figure 6: UltraCamD: colour coded DEM height differences [cm], of DEM based on even against DEM based on odd image numbers – of DEMs based on the block adjustment handled by the software distributor – block adjustments without self calibration, end lap 60%

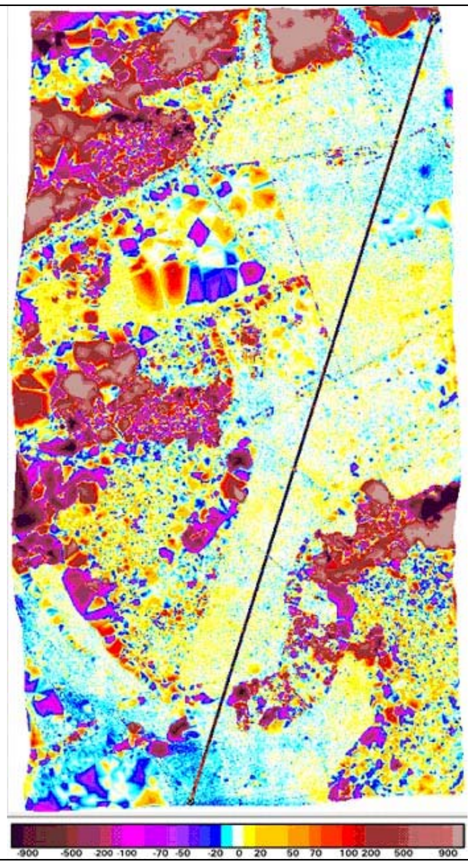


Figure 7: RMK TOP 15: colour coded height differences [cm] of DEM based on even against DEM based on odd image numbers (60% end lap)

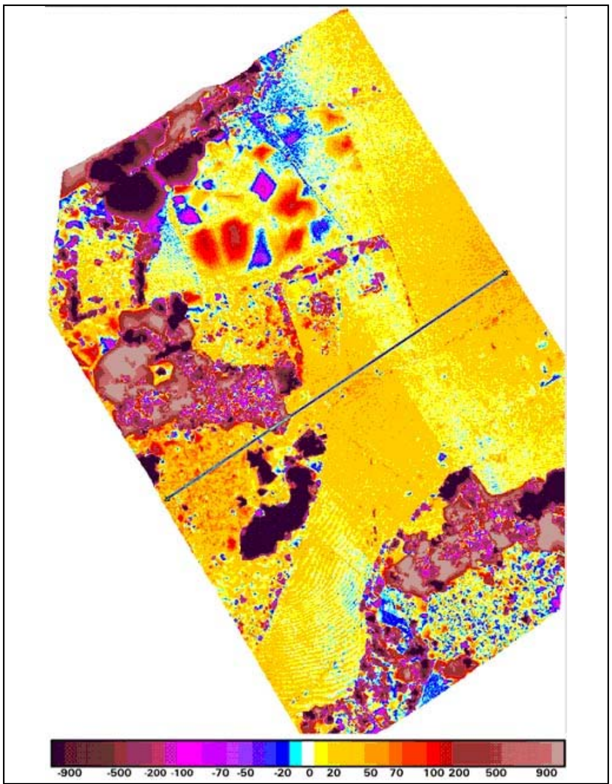

Figure 8: Colour coded height differences [cm] of DEM based on UltraCamD images against DEM from RMK TOP 15 images, both with 60% end lap

The last check was the comparison of the UltraCamD DEM with the DEM of the analogue flight 2005. To be sure that the analogue flight was not influenced by systematic height errors or an inaccurate image scanner, the DEMs from analogue photos with 60% end lap were generated for odd and even image numbers. The DEM differences were within the limit of ±10cm (fig. 7).

The comparison of the 60% end lap DEM from the UltraCamD and the analogue camera RMK TOP 15 shows - besides an offset in height of about 25cm -again the systematic effects in the DEM difference (fig. 8). It is reasonable that the source of these systematic effects has to be within the UltraCamD image data.

## 5. DETAILED ANALYSIS WITH BLUH

For an independent control of the obvious systematic effects, the bundle block adjustment has been made as next step with the Hannover program system BLUH which allows a self calibration by additional parameters.

The analysis was performed for the blocks "DSK-Saar", flown with UltraCamD and RMK TOP 15 and the EuroSDR test field "Frederiksstad", flown with UltraCamD, DMC and RMK TOP 15 (Jacobsen 2007). The EuroSDR is a European organization working in the field of Geographic Information by collaborative research of mapping organizations, universities and industry. The quality of block Frederiksstad is limited by the difficult identification of control and check points. 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 systematic image errors.

| | | | |
|---|---|---|---|
| | x, y = image coordinates normalized to max. radial distance | | |
| | $r^2 = x^2 + y^2$ | b = arctan (y/x) | |
| 1 | $x' = x - y \cdot P1$ | $y' = y - x \cdot P1$ | *angular affinity* |
| 2 | $x' = x - x \cdot P2$ | $y' = y + y \cdot P2$ | *affinity* |
| 3 | $x' = x - x \cdot \cos 2b \cdot P3$ | $y' = y - y \cdot \cos 2b \cdot P3$ | |
| 4 | $x' = x - x \cdot \sin 2b \cdot P4$ | $y' = y - y \cdot \sin 2b \cdot P4$ | |
| 5 | $x' = x - x \cdot \cos b \cdot P5$ | $y' = y - y \cdot \cos b \cdot P5$ | |
| 6 | $x' = x - x \cdot \sin b \cdot P6$ | $y' = y - y \cdot \sin b \cdot P6$ | |
| 7 | $x' = x + y \cdot r \cdot \cos b \cdot P7$ | $y' = y - x \cdot r \cdot \cos b \cdot P7$ | *tangential distortion 1* |
| 8 | $x' = x + y \cdot r \cdot \sin b \cdot P8$ | $y' = y - x \cdot r \cdot \sin b \cdot P8$ | *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 | $x' = x - x \cdot \sin(r \cdot 0.049087) \cdot P10$ <br> $y' = y - y \cdot \sin(r \cdot 0.049087) \cdot P10$ | | *radial symmetric* |
| 11 | $x' = x - x \cdot \sin(r \cdot 0.098174) \cdot P11$ <br> $y' = y - y * \sin(r \cdot 0\ 0.098174) \cdot P11$ | | *radial symmetric* |
| 12 | $x' = x - x \cdot \sin 4b \cdot P12$ | $y' = y - y \cdot \sin 4b \cdot P12$ | |
| 29 | DMC projection center offset | | |
| 30–33 | $x' = x + P32*(x^2 - 32x)$ | | *synchronization of DMC sub-images* |
| 34 | $x' = x – x*y*P34$ | $y' = y$ | *orientation error DMC X 1* |
| 35 | $x' = x$ | $y' = y – x*y*P35$ | *orientation error DMC Y 1* |
| 36–41 | corresponding to 34–35 for other sub-images | | |
| 42–49 | scale parameters for UltraCamD | | |
| 50–57 | shift X parameters for UltraCamD | | |
| 58–65 | shift Y parameters for UltraCamD | | |
| 66–73 | rotation parameters for UltraCamD | | |
| 74–77 | radial symmetric for individual DMC sub-images | | |
| 79 | butterfly shape (caused by focal length of sub cameras) | | |
| 80 | common radial symmetric parameter for all DMC sub-images together | | |

Table 1: General additional parameters (1-12) and special parameters for DMC and UltraCamD of program BLUH

### 5.1 Block "DSK-Saar", Vexcel UltraCamD

The photo flight with the Vexcel UltraCamD version 2.1.3, camera no. 8 for DSK in the Saarland did not include the improved temperature handling that 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 LPS, while the detailed analysis was made with the program system BLUH. In total 46245 object points are available with 298533 image points - or the object points in the average are given in 6.5 images. The image points are evenly distributed in the images with 130 points per image. The GCP distance is in the range of 10 base lengths for 60% end lap.

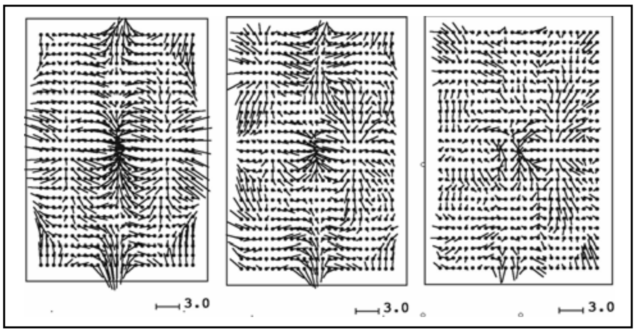


Figure 9: UltraCamD-block “DSK-Saar”, 9cm GSD, averaged residuals of block adjustment without self calibration (left), parameters 1-12 (center) and with parameters 1-12,42-73 (right)

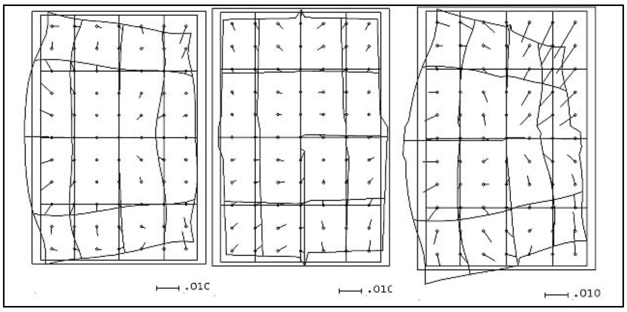


Figure 10: UltraCamD-block “DSK-Saar”: systematic image errors, additional parameters 1-12 (left), 42-73 (center), 1-12, 42-73 (right)

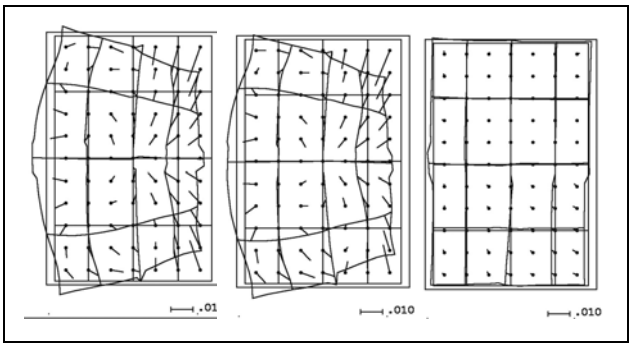


Figure 11: UltraCamD-block “DSK-Saar”: systematic image errors of flight campaign day1 (left) and day2 (center), difference of systematic image errors day1-day2 (right)

The averaged residuals (fig. 9) are indicating the shape of the systematic image errors. For the UltraCamD-data, systematic image errors only can be reduced with the general additional parameters together with the special additional parameters for the used camera. With the general additional parameters, the size of the averaged residuals is reduced, but the shape remains (fig. 9 centre). The averaged residuals for the UltraCamD are approximately 3 times larger than for the DMC (chapter 5.3) and a more detailed fine structure exists – caused by the combination of 9 sub-images to one virtual image. In addition the combination of all additional parameters does not totally eliminate the systematic effects (fig. 9, right). A block adjustment with self calibration is required.

For the UltraCamD-block “DSK-Saar” only a very limited improvement of the results at the check points is reached with the special additional UltraCamD-parameters, even if the averaged residuals (fig. 9) are indicating remaining systematic image errors for the block adjustment just with the standard additional parameters 1–12. 3.1cm at the check points are corresponding to 0.34 pixels and 5.4cm in Z to hypothetical 0.16pixels for the x-parallax.

The systematic image errors (fig. 10) of the UltraCamD are stable - at least within the block. A handling of two sets of images (both photo flight days) together in one block adjustment was leading to negligible differences of the systematic image errors between both sub-blocks (see fig. 11).

### 5.2 EuroSDR block “Frederiksstad”, UltraCamD

The EuroSDR made a test flight over the test field “Frederiksstad” with the UltraCamD no. 2. This camera did not include the improved temperature handling, too. 132 images with 80% end lap and 60% side lap, including a crossing flight line have been taken with 17cm GSD.

An automatic aerotriangulation 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 GCP distance is in the range of 5 base lengths for 60% end lap.

Like before, the averaged residuals (fig. 12), 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 (fig. 12, center). Even here small remaining systematic image errors still exist after block adjustment with the general additional parameters 1-12 together with the special UltraCamD-parameters 42-73.

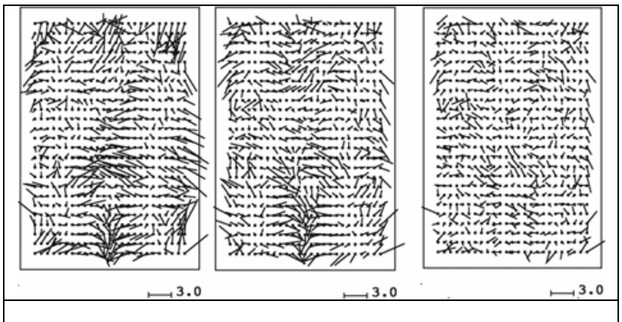


Figure 12: UltraCamD-block “Frederiksstad”, 17cm GSD, averaged residual without self calibration (left), parameters 1-12 (centre) and with parameters 1-12, 42-73 (right)

The systematic image errors (fig. 13) of block “Frederiksstad” have a little different shape like the block “DSK-Saar”, but also here a curvature on the left hand side can be recognized.

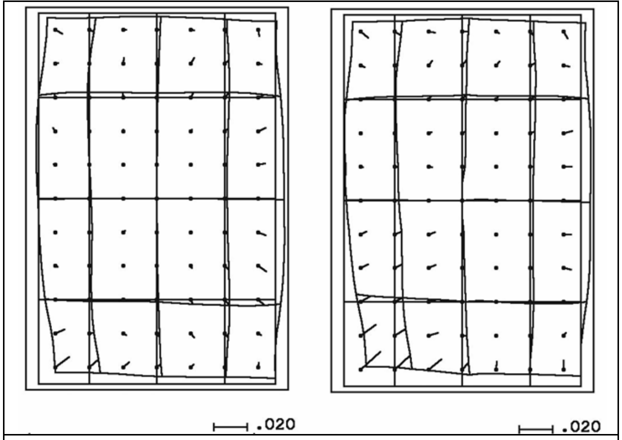


Figure 13: UltraCamD-block "Frederiksstad": systematic image errors, additional parameters 1-12 (left) and 1-12, 42-73 (right)

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

### 5.3 EuroSDR block "Frederiksstad", Intergraph DMC

The lower level flight level taken with the DMC includes 115 images with image scale 1:7666 or 9.2cm GSD. An automatic aerotriangulation with LPS generated 22134 image points and 7028 object points. The averaged residuals only can be reduced with the combination of the general BLUH-parameters 1–12 together with the special DMC parameters (fig. 14).

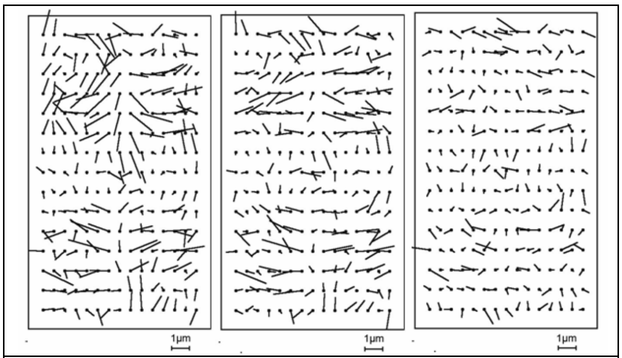


Figure 14: DMC-block "Frederiksstad", 9,2cm GSD, averaged residual without self calibration (left), parameters 1-12 (centre) and with parameters 1-12, 30-41, 74-77 (right)

As expected, the results of the DMC block Frederiksstad show that 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 (Jacobsen 2007). 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.

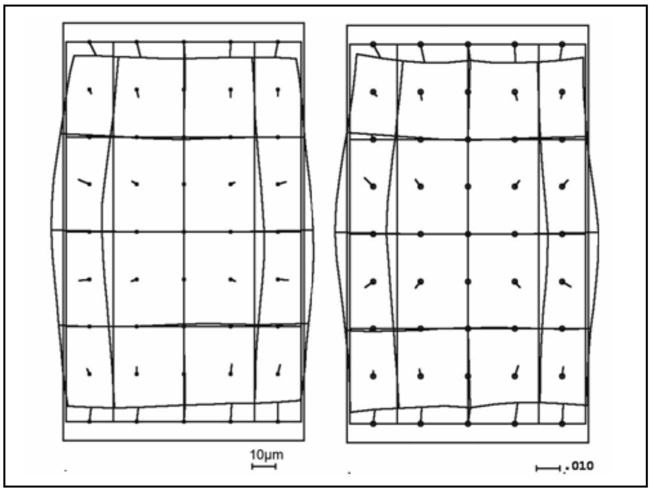


Figure 15: DMC-block "Frederiksstad": systematic image errors, additional parameters 1-12 (left) and 1-12, 30-41, 74-77 (right).

## 6. 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 the horizontal accuracy is usually not a problem. This may be different for the height, especially for digital elevation models, generated by automatic image matching.

### 6.1 Block "DSK-Saar", UltraCamD

The Vexcel UltraCamD images of the block "DSK-Saar" do clearly show not negligible systematic image errors. A bundle block adjustment with the standard additional parameters of program system BLUH, used also for analogue photos, is leading to results not far away from the optimal results - but remaining systematic components require a further improvement. Furthermore a block adjustment with the special UltraCamD-parameters alone is not sufficient; a combination of the standard additional parameters with the special UltraCamD parameters is required. With a sigma0 of 2.3µm corresponding to 0.25 pixels, the block adjustment is within the expectation. But the systematic image errors cause model deformations that are not negligible and which are exceeding the expected standard deviation. There is no change of the systematic image errors during the photo flight.

Compared to DMC in general a stronger influence of the UltraCamD image deformation to the X- and Y-coordinates and a larger difference of the results with self calibration can be seen just with the standard parameters 1-12 to the standard parameters plus the special UltraCamD parameters 42–73 (see fig. 11 and fig. 15).

The shown discrepancies are based on the points used in the block adjustment that are not evenly distributed in the models. One reason for the investigations had been problems by DSK with discrepancies in digital elevation models determined by automatic image matching of UltraCamD images.

The block “DSK-Saar” 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 stereo workstation not respecting the systematic image errors.

The comparison of the overlapping DEMs showed a structure of systematic height differences with averaged discrepancies in the range of 25cm (see fig.6).

With 9cm GSD, an 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 is due to the model deformation caused by systematic image errors that are different for 40%, 60% and for 80% end lap DEMs. It is clear that 80% DEM are not representative for height measurements but it is shown here for completeness (see fig. 16 to 18). In following the results for a similar GSD of about 9cm are regarded.

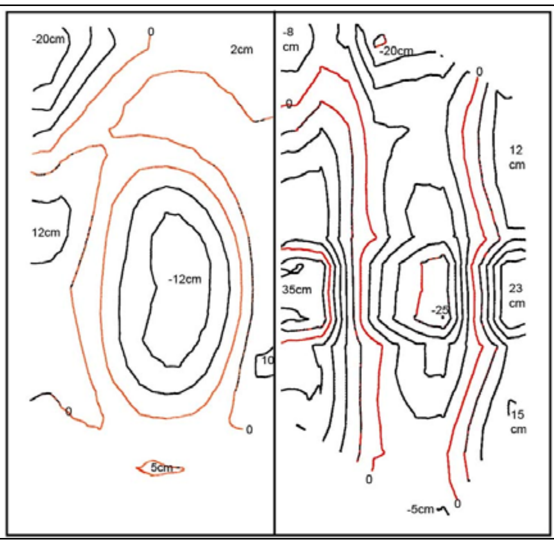


Figure 16: UltraCamD-block “DSK-Saar”: model deformation caused by systematic image errors based on additional parameters 1-12 (left) and 1-12, 42-73 (right); 9cm GSD, **end lap 66,3%,** h/b=4,4. Contour interval: 5cm

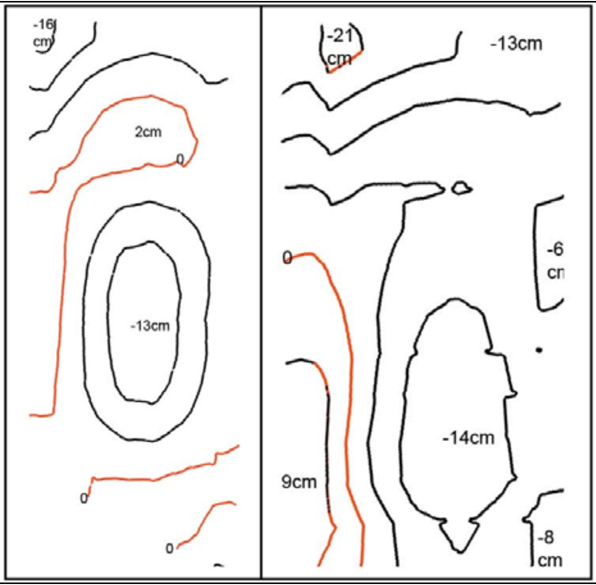


Figure 17: UltraCamD-block “DSK-Saar”: model deformation caused by systematic image errors based on additional parameters 1-12 (left) and 1-12, 42-73 (right); 9cm GSD, **end lap 49,5%**, h/b=2,9. Contour interval: 5cm

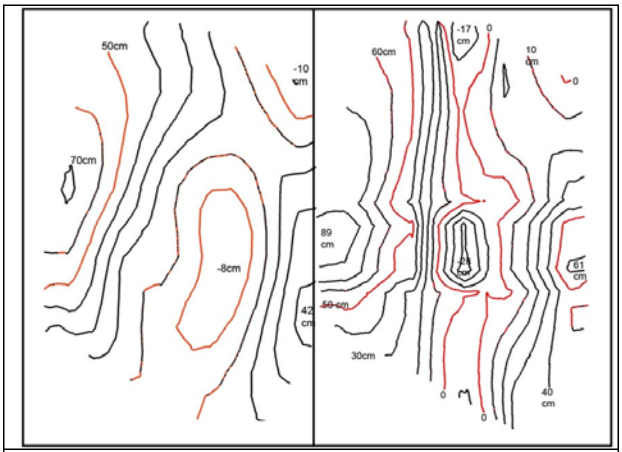


Figure 18: UltraCamD-block “DSK-Saar”: model deformation caused by systematic image errors based on additional parameters 1-12 (left) and 1-12, 42-73 (right); 9cm GSD, **end lap 84%**, h/b=9,3. Contour interval: 10cm

#### 6.2 Block “Frederiksstad”, DMC

The influence of the model deformation shown in figure 19 is not negligible in relation to the expected vertical accuracy of 8cm for the DMC-block “Frederiksstad”. Figure 19 shows the systematic image errors (left) and the corresponding model deformation for the image scale 1:7666 (right).

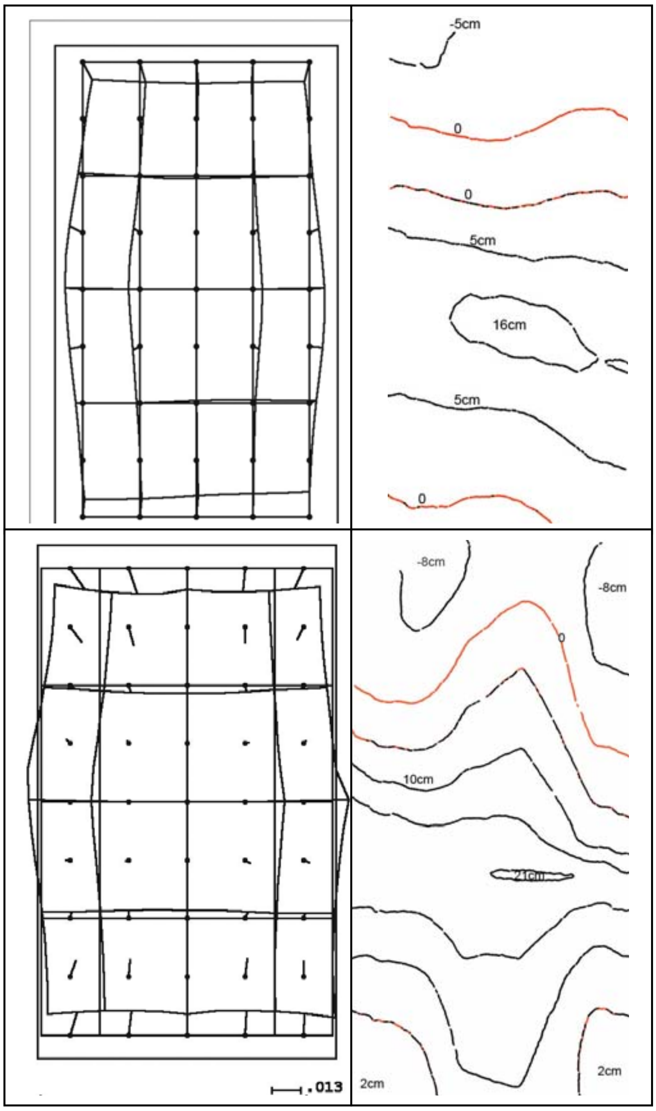


Figure 19: DMC-block “Frederiksstad”: systematic image errors and model deformation, 9,2 cm GSD, **end lap 63%**, parameters 1-12 (top), parameters 1-12, 30-41, 74-77 (bottom); 5cm-contour lines

The influence to the height is smoother for the DMC while it is more complex and local for the UltraCamD. The model deformation cannot be accepted for DEMs. 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. Commercial digital stereo workstations cannot respect the systematic image errors, so the generated object coordinates are influenced by the model deformation. These images can be rectified with the Hannover program IMGEO to images without systematic image errors.

#### 6.3 Analogue block “Frederiksstad”, RMK TOP 15

Model deformation are not a special problem of digital cameras so even models based on analogue cameras are influenced by it. Figure 20 shows the systematic image errors of a RMK TOP 15 used in the test area Frederiksstad (left). Figure 20 (right) shows the corresponding model deformation for the image scale 1:10600, corresponding to 1620m flying height above ground. A height accuracy of 9cm to 16cm was expected. 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.

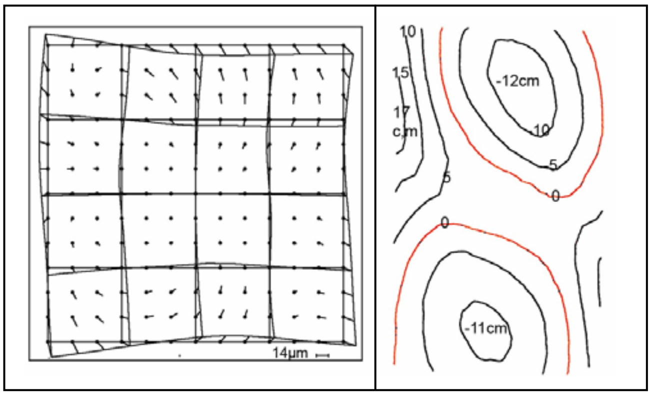


Figure 20: Analogue block “Frederiksstad”: systematic image errors (left) and model deformation (right) for analogue camera RMK TOP 15, photo scale 1:10600, **end lap 61%**, flying height above ground: 1620m

## 7. CONCLUSION

Under operational conditions the comparison of DEMs based on 60% end lap, matched with even or odd image numbers, showed not negligible systematic image errors that led to model deformations for UltraCamD and DMC images. For generation of height values in digital stereo workstations, these systematic image errors have to be corrected or respected.

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. Check point 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 parameters covering the effect of the offset of the sub-camera projection centers, was not required, showing that this has no effect.

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 in this contribution; they are still confirmed by additional blocks.

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. Even analogue images are influenced by systematic image errors, causing model deformations. These model deformations known for analogue and digital cameras are usually ignored.

Because most commercial photogrammetric stereo workstations are not able to respect systematic image errors, DEMs based on automatic image matching have to be improved a posterior by the effect of the systematic image errors, e.g. like with the Hannover program DEMCOR.

A better and more flexible solution would be the on-line use of systematic image errors in digital photogrammetric stereo workstations. For this purpose the program IMGEO for the geometric change of the images based on the systematic image errors has been created solving the problems within the stereo display of photogrammetric workstations.

Of course the best solution could be the direct correction of the recorded images within the process chain from level0 to level3 data by self calibration.

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 elder program versions.

## 8. REFERENCES

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