Geometric Calibration of Space Remote Sensing Cameras for Efficient Processing

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1. Abstract

Different cameras are used in space. From Russian film cameras over panoramic cameras up to digital cameras with more than one CCD-line are in use. A laboratory calibration of the cameras before start can give some geometric information, but the acceleration during satellite launch may change the geometry. So finally only a self-calibration based on images taken from space can lead to the required information. It is necessary to have more than one self-calibration to be able to check the stability of the geometry. This publication is mainly concentrated to the self-calibration.
In addition to the meaning and details of additional parameters, including the required statistical tests, the influence of the reference system together with the refraction is explained. By means of different examples the possibilities of the self calibration is demonstrated.

2. Introduction

The correct geometric reconstruction of imaged objects is only possible with knowledge of the geometric relation of the used sensors and other influencing parameters. If the used sensor has a high mechanical stability, that means the geometry can be reproduced, a pre-calibration is possible. If this is not the case, a self-calibration for every project based on the available over-determination is required. Also a combination between pre- and self-calibration is possible, for example the lens distortion will not change even if the location of the film in a camera is not well defined.

Definition: **Geometric calibration**	= determination of the geometric relation of the imaging process of a camera
Self calibration	= determination of the geometric relation of the imaging process

Space applications do have the disadvantage of a limited number of images in the projects, so the geometric relation usually cannot be determined with tie points, ground control points are required. That means, very often it is not possible to separate between an error of control points and a "systematic image error". The commonly used expression of **"systematic image error"** is misleading, we only do have an **error or lack of knowledge of our mathematical model.**
There is a general difference between the calibration of a central perspective camera and a scanning camera. The central perspective camera is independent upon the movement and rotation of the satellite, which is influencing images of a scanning

camera. Scanning cameras can be line sensor cameras with no active movement during imaging or panoramic cameras. The self-calibration of digital images based on line sensors usually is not limited to the determination of the geometric conditions in the imaging line, it includes also the influence of the sensor movement.
By self-calibration it is not possible to identify the source of geometric problems, only the deviation between the used mathematical model and the imagaging geometry can be determined. If the reason of differences is located for example in the lens system, the image flattening, the refraction or in some cases the ground coordinate system, cannot be seen. By self-calibration only an improvement of the mathematical model without knowledge of the real problems can be reached, but the formulas used by self-calibration should respect the known geometric problems.
Not all effects can be determined by self-calibration. For example, the space cameras usually do have a very limited view angle. In this case the focal length and also the location of the principle point are strongly correlated to the exterior orientation up to a direct mathematical dependency. So it is not possible to separate between an error of the location of the projection center based on known ephemeris and the inner orientation. But finally it is unimportant to have exact knowledge about the reason for the problems, it will not have an influence to the adjusted ground coordinates. Also for the prediction to areas with limited control point information the real reason for geometric problems is not important if corresponding imaging configurations are used.

3. Earth curvature, refraction and map projection

Before a self-calibration can be computed, all influencing parameters which may be important, should be respected. If any pre-information is available, it should be used and included into the mathematical model.
Some of the approximations used for handling usual aerial photos are not acceptable for space images. The mathematical model is based on an orthogonal coordinate system and a perspective image geometry. All differences against this model have to be respected by some corrections. In addition the basic mathematical relation can only be used for perspective images, for scanners not only one projection center is existing, a projection line has to be used.
In the case of a direct adjustment in the national net coordinate system, the effect of the earth curvature is respected by a correction of the image coordinates and the effect of the map projection is neglected. This will lead to not acceptable remaining errors for space images. Not only the size of the earth curvature correction is very large with up to 1mm, there is also a second order effect to the height.

$$\frac{\Delta z}{\Delta Z} = \frac{Zf}{R}$$

Δz = error in height caused by earth curvature correction
ΔZ = height differences on the ground
R = radius of earth Zf = flying height

formula 1: error in height caused by traditional earth curvature correction

The influence of the earth curvature correction is negligible for aerial photos because of the smaller flying height Zf. For a flying height of 800km we do have a scale error of the ground height of 1 : 8 or 12%.
Also the map projection will cause a deformation of the model which cannot be accepted. The deformation is depending upon the size of the model and the location within the coordinate system. For example a Metric-Camera-model can get a

deformation of up to 91m or after scale change up to 36m corresponding to 0.72mm in the map scale 1:50 000 what cannot be accepted.

The problem of the map projection and the earth curvature correction can be solved by use of an orthogonal coordinate system - the geocentric coordinate system or better for practical applications, with a tangential plane coordinate system in relation to the ellipsoid.

$$Dr = \left(0.113 \cdot \frac{(P1 - P2) \cdot Zg}{Zf - Zg} - \left(\frac{Zf \cdot 2410}{Zf^2 - Zf \cdot 6 + 250} - \frac{Zg \cdot 2410}{Zg^2 - Zg \cdot 6 + 250}\right) \cdot \left(r + \frac{r^3}{f^2}\right)\right) \cdot 10^{-6}$$

Zf = flying height above mean sea level [km]
Zg = mean terrain height above mean sea level [km]
f = focal length [mm] r = radial distance in image [mm]
P1 = air pressure mb in terrain height
P2 = air pressure mb in flying height $P = e^{(6.94 - Z \cdot 0.125)}$

formula 2: refraction correction [µm], based on 1959 standard atmosphere

Also the usual formulas for the refraction correction should be checked. Several formulas are based on polynoms only valid up to the usual flying heights for aircraft's and are delivering completely wrong results for space images.

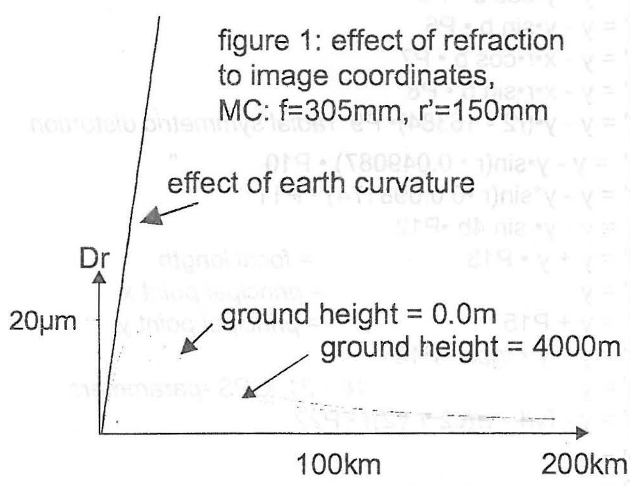


figure 1: effect of refraction to image coordinates, MC: f=305mm, r'=150mm

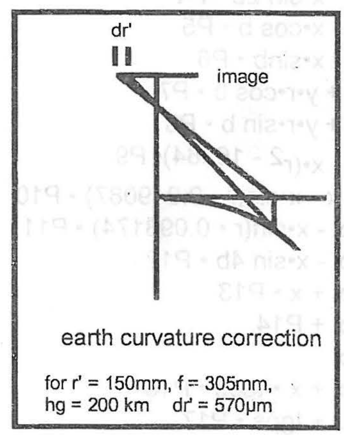


figure 2: earth curvature

4. Self-Calibration

In photogrammetry the commonly used mathematical model is the perspective relation of the incoming bundle of rays to the image coordinates. The collinearity equation is based on the location of the ground point, the projection center and the image point on an imaging ray. The bundle of rays in the object space should be identical to the bundle of rays in the image space and the image plane should be exactly a plane. This mathematical model is only a good approximation of the geometric situation. A lens system is always changing the bundle of rays and this may be also depending upon the used wavelength. Qualified optics do have a characteristic which is close to the mathematical model. In addition a film camera cannot guarantee a total flat location of the film in the camera. There is not only a limitation of the film flattening by vacuum, also the pressure plate is not total plane, it may be curved.

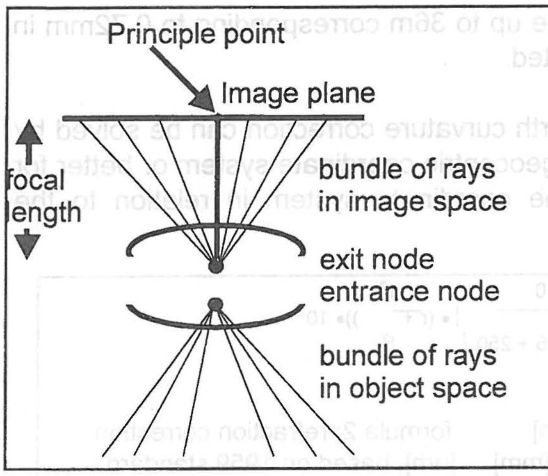


figure 3: mathematical model of perspective relation
bundle of rays in image space = bundle of rays in object space

$r^2 = x2 + y2$ arctan b = 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. $x' = x + y \cdot r \cdot \cos b \cdot P7$	$y' = y - x \cdot r \cdot \cos b \cdot P7$	
8. $x' = x + y \cdot r \cdot \sin b \cdot P8$	$y' = y - x \cdot r \cdot \sin b \cdot P8$	
9. $x' = x - x \cdot (r^2 - 16384) \cdot P9$	$y' = y - y \cdot (r2 - 16384) \cdot P9$	*radial symmetric distortion*
10. $x' = x - x \cdot \sin(r \cdot 0.049087) \cdot P10$	$y' = y - y \cdot \sin(r \cdot 0.049087) \cdot P10$	"
11. $x' = x - x \cdot \sin(r \cdot 0.098174) \cdot P11$	$y' = y - y * \sin(r \cdot 0\ 0.098174) \cdot P11$	"
12. $x' = x - x \cdot \sin 4b \cdot P12$	$y' = y - y \cdot \sin 4b \cdot P12$	
13. $x' = x + x \cdot P13$	$y' = y + y \cdot P13$	*= focal length*
14. $x' = x + P14$	$y' = y$	*= principal point x*
15. $x' = x$	$y' = y + P15$	*= principal point y*
16. $x' = x + x \cdot tgps \cdot P16$	$y' = y + y \cdot tgps \cdot P16$	
17. $x' = x + tgps \cdot P17$	$y' = y$	*16 - 21 GPS -parameters*
22. $x' = x - (y/f - x/r^2) \cdot P22$	$y' = y - (y/f - y/(c2 + y2)) \cdot P22$	
23. $x' = x - \arctan y/x \cdot P23$	$y' = y$	
24. $x' = x - \sin(y/300.) \cdot P24$	$y' = y$	
25. $x' = x$	$y' = y - \sin(y/300) \cdot P25$	
26. $x' = x - \sin(y/150.) \cdot P26$	$y' = y$	*22 - 26 for panoramic images*
27. $x' = x - x \cdot \sin(r*0.08)/r^{3/2} \cdot P27$	$y' = y - y \cdot \sin(r*0.08)/r3/2 \cdot P27$	*27 - 28 for calibration of*
28. $x' = x - x \cdot (r^4 - 2.6843 \cdot 108) \cdot P28$	$y' = y - y \cdot (r4 - 2.6843 \cdot 108) \cdot P28$	*fish eye lenses*

table 1: additional parameters used in program system BLUH

The deviation between the bundle of rays in object space to the bundle of rays in image space can be determined by self-calibration with additional parameters in a bundle adjustment. There are different sets of additional parameters in use, they are based on different assumptions about the distribution of points in the images and the source of the discrepancies. In the Hannover program system for bundle block adjustment BLUH the set of additional parameters listed in table 1 are used.

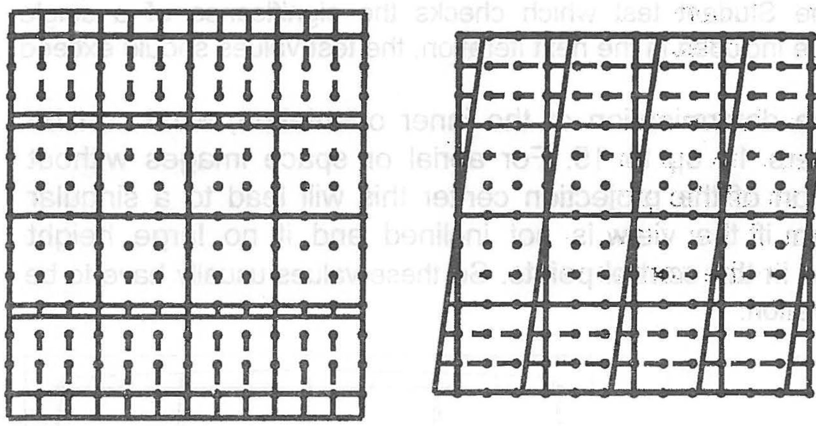


figure 4: effect of additional parameter 1 and 2 to the image coordinates

The set of additional parameters should be able to fit the main part of any "systematic image error". Known geometric problems, like the radial symmetric lens distortion should be covered by special formulas. Usually there is no information about the size and shape of the deviations available in advance. By this reason at first a block adjustment will be made with all additional parameters. Based on the results of the first iteration with additional parameters, the used set of additional parameters should be reduced to the parameters which can be determined and where the corresponding geometric effect is available in the data set. If additional parameters are included in the adjustment which cannot be determined with the present geometric condition, the adjustment can lead to poor results or the normal equation system can get singular.
In the program system BLUH 3 different statistical tests are combined, the student test and also the correlation and total correlation are checked.

$B_i = I - (\text{diag } N * (\text{diag } N^{-1})^{-1}$ **Bi = coefficient of total correlation (diagonal matrix)**
$0 <= b_i <= 1.0$ **I = identity matrix**
diag **N = diagonal of normal equation system**

formula 1: total correlation

By experience a limit of 0.85 for the coefficient of the total correlation was found. If this limit is exceeded, the corresponding additional parameter will be excluded from the adjustment by the program. The total correlation will give information, whether there are large dependencies to the whole group of parameters and orientations or not.

formula 2: student test

$$t_i = \frac{z_i}{\text{sigma0} * q_{ii}}$$

zi = value of the additional parameter
ti = test value of the Student test
sigma0 = standard deviation of unit weight of the block adjustment

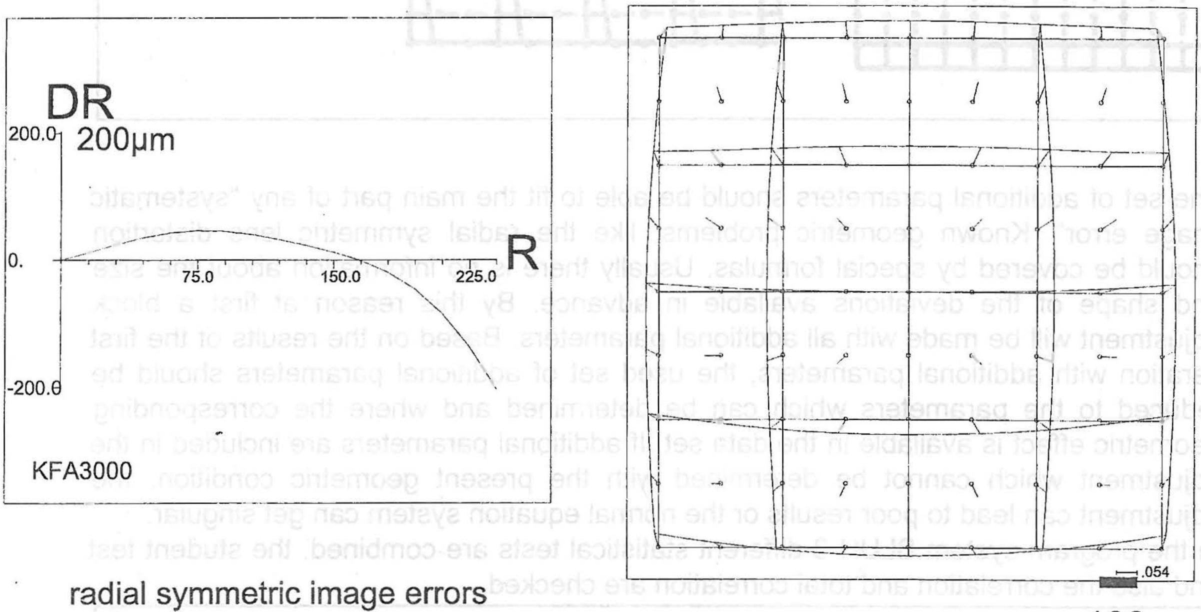
formula 3: correlation

$$r_{ij} = \frac{q_{ij}}{q_{ii} * q_{jj}}$$

q = element of empirical cofactor matrix of the additional parameters
rij = correlation coefficient between parameter i and j

The correlation coefficients shall not exceed 0.85 as well; otherwise one of the two involved coefficients will be excluded from the further iteration. This decision is based on the test values of the Student test which checks the significance of a single additional parameter. To be included in the next iteration, the test values should exceed 1.0.

A typical problem is the determination of the inner orientation, what can be done with the parameters 13 up to 15. For aerial or space images without knowledge of the location of the projection center this will lead to a singular normal equation system if the view is not inclined and if no large height differences are available in the control points. So these values usually have to be determined by a pre-calibration.



radial symmetric image errors
systematic image error 100µm

figure 5: radial symmetric distortion and systematic image errors of KFA3000-images determined by self-calibration

PANORAMIC IMAGES

If the image geometry does not correspond to the perspective model, this has to be respected in the mathematical model and also with the structure of the additional parameters. The Russian space camera KVR1000 is a panoramic camera, that means, the image is scanned via a rotating mirror from one side to the other. As in the case of line scanner images we do not have a projection center, we do have a projection line. The information distributed by Sovinformsputnik, Moscow about the panoramic process is poor, so it was necessary to investigate the geometric relation.

$$y = f \bullet \tan(y/f)$$

$$x' = x/f \bullet \sqrt{f \bullet f + y \bullet y}$$

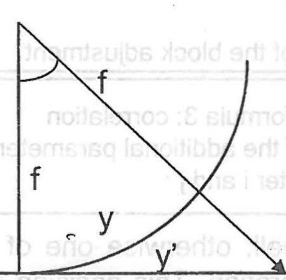


figure 6: transformation of panoramic images to perspective geometry

The dominating effect of the "systematic image error" is the angular affinity caused by the earth rotation during scanning. The typical S-shape of panoramic images (figure 8) is much smaller and cannot be seen in the graphical representation of figure 7. The general panoramic correction was respected in advance (figure 6).

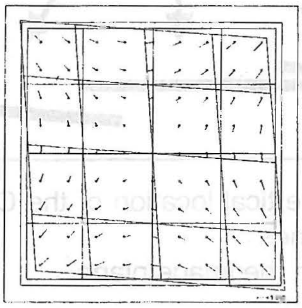


figure 7: geometric deformation of KVR1000 image in the Ruhr Area
image size: 180mm • 180mm
difference against perspective geometry: up to 1.2mm

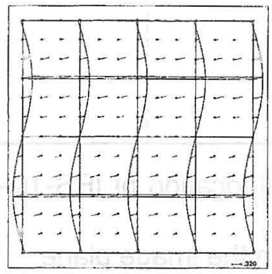


figure 8: typical S-shape deformation of panoramic images

LINE SCANNER IMAGES

The line scanner like IRS-1C, SPOT and MOMS do have the perspective geometry only in the sensor line. In the direction of the orbit the geometry is close to a parallel projection. So the photo coordinates as input for the collinearity equation are simplified to **x' = (x', 0, -f)** for stereo across track or **(0,y',-f)** for stereo in track - the photo coordinate y' or x' is identical to 0.0 (by theory up to 50% of the pixel size can be reached). The pixel coordinates in the orbit-direction of a scene are a function of the satellite position, or reverse, the exterior orientation of the sensor can be determined depending upon the image position in the orbit-direction. With the traditional photogrammetric solution the exterior orientation of each single line cannot be determined. But the orientations of the neighbored lines, or even in the whole scene, are highly correlated. In addition no rapid angular movements are happening.

A fitting of the exterior orientation by an ellipse fixed in the sidereal system – respecting the earth rotation - should be used, this describes the geometric situation in the best way. Because of an extreme correlation between the 6 traditional orientation elements, only the rotations and Zo are used in the Hannover program system BLUH / BLASPO as orientation unknowns. The use of all 6 traditional orientation elements are leading to a singular normal equation systems The remaining errors of the mathematical model, especially the affinity and angular affinity caused by errors of the orbit information have to be fitted by additional parameters.

The IRS-1C-PAN-camera has 12 000 pixel with a size of 7µm. The total size cannot be covered by one CCD-line-sensor, 3 are used, each with 4096 pixel. The relation of the 3 CCD-lines together have to be determined. Based on points, located in the overlapping area of the 3 sub-scenes it is possible to transform the sub-scenes together. In general there are the following geometric problems:

1. the sensors may have a different focal length
2. the sensors may be rotated against a straight line in the image plane
3. there may be a rotation against the image plane
4. there may be a shift in the image plane.

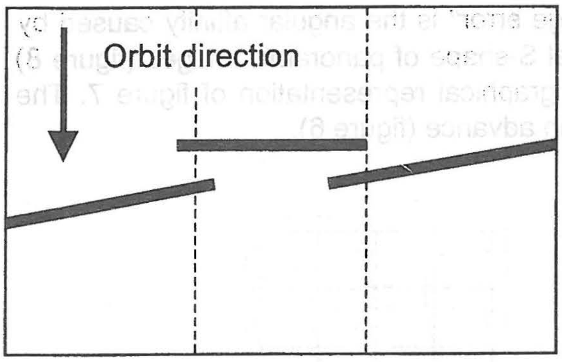


Figure 9: horizontal location of IRS-1C-PAN-camera CCD-lines sensors in the image plane

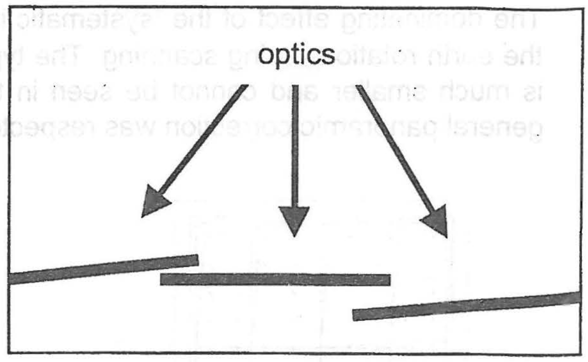


Figure 10: vertical location of the CCD-lines in the image plane

The shift of the IRS-1C-PAN-camera CCD-line sensors in the orbit can be respected by a time shift, or remaining errors by a shift of one scene to the other. A horizontal rotation against the reference CCD-line (figure 9) must be corrected by a resampling or an improved mathematical model of the block adjustment and/or the model handling. A vertical rotation and also a different focal length (figure 10) will cause a scale change in the x-direction (direction of sensor lines) of the outer scenes in relation to the reference scene in the center. There is no influence to the y-direction (orbit direction), a discrepancy of the focal length will only cause an over- or under-sampling.
Based on points located in the overlapping part of the IRS-1C-PAN-scenes, the sub-scenes can be shifted together. A similarity transformation for joining the sub-scenes together is by theory not justified and has also not improved the results.
With the unified sub-scenes of the PAN-camera a bundle adjustment of 2 or more scenes can be computed like with other CCD-line-Scanner-images. Only the possible source of errors caused by not aligned CCD-lines has to be respected by special additional parameters.

```
1   Y = Y +  P1 * Y
2   X = X +  P2 * Y
3   X = X +  P3 * X * Y
4   Y = Y +  P4 * X * Y
5   Y = Y +  P5 * SIN(Y * 0.06283)
6   Y = Y +  P6 * COS(Y * 0.06283)
7   Y = Y +  P7 * SIN(Y * 0.12566)
8   Y = Y +  P8 * COS(Y * 0.12566)
9   Y = Y +  P9 * SIN(X * 0.04500)
10  X = X + P10 * COS(X * 0.03600)
11  X = X + P11 * (X-14.)      if x >  14.
12  X = X + P12 * (X+14.)      if x < -14.
13  Y = Y + P13 * (X-14.)      if x >  14.
14  Y = Y + P14 * (X+14.)      if x < -14.
15  X = X + P15 *SIN(X * 0.11)*SIN(Y*0.03)
```

table 2: additional parameters of program BLASPO

11 – 14 = special parameters for IRS-1C-PAN

In the program BLASPO of the program system BLUH for handling line scanner images a different set of additional parameters is used than in BLUH itself for the handling of perspective images. A dominating effect of perspective images are the radial symmetric errors and by the imaging trough the lens system, a system of additional parameters based on polar image coordinates (parameters 3 – 12 table 1) are justified. This is not the case for line scanner images. In addition to the affine parameters 1 and 2, required for the orbit direction of the sensor, special additional parameters are required for the fitting of not regular movements and rotations of the satellite. The additional parameters 11 up to 14 are special parameters for the PAN-camera, they can determine and respect an error of the sensor alignment.

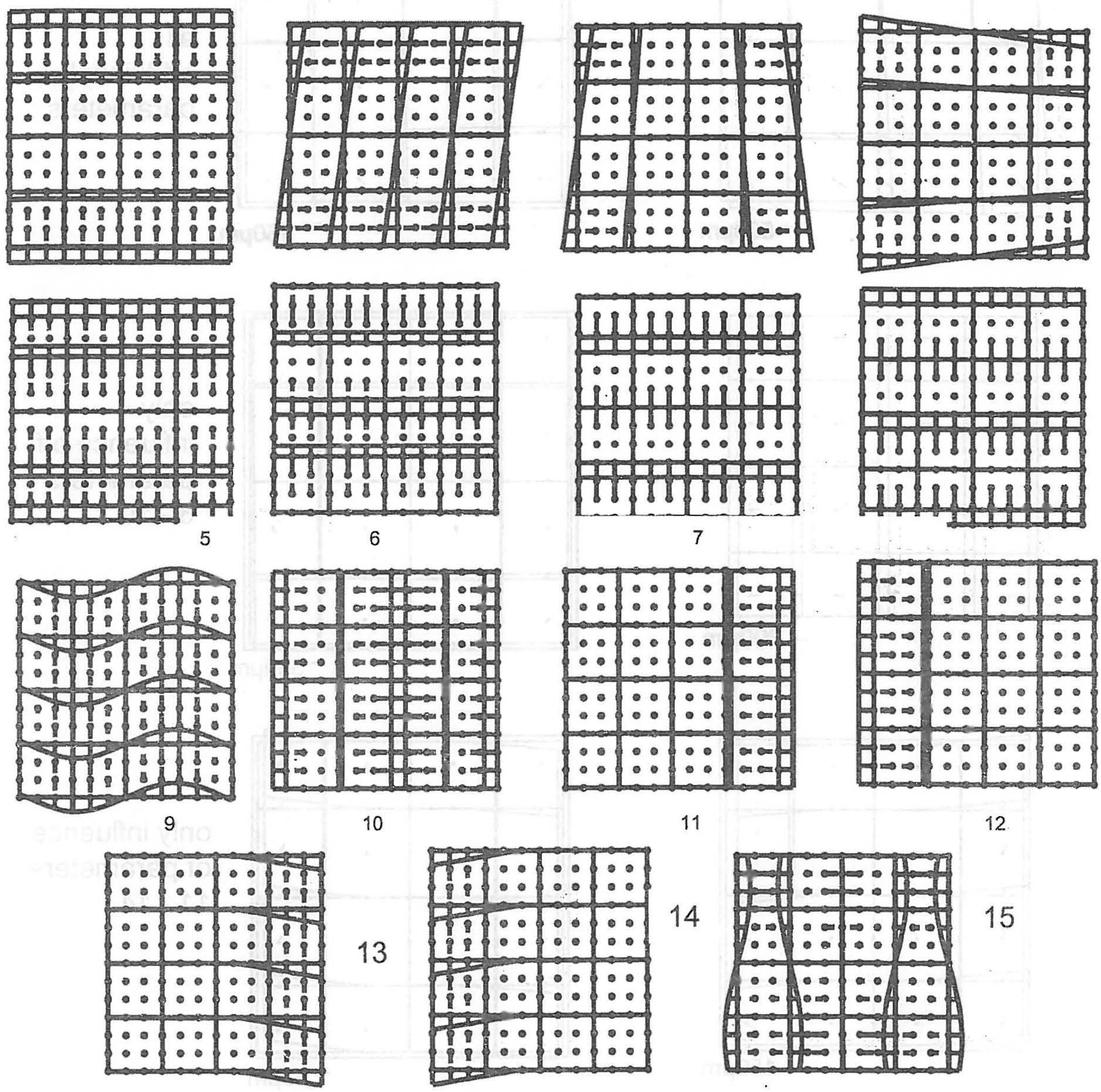


figure 11: effect of the additional parameters (BLASPO) to the image coordinates

A bundle adjustment of 3 IRS-1C-PAN-scenes over the area of Hannover has demonstrated the requirement of the special parameters 11 up to 14. That means, the 3 CCD-lines are not exactly aligned. In addition it was necessary to introduce these parameters separately for every scene. This shows a not stable relation of the CCD-lines, so a self calibration is required.

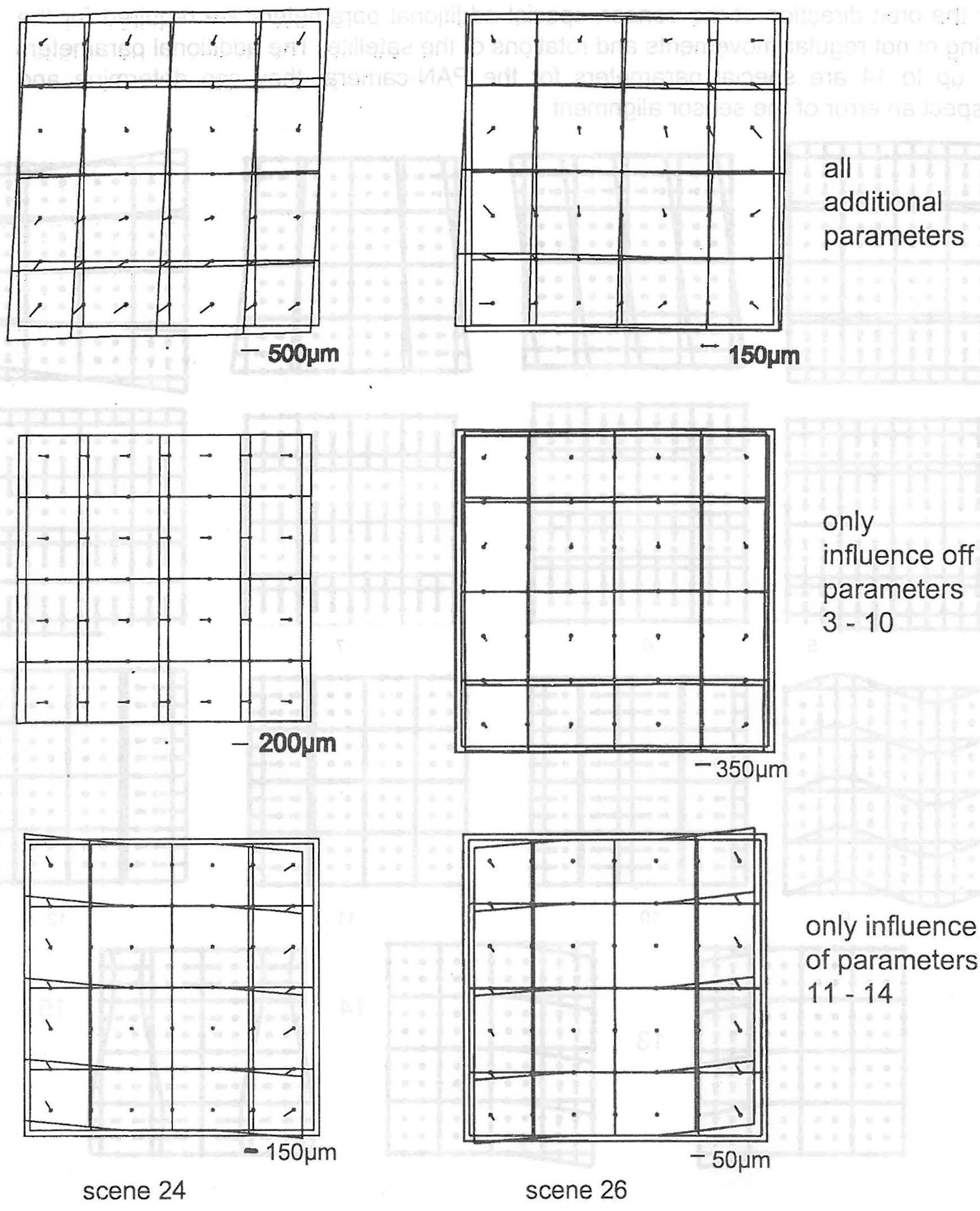


figure 12: systematic image errors IRS-1C-PAN-images, test block Hannover

The size and the shape of the systematic image errors of the 3 scenes of the IRS-1C-PAN-camera test block Hannover are quite different. An adjustment with parameters 1 and 2 individually and the other determined for all 3 scenes together was only leading to a vertical accuracy of +/- 83.2m. If the parameters are determined individually for every scene, the accuracy was improved to SZ=+/- 8.7m. This confirms the result of the shift of the sub-scenes together, the shift was also quite different for every scene. That means, the relation of the 3 CCD-line-sensors is not stable and has to be determined by self-calibration.

The influence of the additional parameters 3 up to 10 which can fit not regular movements and rotations of the satellite are shown with a larger size in figure 12, but there is a strong correlation to the exterior orientation. An adjustment with the parameters 1, 2 and 11 up to 14 are leading to SX=+/-7.1m, SZ=+/-5.0m and SZ=+/-9.7m. The parameters 1 and 2 are belonging to the exterior orientation because they can fit the yaw and the inclination of the orbit. The parameters 11 up to 14 are required for the determination of the CCD-line alignment. An adjustment with all additional parameters is only improving the result to SX=+/-5.5m, SY=+/-4.7m and SZ=+/-8.7m. In the case of the very small view angles of space images such an effect of the correlation between the systematic image errors and the exterior orientation cannot be avoided.

As resume of the IRS-1C-PAN-camera investigation in the test area Hannover it is obvious that the special additional parameters for the PAN-camera (11 – 14) are required, they have to be determined based on an adjustment with at least 5 well distributed control points in the stereo scene. The general parameters 3 up to 10 are not so important.

In the case of MOMS and SPOT we do not have the problem of 3 CCD-line sensors in the camera and corresponding to this, only the parameters 1 and 2 are required. The general parameters 3 – 10 are improving the results only slightly corresponding to the preceding results.

Conclusion

A combination between pre- and self-calibration of photographic and digital sensors is required if the sensor geometry is not stable. This is the case for all photographic sensors, but also for the PAN-camera of IRS-1C. The focal length and location of the principal point cannot be determined by self-calibration if no exact ephemeris are available. An adjustment with self-calibration by additional parameters is leading to sufficient results.

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