DMC – PHOTOGRAMMETRIC ACCURACY –

CALIBRATION ASPECTS AND GENERATION OF SYNTHETIC DMC IMAGES

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ABSTRACT

For a reasonable financial amount, today no CCD-arrays are available with an information content close to traditional photogrammetric aerial cameras. By this reason the Digital Mapping Camera DMC of Z/I Imaging is using a combination of 4 CCD-arrays, each with app. 4000 x 7000 pixels. As CCD-arrays cannot be fitted together without gaps, the 4 individual optics of a DMC camera are combined in a convergent arrangement. For easy handling, the images of the individual optics have to be arranged together to a single virtual image, corresponding to the geometry of one single perspective camera. In spite of a very stable mounting, small movements of one optic against the other cannot be avoided. By this reason, the sub-images are transformed together based on tie points in the overlapping areas by bundle adjustment solution. This is resulting in a sub-pixel accuracy of the virtual image based on the availability of a precise determination of the interior orientation of the single camera heads.

1. INTRODUCTION

The DMC system is composed of several opto-mechanical elements been put together to build a high precision, high performance aerial camera system. To achieve high accuracies in the end products Z/I spend huge effort to both, geometric and radiometric calibration of single camera heads as well as into an “on-the-fly” calibration for each image composed of component images from 4 up to 8 single camera heads.

The DMC principle design is based on up-to-date sensor technology in combination with image processing techniques partly known from aerial photogrammetry or remote sensing (Hinz, Dörstel, et. al. 2000, Hinz, Dörstel, et. al. 2001).

The DMC design was proofed in several test flights (Heier, Hinz 2002). Theoretical investigations with cooperative partners like the Hannover and Stuttgart Institute for Photogrammetry accomplished in the early development phase have contributed to optimize the overall system design (Tang, Dörstel, et. al. 2000).

This paper presents the results of the cooperation’s and describes the single head geometric calibration approach used for DMC cameras, the “on-the-fly” platform calibration process for mosaicked images as well as the resulting photogrammetric accuracy reached with the camera.

2. SINGLE HEAD CAMERA GEOMETRIC CALIBRATION

Aim of the single camera geometric calibration is to determine the interior orientation of the camera and modeling systematic geometric deviations/distortions from the perspective geometry. The single camera head consist of two main components: (1) the lens system and (2) the CCD sensor which is mounted in the image plane. The lens system is a component specially designed and manufactured at Carl Zeiss Jena. The CCD sensor is made by DALSA (former Philips) and has an array size of 7K x 4K and a pixel size of 12 µm x 12 µm . This system is designed to form a "metric" camera system providing a high image-quality and low deviations from the photogrammetric camera model. The photogrammetric camera model describes the camera geometry by a set of elements called exterior and interior orientation parameters. The photogrammetric model is extended by Additional Parameter's (APs) to model systematic geometric deviations/distortions from the perspective geometry.

The geometric distortions are modeled by a set of APs designed for self-calibration of digital cameras (Fraser 1997). This AP set is a sub-set of a mixed empirical and analytical model developed by Brown (1974, 1976). Browns AP set can be grouped in terms modeling the different effects:

$$\Delta x = \Delta x_i + \Delta x_r + \Delta x_d + \Delta x_u + \Delta x_f$$
$$\Delta y = \Delta y_i + \Delta y_r + \Delta y_d + \Delta y_u + \Delta y_f$$

Where the subscript *i* denotes the interior orientation, *r* the radial distortion, *d* the decentring distortion, *u* the out-of-plane unflatness and *f* the in-plane distortion. The full AP set by Brown consist of 29 parameters but only 10 thereof are used for digital cameras. Browns AP set is widely used for close-range applications applicable for analogue as well as for digital cameras, e.g. Beyer (1992) and Fraser (1997).

2.1 Interior Orientation

In all cases the elements of interior orientation - principle point location x_p, y_p and principle distance c – have to be determined. These parameters defining the position of the CCD sensor in respect to the projection centre. As part of the AP set, not the elements itself are determined but changes of these parameters Δx_p, Δy_p and Δc:

$$\Delta x_i = \Delta x_p - \frac{\bar{x}}{\bar{z}} \Delta c$$
$$\Delta y_i = \Delta y_p - \frac{\bar{y}}{\bar{z}} \Delta c$$

In which the photo-coordinates defined as follows:

$$\bar{x} = x - x_p$$
$$\bar{y} = y - y_p$$
$$\bar{z} = -c$$

2.2 Radial lens distortion

The radial distortion is represented by a polynomial:

$$\Delta x_r = K_1 r^3 + K_2 r^5 + K_3 r^7$$
$$\Delta y_r = K_1 r^3 + K_2 r^5 + K_3 r^7$$

Where the terms of K_i represent the coefficients of radial distortion and r the radial distance:

$$r^2 = \overline{x}^2 + \overline{y}^2$$

The radial distortion for wide angle lenses like the lenses used for DMC are small but they are noticeable. However, the distortion effect is about 1 to 2 pixel at the border of the CCD sensor. Due to the definition of the radial distortion, there is a large correlation between distortion coefficients itself $K_1 \leftrightarrow K_2 \leftrightarrow K_3$ and between the principle distance, $K_i \leftrightarrow c$. The connection between the radial distortion and the principle distance is intended. Due to the proper selection of the principle distance the average deviation will computed to be a minimum.

2.3 Decentring distortion

It is not possible to align the elements of the lens system strictly collinear. This defect results in decentring distortion. This distortion is described by the expression:

$$\Delta x_d = P_1(3\overline{x}^2 + \overline{y}^2) + 2P_2\overline{xy}$$
$$\Delta y_d = 2P_1\overline{xy} + P_2(3\overline{y}^2 + \overline{x}^2)$$

Where P_i are the coefficients of the decentring distortion. For high quality lens systems the magnitude of these parameters is very small. Usually the decentring distortion parameters are tested to be not significant. Furthermore dependencies between the decentring distortion parameters and the principle point exist, so a remaining distortion will be absorbed by the principle point position and therefore the decentring distortion parameters are usually eliminated in the adjustment.

2.4 Out-of-plane unflattness

The knowledge regarding the sensor flatness or topography is very small. According to Fraser (1997) is the RMS departure from planarity is about 0.3µm measured for a Kodak KAF-1600 1K x 1K CCD chip. The out-of-plane unflatness is not determinable by photogrammetric techniques. Only the direct measurement of the CCD chip surface could establish a good control of this effect.

2.5 In-plane distortion

The in-plane distortion parameters are empirical in nature and modeled by a polynomial. For digital cameras the total number of parameters is reduced from 12 to a sub-set of 2, which are the “scale”, parameter b_1 and the “shear”, parameter b_2:

$$\Delta x_f = b_1\overline{x} + b_2\overline{y}$$
$$\Delta y_f = 0$$

The selection of the used sub-set differs, e.g. Beyer (1992) and Fraser (1997) using slightly different parameters. The two remaining parameters have also a physical meaning. The scale parameter b_1 models a no-square pixel size and shear parameter b_2 compensates for a non-orthogonality in the pixel array. A different scaling between the horizontal and vertical sensor elements can not be excluded. But surprisingly the occurrence of the shear parameter is not always insignificant.

The technical equipment for the single head camera calibration consists of a combination of a goniometer and a single collimator as light source. The goniometer allows the precise measurement of angles in one direction. And the collimator simulates a target at infinite distance (like a beam of parallel light rays).

The calibration measurements were done using the calibration stand for aerial camera calibration at the Carl Zeiss Camera Calibration Center in Oberkochen. This goniometer was primarily designed for calibration of Zeiss RMK mapping cameras. The goniometer is based on a Zeiss Theodolite Th2. The horizontal glass circle is validated by the "Physikalisch-Technische Bundesanstalt" (PTB). With this instrument a standard deviation of 1" can be achieved in one direction. Assuming a focal length of 120 mm the angular accuracy is equivalent to 0.6 µm or 1/20 pixel in image space. This angular accuracy delivers a stable geometry and allows the precise determination of the interior orientation and the APs.

Unfortunately, without modification of the camera mount, the collimator and the camera cannot be aligned. Therefore the principle point of auto-collimation is not adjustable. And furthermore for every camera position three rotation parameters as additional degrees of freedom have to be added.

For the calibration the measurements were done in four camera positions: horizontal, vertical and on both diagonals. For each collimator position we get as observations a (horizontal) direction measured with the Theodolite and an image of the collimator target (cross) projected to the CCD sensor. The position of the imaged collimator cross is than precisely determined applying least-squares template matching technique. The horizontal directions are converted into "object point coordinates" in respect to the projection centre.

The calculation of the APs is done using a self-calibrating bundle adjustment. All unknown parameters – orientation parameters and APs – are derived simultaneously in the bundle adjustment. To reach a great flexibility of the bundle program all unknown parameters are introduced as direct observations (Grün 1986). So the behavior of an individual parameter depends on the given standard deviation respectively on their weight p. Using the weight $p=0$ the parameter is unconstrained (free) and for $p=\infty$ the parameter is constrained (eliminated).

All "object point coordinates" are used as fixed "control points" with a high weight. For the four camera positions we suppose a constant position of the projection centre and introduce three rotation parameters to model the orientation of the camera. The APs are regarded as being common for all camera positions. In fact we do a spatial resection extended by a self-calibration see figure 1. As mentioned before the interior orientation parameters are used as constants and only changes of these parameters are determined.

```
ID     :  02109368
Type   :  AP Australis

Param.    Adjusted     Std.dev.

Param. State Initial      Adjusted     Change       Std.dev.

dxp    unk   0.000e+000   2.465e-004   2.465e-004   2.335e-006  is significant
dyp    unk   0.000e+000   3.920e-005   3.920e-005   4.606e-006  is significant
dc     unk   0.000e+000  -3.811e-004  -3.811e-004   2.744e-006  is significant
K1     unk   0.000e+000   4.712e-001   4.712e-001   6.793e-002  is significant
K2     unk   0.000e+000  -2.623e+002  -2.623e+002   6.089e+001  is significant
K3     unk   0.000e+000  -2.433e+004  -2.433e+004   1.599e+004  not significant
P1     eli   0.000e+000   0.000e+000   0.000e+000   1.000e-031  is eliminated
P2     eli   0.000e+000   0.000e+000   0.000e+000   1.000e-031  is eliminated
b1     unk   0.000e+000  -8.375e-005  -8.375e-005   1.870e-005  is significant
b2     unk   0.000e+000   2.011e-006   2.011e-006   9.262e-006  not significant
```

Figure 1: Camera Calibration Protocol of serial production camera

The significance of the 12 APs is determined by a Student-Test. The remark “is eliminated” means that this value was 1st discovered to be “not significant” and there for in the final computation disabled.

As mentioned above, the parameters P1 and P2 mainly model the accuracy of the optical lens system. Due to the high precision manufacturing of the optics which is indicated by the certification measurement / protocol, P1 and P2 can be switched off.

The RMS of residuals in the image space is less than 1.8 μm respectively 0.15 pixel and there for delivers high accuracy results.

The “re-calibration” of a set of cameras which where in use for over 5 month and flown in several missions has shown that the recalibration does not discover any significant changes in the calibration parameters. The “re-calibration” causes maximum corrections of the image coordinates of 1/10 of a pixel. This shows the high stability of the DMC camera systems.

3. GENERATION OF AN IMAGE COMPOSITE OUT OF 4 SUB-IMAGES

DMC was designed not just to reduce the influences of possible error sources but to put sense full design requirements to each component used. As a result of this following design principles were realized:

- Synchronous exposure of all camera heads
- Limited deformations in the camera mount

A synchronous use of the cameras includes the advantage of well defined conditions. The geometric influence of the projection centre offset can be estimated. If the offset in the flight direction will be compensated by a delay of the exposure, the influence of the change of the view direction caused by vibrations cannot be controlled. To solve this problem the requirement to the DMC shutter was to release the single camera heads within a precision of less than 1/100 msec. This ensures that we can assume all 8 images of one exposure time (4 panchromatic and 4 multi spectral images) taken at the same time and location. Thus we do not need to model for influences of different TDI shifts or to compute for different distances of the coordinates of the projection centers for one image shot.

As a mechanical part inside an aircraft can never be constructed to be absolutely stable over long and short time the camera mount for DMC was designed to allow angular deformations. This leads to a further assumption for our platform calibration model. The high correlation which exists between the observation of a vector caused by a translation or rotation could be solved. As just angular deformations are allowed the mathematical approach for the platform calibration is a straight solution to model for omega, phi and kappa of each camera head.

To form an image composite several calibration steps are necessary. First of all, each of the 4 camera heads needs a precise geometric calibration as described above. This step is also known as ‘single head camera geometric calibration’ and applied at manufacturing site. The information generated during this procedure is delivered on a calibration CD to the customer together with the complete DMC System. During system installation the calibration data is stored at the post processing work station. At landing of the aircraft the mission data is transferred to the post processing work station.

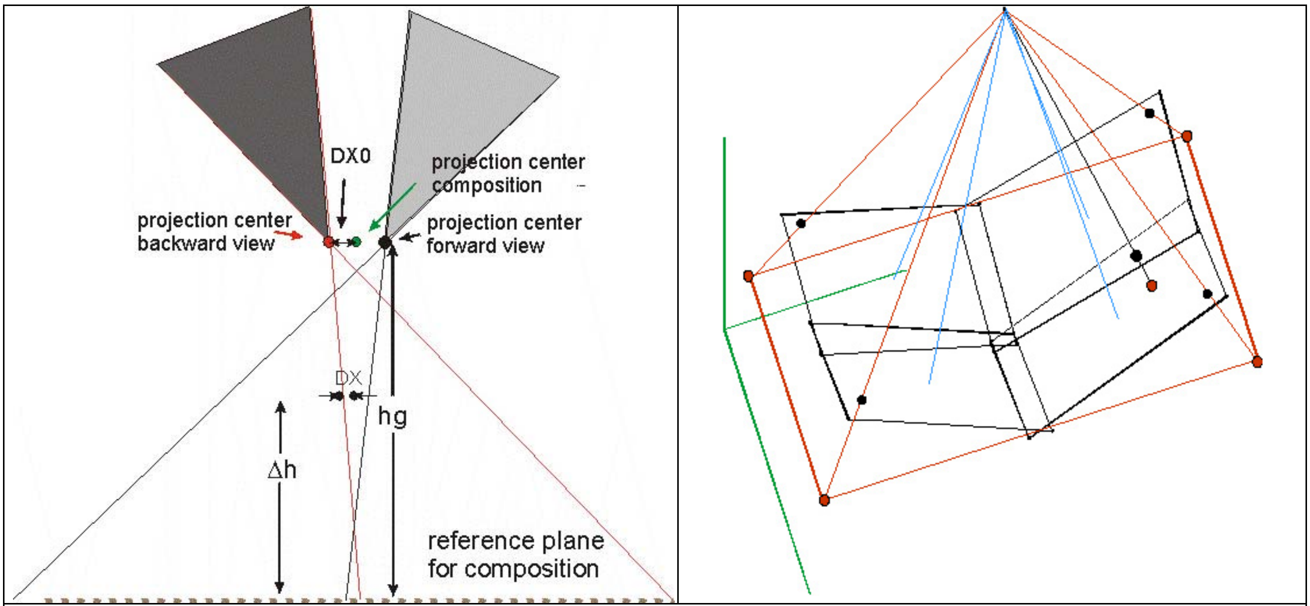

Figure 2: Principle of the combination of convergent sub-images to an image composite

To form the high resolution panchromatic images, the DMC is using a convergent combination of 4 cameras, each with a CCD of 7168 x 4096 pixels combining the single images to a image composite of a size of 13824 x 7680 pixels. In Figure 2 the relation between the individual small angle cameras and the virtual plane of an image composite is depicted. The fields of view of the four physical available cameras are overlapping. Based on the overlap by means of tie points (Fig. 3) the individual images can be merged together to a homogenous virtual image. This step can accept lens distortions in the individual cameras but it is required to correct the image coordinates prior to the adjustment. The resulting image composite is a distortion free combined image with a free chosen focal length. This focal length should be close to the focal length of the physical cameras (Fig. 7)to avoid under- or over-sampling.

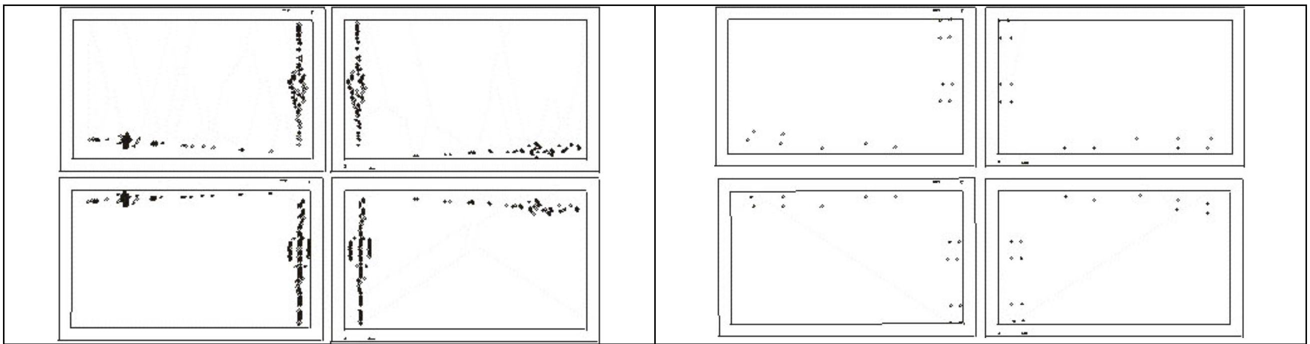

Figure 3: Tie point configuration of the individual images

The three-dimensional relation of the individual images is determined by a bundle block adjustment. The typical configuration of the tie points can be seen in Fig. 3. Not so many tie points like shown on the left hand side are required because of the very strong connection of the internal block. Investigations have shown that very good results can be achieved by using 30-50 well distributed points. As typical sigma0 of the bundle adjustment for matching the sub-images together, values between 1 and 2 microns are reached (Fig. 4, Fig. 7), corresponding to 1/12 up to 1/6 pixel. Because of the synchronous imaging, also moving objects like cars and waves can be used as tie points.

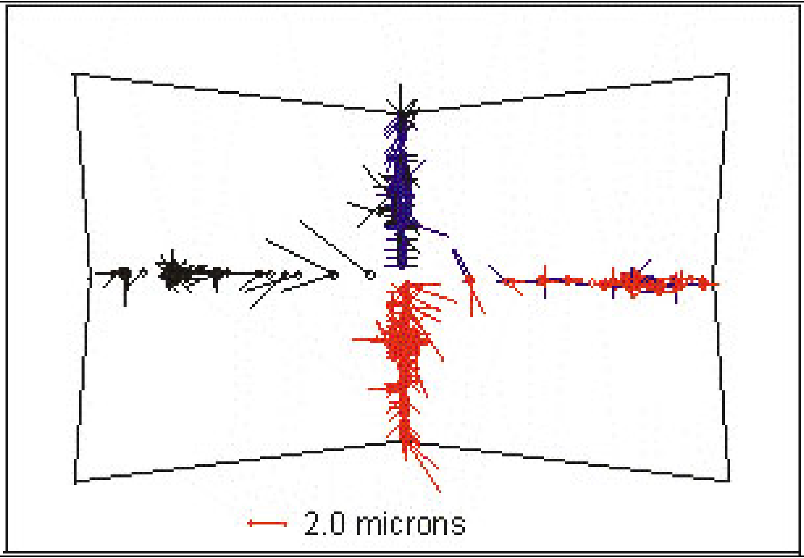

Figure 4: Residuals of bundle orientation at the tie points
reached sigma0 = 0.82 µm based on 999 observations

For a sufficient image quality also for low altitude flight and under unfavorable light conditions, the DMC is using the transfer delay and integration (TDI) function of the CCDs. The reflected energy is integrated not only in one CCD-element, the generated charge is shifted with the speed of the image motion over few neighbored CCD-elements. This is influencing the inner orientation similar to a motion of the principal point. Theoretical investigations (Zeitler, Dörstel, Jacobsen 2002) have shown an influence far below 0.1 µm, so it is negligible.

A combination of cameras as used in the DMC has several projection centers. Of course the distance and the tilting angle of such an assembly need to be optimized so that the whole camera is completely compatible with existing aircraft installations. Several investigations have been done to proof the influence of this assembly (Tang, Dörstel, et. al. 2000). However, the offset of the projection centers is causing some deformation of the composed image depending upon the height distribution in the object space. The composed image can be free of error if the terrain is flat, but elevated points may show small discrepancies as visible in Fig. 5. Under usual operating conditions, the discrepancies are negligible.

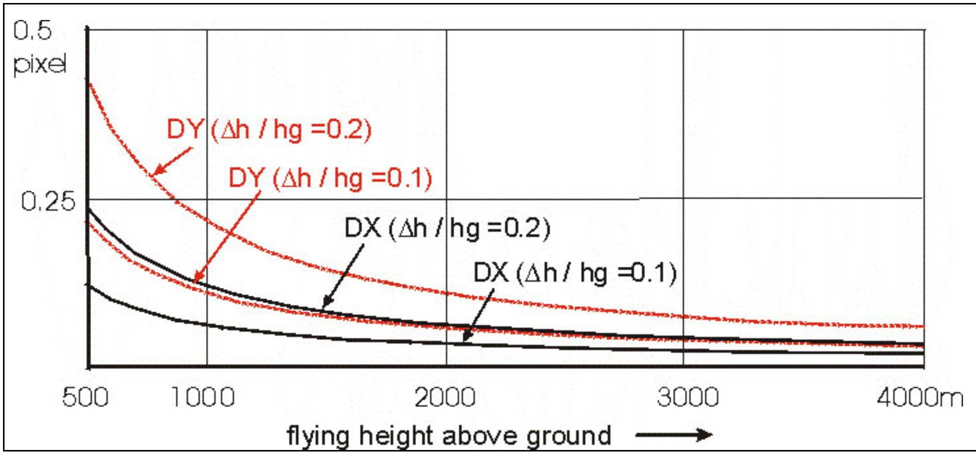

Figure 5: Influence of the projection centre offset to the image composite as a function of the height differences (Δh) in the imaged area to the flying height above ground (hg)

The resulting images of the DMC are one perspective image for each exposure which can be handled in any digital photogrammetric workstation without special software.

4. RESULTS

Newest test flights performed still showing excellent geometric performance of the DMC platform calibration in combination with the high accuracy single head geometric camera calibration. The results shown in Fig.6 received from images taken with a camera at several scales from 1:12500 down to engineering scale of 1:5000 showing a sigma0 of the platform calibration between 1/12 and 1/6 of a pixel. The mean sigma0 reached by processing 847 images was 1.6 µm. Out layers as shown in Fig. 6 are overcome by special error handling techniques implemented in the post processing software. Such cases can be areas of low texture in the overlapping areas. The blocks processed below with ISAT showing a final sigma0 of about 2.4 to 2.5 µm for the internal adjustment and the Block Elchingen 1:8000 flown at 960 m altitude delivers a final sigma0 of 2.3 µm with a RMSx,y of 2.1 µm.

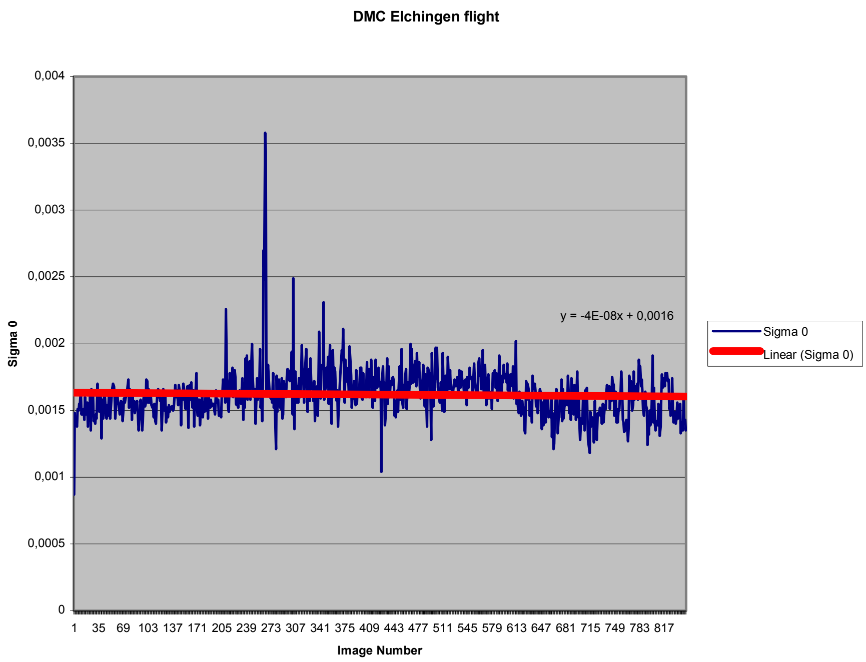

Figure 6: Sigma0 of Platform Calibration results from serial production camera

The results of the platform calibration are logged for investigation purpose (Fig. 7). The file blow shows the result of a platform calibration with a sigma0 of 0.87µm. The principal distance of camera 1 is fixed and the principle distance of camera 2 to 4 is adjusted to be close to the nominal focal length of 120 [mm] which is used to project the single images into the virtual image space.
Further on the corrections of the observations are listed. The complete list was reduced by the points matched in the inner overlapping area (100008-100015, 100024-100031, 100040-100047). The deleted points did not show any significant corrections, all had corrections of ± 0.001 [mm]. This is according our expectation as the largest corrections are expected in the outer parts of the image overlaps. It has to be recognized that even single measurements, point 100003 which got a correction of 0.003[mm] for x, do not badly affect the adjustment result.

```
SIGMA:    0.00087   ITERATION 140       115 OBSERVATIONS   12 UNKNOWNS
=================================================================
              PHI          OMEGA        KAPPA         STANDARD DEVIATION
IMAGE  2   -10.64778    17.69558    89.17351  +/- 0.00010 0.00009 0.00035
IMAGE  3   -10.59229   -17.65221   -90.02507  +/- 0.00013 0.00012 0.00040
IMAGE  4    10.64356   -17.69593   -89.79833  +/- 0.00012 0.00011 0.00039
```

```
FOCAL L.    119.9906    119.9910    120.0034  +/- 0.00071 0.00081 0.00079

     CORRECTIONS OF OBSERVATIONS   [MM]
          POINT      IMAGE 2           IMAGE 3          IMAGE 4
         100002   0.001  -0.001   0.0      0.0      0.0      0.0
         100003   0.003  -0.001   0.0      0.0      0.0      0.0
         100006   0.000   0.001   0.0      0.0      0.0      0.0
         100007   0.000   0.001   0.0      0.0      0.0      0.0
     ....
         100016   0.0     0.0     0.0      0.0      0.000    0.001
         100017   0.0     0.0     0.0      0.0      0.000    0.001
         100018   0.0     0.0     0.0      0.0      0.000    0.001
         100019   0.0     0.0     0.0      0.0     -0.001    0.001
         100020   0.0     0.0     0.0      0.0      0.001    0.002
         100021   0.0     0.0     0.0      0.0     -0.001    0.001
     ....
         100037  -0.001   0.001  -0.001    0.001    0.0      0.0
         100038  -0.001   0.001  -0.001    0.001    0.0      0.0
         100039   0.000   0.001   0.000    0.002    0.0      0.0
     ....
         100032   0.0     0.0    -0.001    0.000    0.001    0.000
         100033   0.0     0.0     0.000    0.000    0.000    0.000
         100034   0.0     0.0     0.000    0.000    0.000    0.000
         100035   0.0     0.0     0.000    0.000    0.001    0.000
         100036   0.0     0.0     0.000    0.000    0.000    0.001
```

Figure 7: Platform Calibration Results from serial production camera

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