ISSUES AND METHOD FOR IN-FLIGHT AND ON-ORBIT CALIBRATION

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ABSTRACT

The result of a geometric laboratory and an in-flight calibration of analogue or digital cameras may be not the same, caused by the quite different environmental conditions and the mechanical stress during transportation. The mathematical model for the handling of the images has to respect the instant geometry. Of course not all components of the laboratory calibration will change; especially distortion values are usually stable over longer time. On the other hand, the focal length and also the principal points are not very stable.

By self calibration with additional parameters the real geometry of a sensor can be determined and the results can be used partially also as a pre-correction for other images. The individual additional parameters have to be able to solve special geometric problems, so the used formulas have to be fitted to the special geometric problems of the sensor. The residuals at ground control points and in the images have to be analysed for unsolved geometric problems. Not all parameters can be determined by self calibration; especially the focal length can only be improved if control points with quite different elevations in the same test area are available or if the position of the projection centers is known. The common use of a larger number of additional parameters usually is causing high correlation, this may cause misleading results. By this reason the additional unknowns have to be checked for their significance and for exceeding a correlation tolerance limit. Finally only the required additional parameters have to be used.

1 INTRODUCTION

A correct determination of the two- or three-dimensional geometry of imaged objects requires the reconstruction of the imaging rays. This includes the exterior and the interior orientation. The exterior orientation describes the location of the projection center and the attitude of the bundle of rays while the geometry of the bundle of rays will be reconstructed by the measured image position and the interior orientation. We do have one projection center for perspective images like taken by an analogue frame camera or digital cameras using a CCD-array. Digital cameras based on a CCD-line or panoramic cameras do have the same exterior orientation only for an image line; corresponding to this, the interior orientation is restricted to this line. For this group of sensors, the reconstruction of the image geometry is mixing the interior and exterior orientation. Still more difficult it is for systems using just an imaging detector like Landsat – here the interior orientation is reduced to the relation of the moving parts.

 The simple mathematical model is based on the colinearity condition – object point, projection center and image point are located on a straight line and the image is generated in a perfect plane or line. Of course this is not respecting the real physical situation, the refraction has to be respected, the imaging surface is not a perfect plane, the CCD-lines are not totally straight lines and the imaging ray does not path the optics without change of the direction. Of course the expression

"imaging ray" is a simplification because of the wave-structure of the light, nevertheless it is used for the geometric reconstruction. The field of view is a function of the focal length, usually it is determined by laboratory calibration, but it is changing under the environmental conditions. So the calibrated focal length is only an approximation.

2 AERIAL APPLICATIONS

2.1 PERSPECTIVE CAMERAS

Figure 1: optical system	Figure 2: simplified model
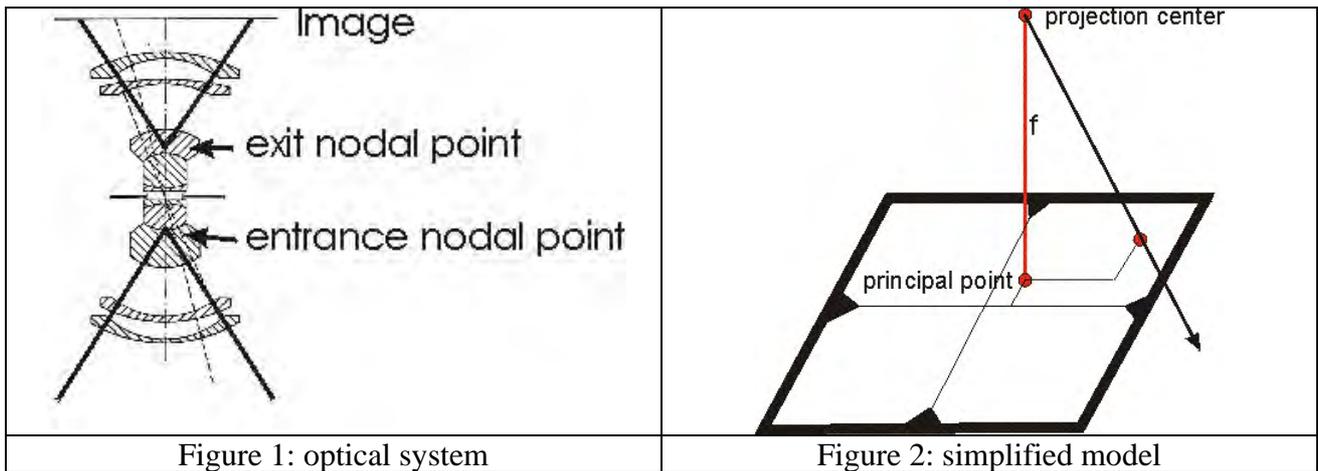
The physical situation of a perspective camera is shown in figure 1. The difference between the entrance nodal point, which is identical to the projection center in the object space and the exit nodal point - the projection center in the image space, will only be respected in the case of direct observations of the projection centers like for combined block adjustment with projection center coordinates or by direct sensor orientation. Usually the simplified model shown in figure 2 with the positive location of the image will be used. The geometric condition of the original image above the projection center is identical to the positive location below the projection center. In the simplified model we do have a projection centre with the distance of the focal length f from the image plane and a principal point which has the closest distance from the image plane to the projection center. Like the focal length, the location of the principal point will be determined by laboratory calibration, but it also may change slightly over the time or by thermal influences. Analogue film cameras do describe the location of the principal point indirectly by means of the fiducial marks. CCD-array cameras do not need fiducial marks; the CCD-array is fixed in the camera, so the location of the principal point is known from the laboratory calibration with the row and column.
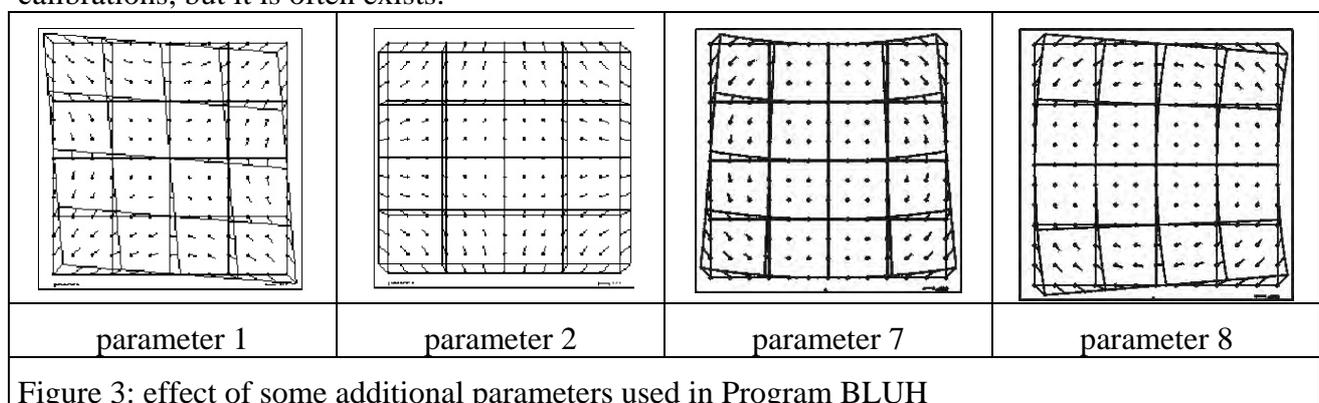
Analogue film is not as stable as it should be, it will change the dimension by shrinking after the film development. Own investigations (Koch 1987) have shown a scale reduction of up to 0.4‰ corresponding to 92 microns over 230mm film format. The dimensional change is different in the x'- and the y'-direction; up to 0.3‰ corresponding to 69 microns have been detected. In addition there may be also an angular affinity up to 0.15‰ corresponding to 35 microns. The change of the film dimension is not the same for all photos of a film roll, a variation of 0.1‰ corresponding to 23 microns is usual. But the change of the film dimension is not a problem; it will be compensated by the standard affine transformation to the calibrated fiducial mark coordinates. Only a deformation of the fiducial mark location will cause an affine deformation of all images taken by this camera.

The over-determination of the image orientation by bundle block adjustment allows a self-calibration by additional parameters. Systematic discrepancies of the image coordinates against the used mathematical model can be detected and respected with additional unknowns. There are

different sets of formulas for additional parameters of perspective images. Gotthardt (1975) has developed a set which is able to eliminate systematic image errors at the position of the Gruber points (3 x 3 positions). This set of formulas was used by Ebner (1976) and is known under his name. Grün (1979) has extended this set of formulas to 5 x 5 image positions (Gruber points and the points on half the distances). The formulas used by Ebner are optimal, if the image points are just located in the Gruber points. The set extended by Grün often is causing problems with the too high number of parameters which do show strong correlation. The author has developed the set of parameters shown as formula 1.

$r^2 = x^2 + y^2$ arctan b = y/x   (constant values in parameters 9-11 are scaled to the actual image size)   (the listed constant values are valid for maximal radial distance in the image of 162.6mm $= 115.0 \cdot 2^{1/2}$)

1. x' = x - y•P1   y' = y - x•P1
2. x' = x - x•P2   y' = y + y•P2
3. x' = x - x•cos 2b • P3   y' = y - y•cos 2b • P3
4. x' = x - x•sin 2b • P4   y' = y - y•sin 2b • P4
5. x' = x - x•cos b • P5   y' = y - y•cos b • P5
6. x' = x - x•sinb • P6   y' = y - y•sin b • P6
7. x' = x + y•r•cos b • P7   y' = y - x•r•cos b • P7
8. x' = x + y•r•sin b • P8   y' = y - x•r•sin b • P8
9. x' = x - x•(r^2 –16384) •P9   y' = y - y•(r^2 –16384) •P9
10. x ' = x - x•sin(r • 0.049087) • P10   y' = y - y•sin(r • 0.049087) • P10
11. x' = x - x•sin(r • 0.098174) • P11   y' = y - y*sin(r •0 0.098174) • P11
12. x' = x - x•sin 4b • P12   y' = y - y• sin 4b •P12

Formula 1: additional parameters for perspective images used in program system BLUH

This set of parameters is a combination of physical justified values extended by some general parameters. Parameter 1 and 2 are describing an angular affine and an affine deformation. The parameters 9 up to 11 can compensate radial symmetric distortions, while 7 and 8 are for tangential distortion (see also figure 3). The other parameters are similar to a Fourier serious in polar coordinates and they are able to fit remaining systematic effects. If the image positions are well distributed like usual, this set of parameters shows small correlation of one to each other and has in addition the advantage of some physical explanations. A tangential distortion can be caused by a not centric location of individual lenses. This problem will not be checked by the standard laboratory calibrations, but it is often exists.
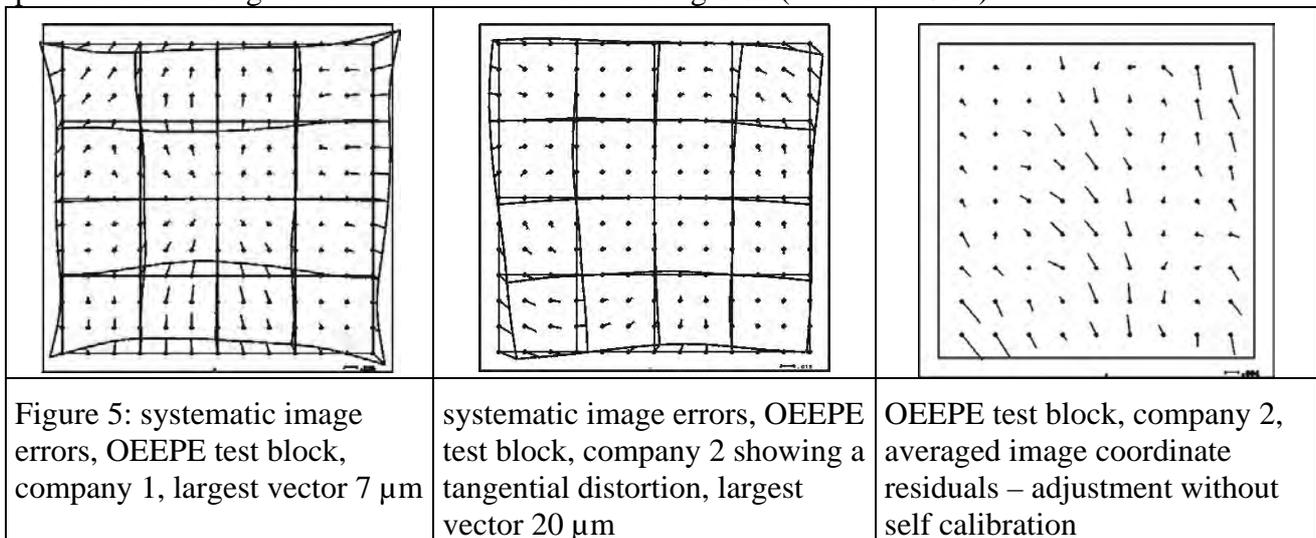

| parameter 1 | parameter 2 | parameter 7 | parameter 8 |

Figure 3: effect of some additional parameters used in Program BLUH

Very often, especially for close range applications, a set of polynomial parameters are used for the radial symmetric distortion like   K1* r^3 , K2* r^5 , K3* r^7 . This set has the disadvantage of strong correlation and the higher degree values are only effective in the extreme image corner. With a set of 11 aerial images the values K1 and K2 have been adjusted, leading to a correlation between both

of 0.91 which is above the critical value. The same data set handled with parameters 9, 10 and 11 was leading just to a maximal correlation of 0.32. All radial symmetric additional parameters are highly significant with Student test values larger than 4.5.

radial symmetric distortion by polynomial K1	radial symmetric distortion by parameters 9 – 11

Figure 4: radial symmetric lens distortion
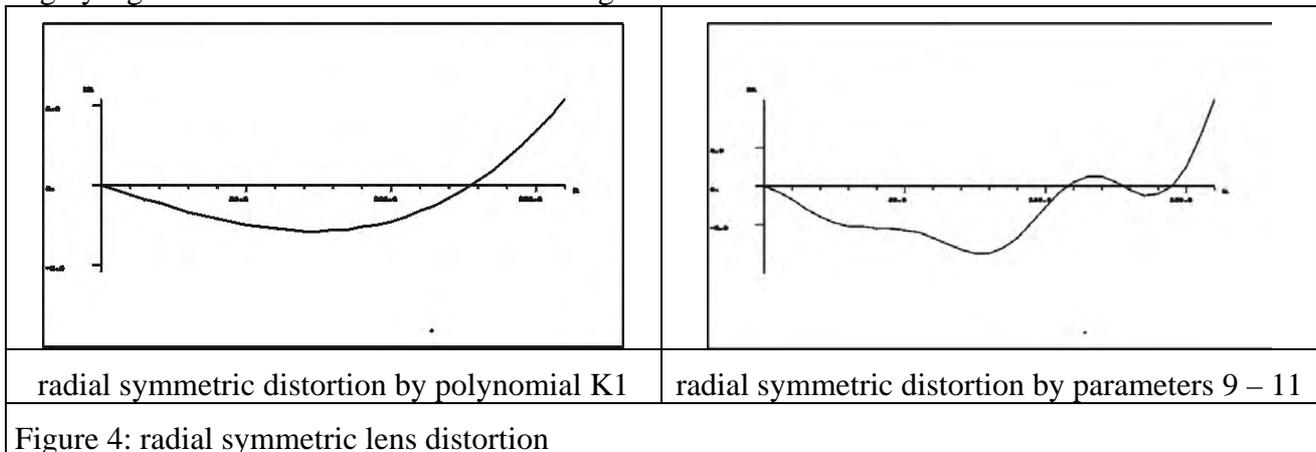
Because of the strong correlation, the parameter K2 was not accepted, so only with K1 the radial distortion shown on the left hand side of figure 4 could be determined. With the parameters 9 up to 11 the more detailed situation shown on the right hand side of figure 4 could be determined.

Empirical tests showed the negative influence of highly correlated and not justified additional parameters (Jacobsen, 1980). The not justified parameters should be excluded from the adjustment as well as the very strong correlated ones. In program system BLUH the additional parameters are analysed by a Student test. The parameters with values below T=1.0 are excluded as well as parameters causing correlation coefficients exceeding 0.85 (Jacobsen 1982).

Figure 5: systematic image errors, OEEPE test block, company 1, largest vector 7 µm	systematic image errors, OEEPE test block, company 2 showing a tangential distortion, largest vector 20 µm	OEEPE test block, company 2, averaged image coordinate residuals – adjustment without self calibration

The effect of the additional parameters to the image coordinates is called "systematic image errors". This is not a very precise expression because it is just showing the difference of the mathematical model of perspective images to the real situation. Figure 5 shows the "systematic image errors" determined by self calibration with the above listed set of additional parameters for images taken with aerial cameras. The bundle block adjustment used the precise test field Frederikstad, Norway with the data of the OEEPE test block "direct sensor orientation" (Heipke et al 2001). The second data set (151 photos, 4203 photo points) has been handled also without self calibration. The resulting image coordinate residuals have been averaged in 9 x 9 image sub-areas (figure 5, right hand side). The trend of the discrepancies agrees very well with the corresponding systematic image errors (figure 5, center). Such a good fit requires a higher number of observations. In general the

analysis of residuals can be used for the determination of remaining systematic effects which could not be handled with the used set of additional parameters.

The "systematic image errors" determined by additional parameters can be used for a pre-correction of the image coordinates. This is only correct if the "systematic image errors" do not change. The image geometry of analogue aerial photos is not only depending upon the camera itself, the film magazine including the pressure plate has also a strong influence. In addition the "systematic image errors" do change from photo flight to photo flight. Only the radial and tangential symmetric lens distortion and the affine deformation do show a more stable condition. The radial and tangential deformation can be determined with only few images and also with a minimum of control points. The affine deformation requires control points or crossing flight strips.

Under usual conditions of an aerial flight, the focal length cannot be determined by bundle block adjustment with self calibration. As geometric information for this, only the Z-variation of the control points is counting. The standard deviation of well defined ground point heights determined with by wide angle photos taken from a flying height of 1000m is SZ=48mm under the optimal condition of a x-parallax accuracy of 5µm, that means for a height difference $SDZ = SZ \bullet \sqrt{2} =$ 68mm. If only a standard deviation of the focal length of 15µm shall be reached, a height difference between vertical control points of 153mm/15µm x 68mm = 680m is required. Of course with 9 control points in both height levels this would be reduced by the factor of 3, corresponding to a height difference of 330m in relation to the flying height of 1000m. But even under such conditions there are configuration problems and a standard deviation of 15µm for the focal length is not sufficient. We do have a different situation, if the projection center coordinates are available from relative kinematic GPS-positioning. With this, the focal length can be determined, but it will be totally correlated to constant Z-errors of the GPS-positioning which cannot be avoided. Only in a combined adjustment with images taken from at least 2 different height levels, the constant GPS-errors can be separated from the focal length. With the data set of the mentioned OEEPE test block standard deviations of the focal length of Sf = 3 to 4µm could be reached. But also here we do have a limitation, because the focal length may change depending upon the air temperature and pressure (Meier 1978). So we are still limited to a three-dimensional interpolation which will lead to sufficient results. The use of the determined focal length also for other projects with an image scale outside of the range which has been used for the in-flight calibration, is still limited, but it is a better estimation of the real condition than the focal length from the laboratory calibration. For the location of the principal point we do have very similar conditions.

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                           GPS-SHIFT              STANDARD DEVIATION
                        X       Y       Z          SX    SY    SZ
GPS DATA FOR DATA SET  1     .001    .003    .086        .007  .007  .004
GPS DATA FOR DATA SET  2    -.016    .054    .257        .014  .014  .006


CHANGE OF FOCAL LENGTH                        -.037 = CORR. FOR F ->  153.652
GPS-SHIFT ABSOLUT                             -.095


ADDITIONAL PARAMETER 14001 CORRESPONDS PRINCIPAL POINT X    .001
ADDITIONAL PARAMETER 15001 CORRESPONDS PRINCIPAL POINT Y    .000
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Figure 6: correction of focal length and principal point by bundle block adjustment using GPS-values of projection centers in 2 different height levels (program system BLUH)

A camera calibration under flight conditions requires a correct data handling. The effect of the earth curvature and the net projection should be respected. The exact data handling requires an adjustment in an orthogonal coordinate system like a tangential system to the earth ellipsoid. Also the refraction has to be respected. Most published formulas for the refraction correction are valid up

to a flying height of only approximately 14km; polynomial formulas are leading to totally wrong results for space application.

The deformation of the rays by atmospheric refraction can be respected by a correction of the image coordinates.

Z_f = *flying height above mean sea level [km]*
Z_g = *mean terrain height above mean sea level [km]*
c = *calibrated focal length mm*
r = *radial distance to principal point mm*
$P1$ = *air pressure [mb] in terrain height*
$P2$ = *air pressure [mb] in flying height*
$P = e^{(6.94 - Z \bullet 0.125)}$ *[Z in km]*
Dr = *correction of image coordinates*

$$Dr = \left(0.113 \bullet \frac{(P1-P2) \bullet Zg}{Zf - Zg} - \left(\frac{Zf \bullet 2410}{Zf \bullet Zf - Zf \bullet 6 + 250} - \frac{Zg \bullet 2410}{Zg \bullet Zg - Zg \bullet 6 + 250} \right) \right) \bullet \left(r + \frac{r \bullet r \bullet r}{f \bullet f} \right) \bullet 10 \uparrow -6$$

Formula 2: refraction correction for image coordinates of vertical images valid up to space

This formula (Jacobsen 1986) is based on the 1959 ARDC standard atmosphere and is valid up to space. It was developed based on formulas published by Bertram 1966 and Albertz et al 1980. The refraction correction is not sensitive, it is not necessary to respect the actual conditions of the atmosphere.

The situation for digital perspective cameras is more simple like for analogue film cameras. CCD-arrays do have the advantage a fixed surface, usually they are perfect flat and the CCD does not have any temporal deformations. In addition, the positions inside the CCD are usually perfect. Existing distortions are dominated by the influence of the optics. Experiences with the Z/I Imaging DMC have shown the high internal stability of this system. The synthetic image generated from the DMC is based a configuration of 4 individual CCD-cameras, each of this is calibrated and the calibration values are respected. So the synthetic image should be free from systematic image errors. A bundle block adjustment over a test field with some crossing flight lines showed only a small affine deformation. A check of the used CCDs confirmed this; the CCD elements have not had exactly a square size. After this test, the affine deformation was respected in the generation of the synthetic image, leading to images free of systematic image errors.
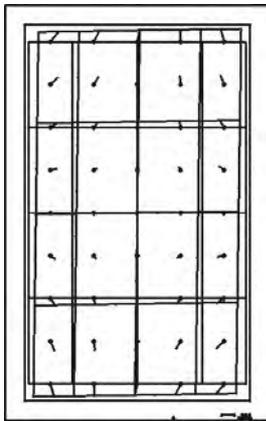
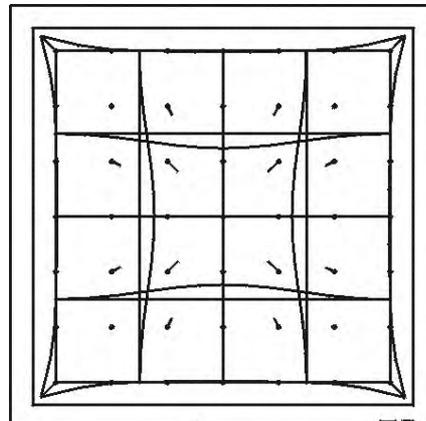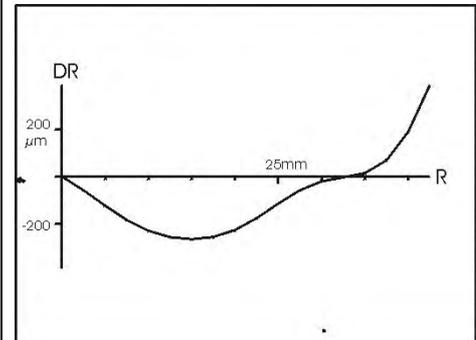|		
Figure 7: systematic image errors of Z/I DMC, largest vector = 11µm	Figure 8: systematic image error of Rollei Q16, f=41mm, largest vector = 270µm	Figure 9: radial symmetric distortion of Rollei Q16, f=41mm

Other digital cameras equipped with only one CCD-array showed a dominating radial symmetric characteristic (see figure 8). The used lens systems are of the shelf and not made especially for photogrammetric purposes. So no special care was taken for a distortion free geometry and radial symmetric distortions in the range of 200 µm are usual. The distortion of the Rollei Q16, 41mm-optics, shown in figures 8 and 9, has been determined with 12 well overlapping images. The radial symmetric additional parameters 9, 10 and 11 do have Student test values between 302 and 67 (size of the parameters in relation to their own standard deviation). The significance level always starts at the value 3. The correlation between these parameters is not exceeding 0.10 showing the optimal configuration of the additional parameters and the save determination.
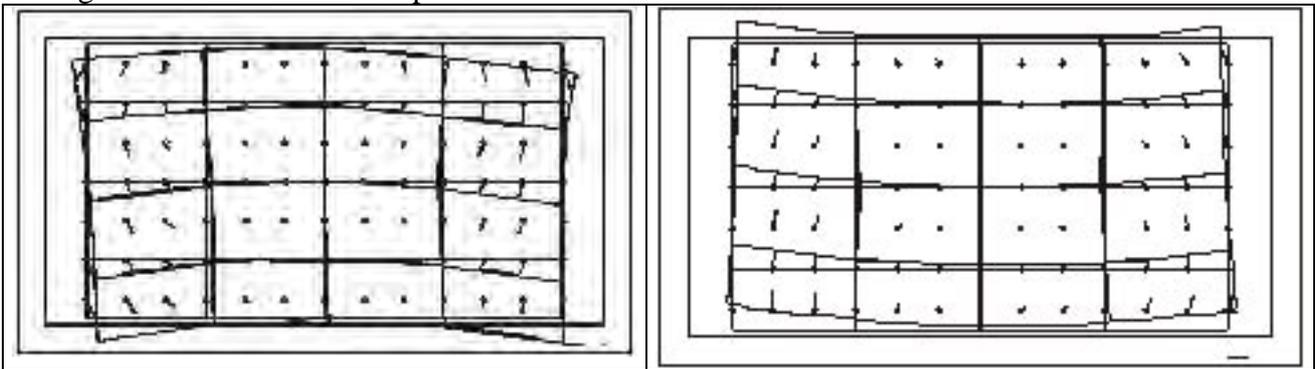

Figure 10: systematic image errors of the ThermScan camera, left: wide angle optics – largest vector 1.5 pixels, right: normal angle optics – largest vector 1.7 pixels

Cameras with not so stable optics like the thermal camera ThermScan with a variable focus may show a tangential distortion like sown in figure 10. A variable focus does not allow a calibration. Even if the focus will be set to infinity, after changing the focus and setting it back to infinity, the geometric condition will not be the same. The same problem exists if the optics are exchanged. If they are mounted again, the old situation will not be reached exactly. Of course, if the optics are fixed, they can be calibrated and may be stable up to a change of the optical system. This is not the case for zoom lenses; the inner optical system usually is not fixed very well and so the camera geometry may change after shaking the camera only gently.

2.1 OTHER SYSTEMS

Figure 11: systematic discrepancies of a panoramic camera
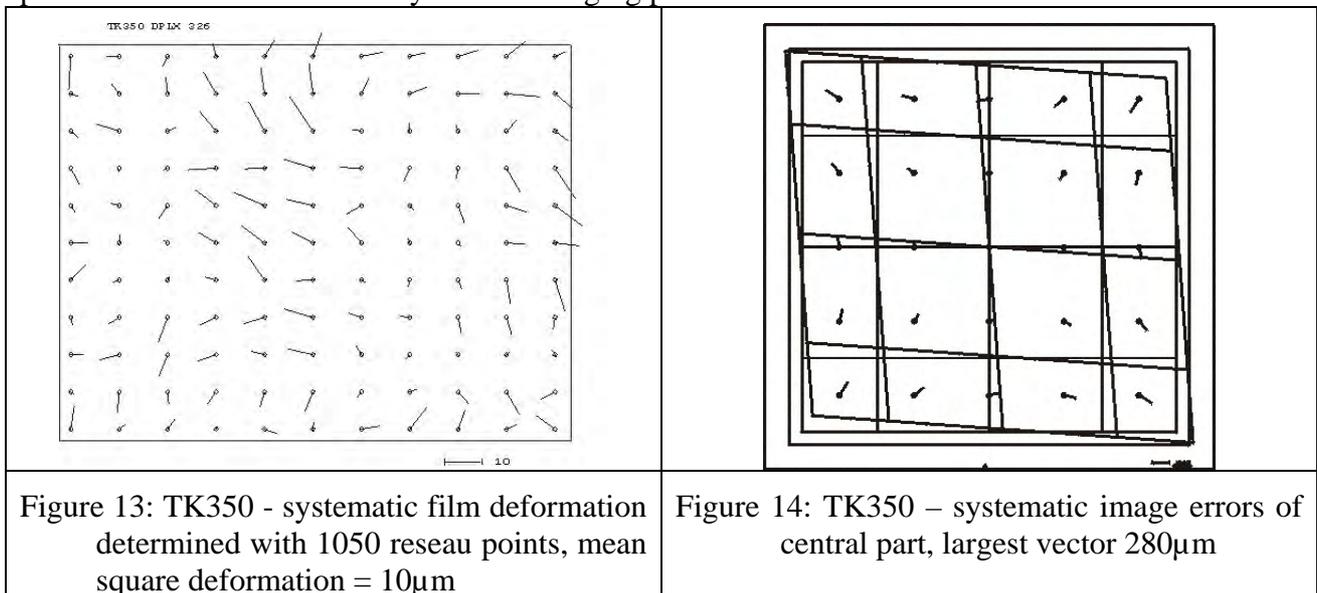
Figure 12: HRSC CCD-line linearity
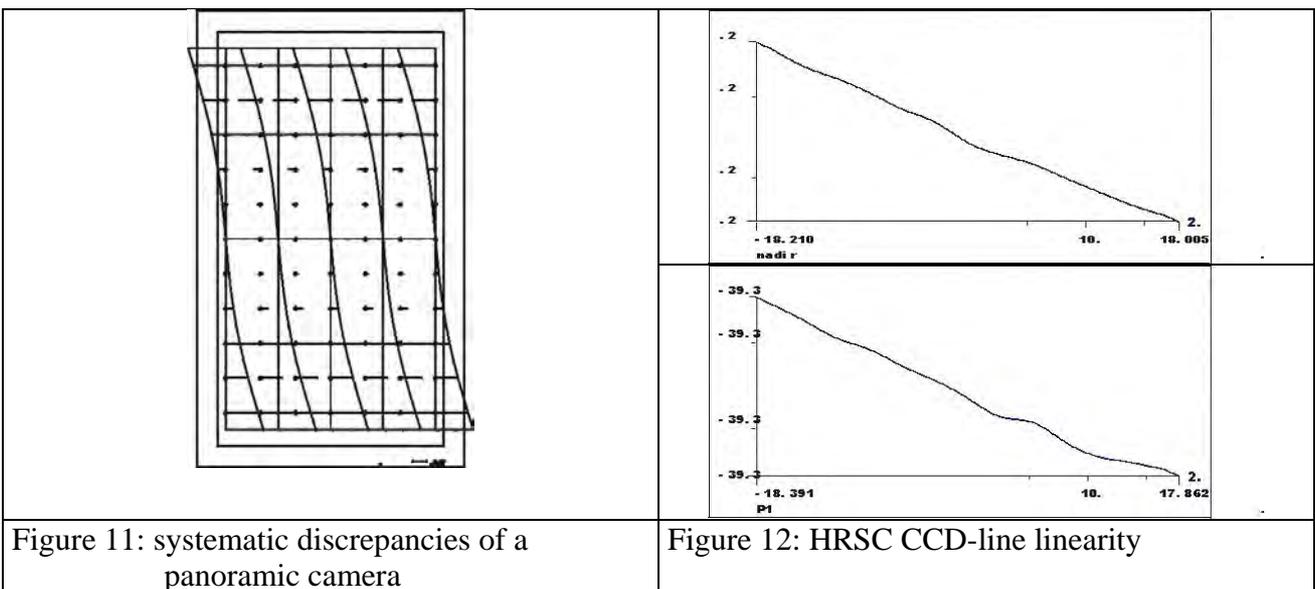
Not perspective aerial cameras are panoramic cameras and CCD-line scanners. The self calibration by additional parameters of panoramic cameras is not a calibration; with the determined geometry shown in figure 11, the dynamic effect of the scan is computed. It is depending upon the scan speed and the aircraft speed but also upon angular effects of roll, pitch and yaw. The linearity of the image line usually cannot be calibrated under flight conditions and it is also negligible in relation to the dynamic effects.

In figure 12 the laboratory calibrations of 2 HRSC CCD-lines are shown, this includes the non-linearity of the CCD-line and the rotation against the reference direction. The general trend also can be determined under flight conditions if crossing flight lines are available or based on a higher number of control points, but there is no need for an improvement of the laboratory values. For the HRSC like the corresponding Leica ADS40 the relation of the inertial measurement unit (IMU) to the CCD-line cameras is more important. This boresight misalignment has to be determined under flight conditions.

3 SPACE APPLICATIONS

By theory there are no differences between aerial and space applications. The difference is caused by the used sensors and the restriction of the orbit. Because of the large areas covered by space images a mathematical correct handling of the ground coordinate system is required. Also with an earth curvature correction a direct handling in national net coordinates leads to a loss of accuracy.

Only Russia is still using photos taken from space. For these photos similar conditions like for aerial images do exist. Some images, like the TK350 do have a reseau platen. This is reducing the problems with the film stability and the imaging plane.

| Figure 13: TK350 - systematic film deformation determined with 1050 reseau points, mean square deformation = 10μm | Figure 14: TK350 – systematic image errors of central part, largest vector 280μm |

The systematic film deformation of a TK350 photo determined by the reseau can be seen in figure 13. This is an individual film correction not requiring a calibration. The systematic image errors (figure 14) do show some geometric problems of the camera. Of course the results of a single determination of the image geometry has to be verified by independent data sets. The determined geometry of aerial images computed by self calibration with additional parameters is mainly based on the over-determination of a bundle block adjustment. If crossing flight directions are available, ground control points do have more or less no influence. This is different for space images; here we do have usually single images or models. The geometric characteristics of single images only can be determined by control points, but also in the case of a model (2 overlapping images) the influence

of the control points is dominating. So for the geometric analysis of space images a higher number of accurate and well distributed ground control points is required. The accuracy of the control points cannot be separated from the possibility of a good identification in the image. Points located on corners cannot be identified as well as symmetric points. Corner points always are shifted from the bright image parts to the dark parts. For symmetric points such a shift is unimportant because it is equal in all directions. We do have the same situation for photos like for digital images.

Only small satellites are equipped with CCD-array cameras, like the group constructed by Surrey Satellite Technologies (SSTL) - for example the UoSAT-12 and the BILSAT-1. The calibration of these systems is reduced to the influence of the optics - the radial symmetric and the tangential distortion – as well as the focal length and the location of the principal point. In addition the CCD-array may have a slightly different dimension in both directions. The very narrow field of view does not really require the determination of the principal point – the bundle of rays will not be deformed by a small offset from the center. Also the focal length is not so important because the rays are close to parallel. The radial and tangential lens distortion can be determined without problems with a limited number of control points and overlapping images.

The dominating number of space sensors used for mapping purposes, are CCD-line sensors. An area will be imaged with the movement of the satellite in the orbit and/or a rotation of the system. Most systems are not just equipped with only one solid CCD-line but with a group of shorter lines combined together.
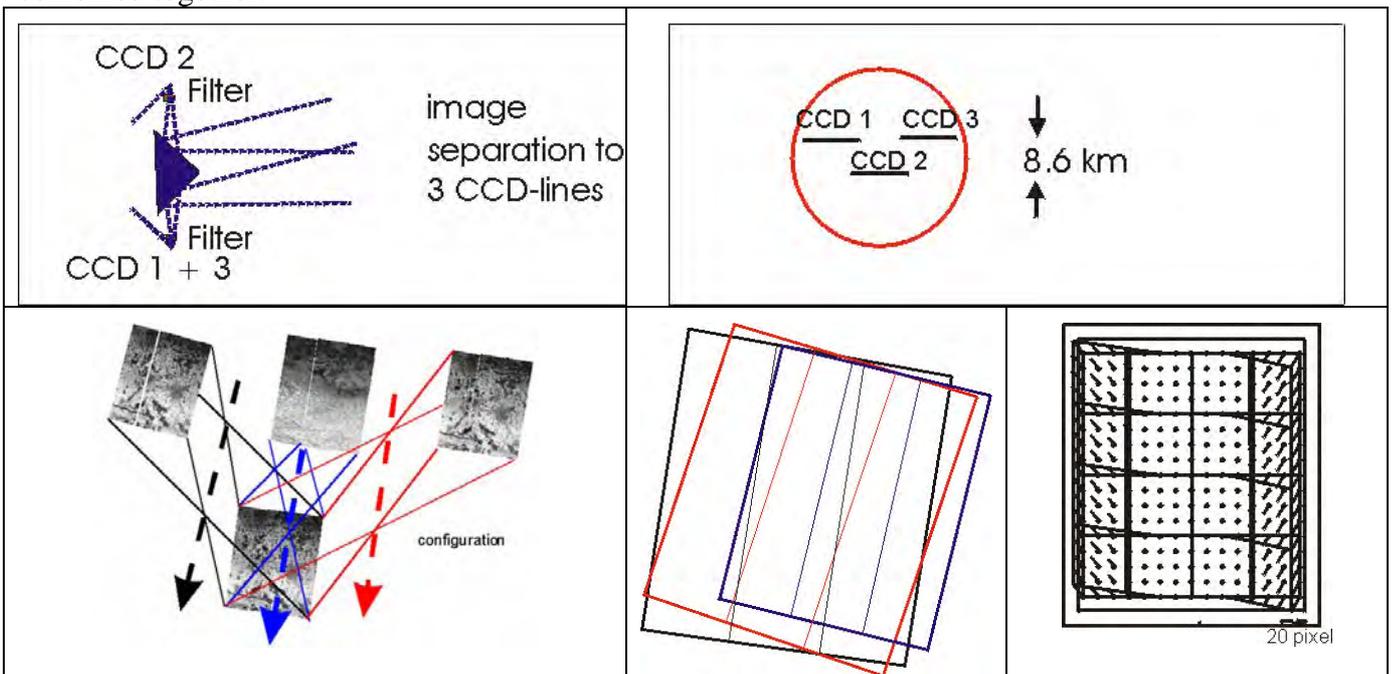

Figure 15: calibration of IRS-1C Pan-camera

upper left: configuration of CCD-lines in camera   upper right: imaged elements on ground

lower left and center: configuration of used test data set   lower right: image geometry of full scene

The geometric relation of the IRS-1C Pan-camera has been investigated based on the original sub-images (Jacobsen 1998). The IRS-1C Pan-camera has three CCD-lines; the parts imaged at the same instant on the ground are shown in figure 15, upper right. The time delay of CCD2 can be respected by the matching of the slightly overlapping sub-images. With a configuration of three scenes in the area of Hannover (figure 15 lower left) where enough control points are available, the system has been calibrated. With a special group of additional parameters (formula 3) the relation of the roughly merged sub-images could be determined by bundle orientation with the Hannover

program BLASPO for handling satellite line scanner images. The geometric relation can be seen in the lower right part of figure 15. Obviously the CCD-lines are not exactly aligned. This calibration information has to be used for the matching of the sub-images to a more or less error free synthetic image.

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X = X + P11 * (X-14.)      if x >  14.
X = X + P12 * (X+14.)      if x < -14.
Y = Y + P13 * (X-14.)      if x >  14.
Y = Y + P14 * (X+14.)      if x < -14.
X = X + P15 *SIN(X * 0.11)*SIN(Y*0.03)
```

Formula 3 : special additional parameters for the IRS-1C-calibration

Such a calibration is possible just with one scene, based on control points. The used configuration of 3 scenes, taken from different directions has the advantage that one sub-scene is stabilising the other (see figure 15 lower center), connected by tie points. So by theory, the calibration with additional parameters is also possible with a minimum of control points.

The described calibration has to be made for all space system based on a configuration of CCD-lines. It belongs to the calibration phase which takes for the very high resolution space systems between one and two month. Only so the reached sub-pixel accuracy is possible with SPOT, IKONOS, QuickBird and the other SPACE images.

Figure 16: systematic image errors

QuickBird	SPOT	ASTER
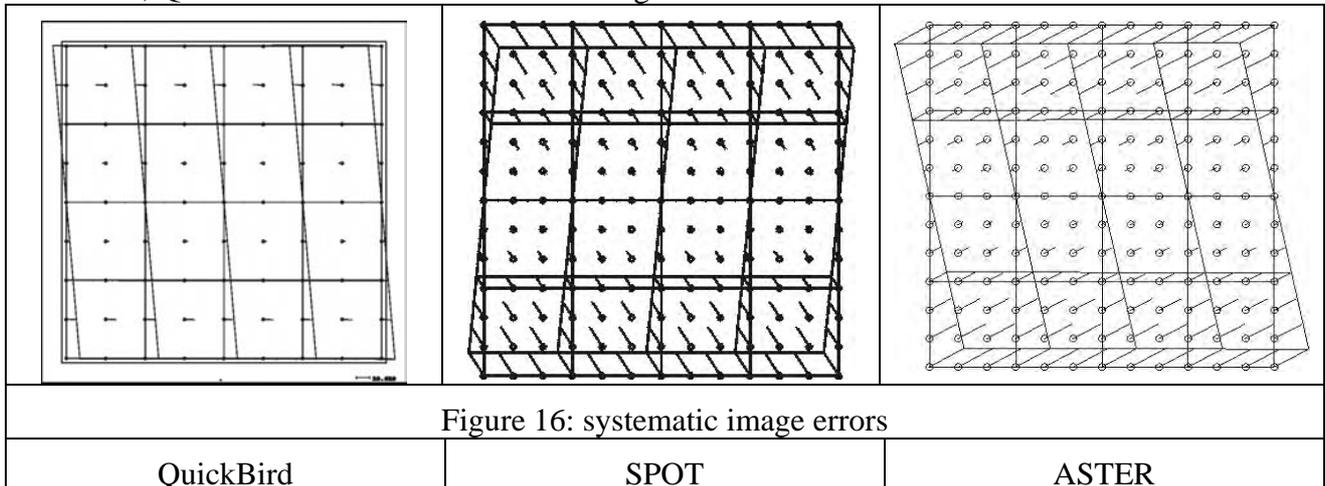
Bundle adjustments of different original space images with program BLASPO resulted in "systematic image errors" shown in figure 16. In no case a deformation of the imaging line could be detected – only this would justify an additional calibration of the CCD-line sensors. The shown deformations are just compensating discrepancies of the orbit and attitude information; that means the individual exterior orientation. The values are in the range of just few pixels.

Rectified space images like IKONOS Geo and QuickBird Standard and OrthoReady have not shown any systematic effects. For the exact handling of old IKONOS Geo data without the information of the rectification plane height level, in addition to the relief displacement an affine transformation to control points is necessary. The reached sub-pixel accuracy did not show any systematic effects, confirming the used calibration. Of course also the available exterior orientation can be analysed, leading to a system calibration which is including also the relation of the imaging sensor to the inertial measurement unit and the star cameras as well as the focal length. The very narrow field of view does not allow a separation between effects of the focal length and the flying height (satellite orbit ellipse). For the boresight calibration a higher number of controlled scenes in different areas are required.

SUMMARY

The geometry of perspective aerial cameras can and should be determined under flight conditions by a bundle block adjustment with self calibration by additional parameters. The difference of the real geometry against the mathematical model of perspective is shown by the "systematic image errors". Only some parts do show a long time stability like the radial symmetric distortion. The focal length and the location of the principle point usually can be determined only by using projection center coordinates determined by relative kinematic GPS-positioning in two different height levels. The used set of additional parameters has to be reduced to the required parameters which do have a limited correlation. This should be done automatically by the bundle adjustment program using statistic tests. The self calibration should not include additional parameters which are highly correlated under usual conditions like the radial symmetric components as a polynomial function of the radius.

CCD-line scanner do often use a combination of shorter CCD-lines. The calibration of such a system can be made under flight conditions. For aerial systems the geometric advantages of crossing flight lines can be used, which is reducing the number of required control points to a minimum. Also for space sensors the number of required control points can be reduced if images of the same area taken from different orbits are available. The calibration of a single image requires a higher number of precise control points.

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