System Calibration for
Direct and Integrated Sensor Orientation

Karsten Jacobsen

Institute of Photogrammetry and GeoInformation, University of Hannover
Nienburger Str. 1, D-30167 Hannover
jacobsen@ipi.uni-hannover.de

Keywords: direct sensor orientation, calibration, coordinate system

Abstract

The precise determination of camera orientation by direct sensor orientation is depending upon a better knowledge of the camera geometry like required for standard block adjustment. The correlation of the flying height to the focal length plays an important role if the boresight misalignment is calibrated under different conditions like in the project area. But also the "systematic image errors" are influencing the results of the boresight misalignment and they may change depending upon the different conditions of the camera operation like caused by the air temperature and changed film cartridges. The significance of additional parameters has to be respected like also the correlation of the group of unknowns. In addition a correct mathematical model for the boresight calibration and the use of the calculated image orientations for ground coordinate determination is required.

1. Introduction

The direct sensor orientation with a combination of relative kinematic GPS-positioning and an inertial measurement system is used for the determination of ground positions based on sensor information. This presentation is limited to aerial cameras as sensors, but the system calibration is similar also for other sensors. The ground positions are determined from the projection centers, so we do have an extrapolation out of the area of the direct positioning. Such an extrapolation is very sensitive for any type of error or not accurate calibration, requiring a calibration of all parts and the whole system. Also the mathematical model has to be followed strictly. Opposite to this, the classic image orientation is an interpolation between control points which is not sensitive for limited calibration accuracy, the mathematical model and also for the high correlation of the exterior orientation components.

Some geometric problems of the direct sensor orientation can be solved by a combination of the observed image orientation together with image coordinates of tie points in a combined adjustment, the integrated sensor orientation.

2. Classic Determination of Image Orientation

The standard method for the determination of image orientations today is the bundle block adjustment. Based on control points, the image orientations are adjusted and they are used for the determination of the ground points. This is indirectly an interpolation of the ground points in the frame of the control points and not very sensitive for a not strict handling of the data.

The focal length and the location of the principal point from the calibration certificate cannot be improved by a usual block adjustment with control points located in a limited range of height in relation to the flying height above ground. Even with a combined bundle adjustment with projection centers determined by relative kinematic GPS-positioning this is not possible because of existing GPS-offsets and constant time errors if approximately the same image scale is used for the whole photo flight. Under flight conditions, the focal length is not the same like in the laboratory where it will be calibrated for the calibration certificate (Meier 1978). The focal length may change up to 0.05% depending upon the flying height. This is not a problem for the classical application; it will only cause an affine deformation of the photogrammetric model with a changed scale in Z. In the case of the OEEPE test block (Heipke et al 2000) the focal length could be determined based on direct sensor orientation from two different height levels with image scales 1 : 5000 and 1 : 10 000 together with control points (Jacobsen 2001). Against the calibrated focal length, discrepancies up to 41 µm have been shown. For the existing ground height differences of 60m against the level of the control points, this is causing a displacement in Z of 1.6cm which is not important for a flying height of 1500m above ground and usually will not be recognized. Different is the situation if the ground coordinates shall be determined by direct sensor orientation from a flying height of 1500m - 41µm change of the focal length is resulting in a Z-shift of 40cm – quite more than the general accuracy.

Usually the bundle block adjustments and also the data handling in the digital and analytical photogrammetric workstation will be done directly in the national coordinate system. This is not an orthogonal coordinate system like specified in the mathematical model. As a standard only the earth curvature correction will be respected.

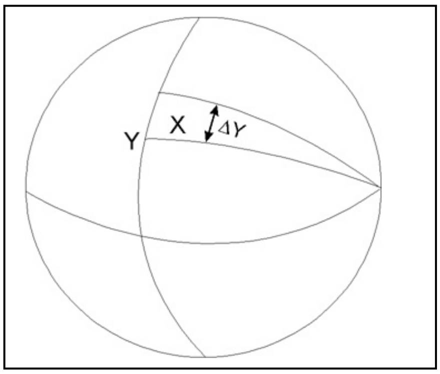

Figure 1: net projection

The national coordinate systems are flattening the earth. This is deforming the geometric relation. For keeping the influence small, all modern coordinate systems are conform, that means the angular relations over short distances are not influenced by the net projection. In the case of the transverse Mercator systems, the enlargement of ΔY by the flattening is compensated by an incremental enlargement of X (see figure 1). This is causing a scale change depending upon the distance from the reference meridian (formula 1). This scale change will happen only for the horizontal components X and Y. The height has a different definition and is independent upon the net projection; it always has the scale factor 1.0.

The usual photogrammetric data handling does not take care about the difference in scale in the horizontal components in relation to the height values. The model scale for the handling of aerial or space images is determined by the horizontal control points. The vertical control points usually do have no or only a negligible influence to the model scale because of the limited Z-range. So the horizontal scale will be used also for the vertical component that means the heights are directly affected by the local scale of the national net. The scale for the reference meridian of UTM-coordinates is fixed to 0.9996 causing a deviation of 4cm for a height difference of Δh=100m at the reference meridian.

$$scale = S0 \bullet \left(1 + \frac{X^2}{2R^2}\right)$$

S0 = scale factor for meridian
R = earth radius
X = distance from meridian

Formula 1: local scale of transverse Mercator system (first term)

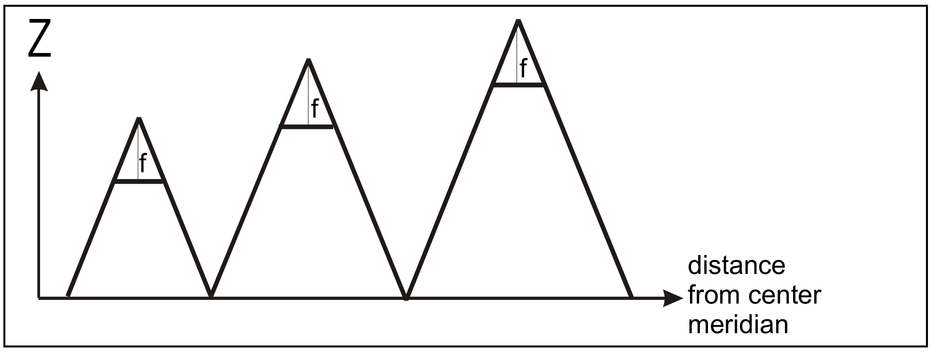

Figure 2: influence of the national net scale to the exterior orientation

The influence to the ground heights is usually within the accuracy range of the point determination. This is different for the projection centers (see figure 2). For the above mentioned OEEPE-test the distance from the reference meridian is in the range of 110km corresponding to a local scale in the UTM system of 1 : 0.99975, causing a 20cm shift of the projection centers for the image scale 1 : 5000 and 40cm for the image scale 1:10 000.

The affine model deformation can be compensated with a modified focal length (fc = f /local scale). This will compensate the scale difference between the horizontal and vertical scale in a sufficient manner for close to vertical view directions (see figure 3). The transfer of the so determined orientations to analytical or digital photogrammetric work stations has to respect the used geometric configuration.

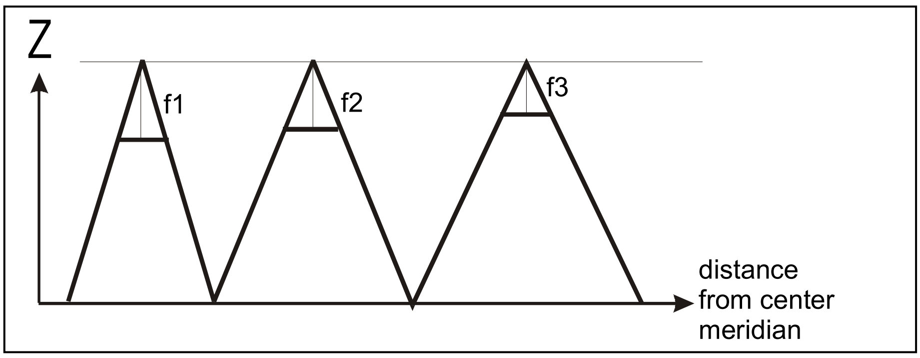

Figure 3: compensation of the scale difference between Z and X,Y by modified focal length

The flattening of the earth is also changing the base to height relation which is directly influencing the vertical scale but this is respected by the earth curvature correction.

All these problems do not exist if the photogrammetric data handling will be done in an orthogonal coordinate system, but this requires also a transformation of the coordinates and the orientation data. Of course independent upon the coordinate system also the refraction correction has to be respected.

3. Boresight Misalignment

The direct georeferencing is based on the attitude data determined by an inertial measuring unit (IMU) and relative kinematic GPS-positioning. The IMU contains giros for the determination of the 3 rotations and 3 accelerometer which information can be double integrated to deliver together with the attitude data coordinate differences. The IMU has a poor long time stability, so it must be supported by GPS, but is has a very high frequency which is supporting the GPS. The information of both systems is combined by Kalman filtering.

The IMU is fixed to the camera body, but the system of axis cannot be parallel to the camera coordinate system. This requires the determination of the relation of both systems of axis together with the offset of both origins. The offset of the GPS-antenna can be measured and respected. More difficult is the relation of the IMU to the camera. This boresight misalignment has to be determined by comparison of the IMU-rotations with the rotations of a controlled block adjustment. In addition also the shift values can be computed. As reference at least a block containing 2 flight strips, flown in opposite direction, should be used to enable the separation of shift values in the ground coordinate system from shift values depending upon the flight direction. If only one flying height level will be used for the reference block, it is not possible to separate the shift parameters mainly caused by the GPS-positioning from the influence of a discrepancy in the focal length. If the reference block will be flown with the same image scale like the project block, a separation of both parameter groups is not so important and the final effect to the ground coordinates is similar to the effect of a classic bundle block adjustment described before. If a reference block of the flight company will be used, which is usually close to the home airport, a change of the image scale cannot be avoided and the actual focal length has to be determined in addition to the misalignment. The common determination requires at least two different flying height levels. The accuracy is depending upon the height difference of the reference flight levels.

Under the condition of a dependency of the focal length from the flying altitude like described by (Meier 1978), by theory also two different reference flight levels are not sufficient, but indirectly the determination of the boresight misalignment together with the focal length has an effect to the indirectly computed ground coordinates in photogrammetric models like a three-dimensional interpolation and the second order effects are not so important.

For the determination of the boresight misalignment, the original attitude information, available as roll, pitch and yaw in the ARINC 705 definition (see ARINC 705 and Bäumker, Heimes 2001) has to be transformed into the form used in photogrammetry. The original attitude angles are related to geographic North, so the convergence of meridian has to be computed in addition to the other required transformations to the used coordinate system.

It is an open question, how often the boresight misalignment shall be determined. Of course this is depending upon the required accuracy and the used system. The new digital aerial cameras are designed for a stable connection of the IMU, so long time stability can be expected. But this is not the case for the analogue cameras which have not been constructed for this and changes of the boresight misalignment cannot be avoided. In a large project Hansa Luftbild (Dreesen 2001) made a check at every flight day over a period of 42 days showing two times a sudden change of the attitude data (figure 4).

A change in pitch or roll of 0.02° corresponds to 53µm and a change of yaw corresponds to up to 40µm in an image taken with a wide angle camera. That means, a general calibration for the whole project can be accepted for some orthoimage projects, but not for every task with higher accuracy requirements.

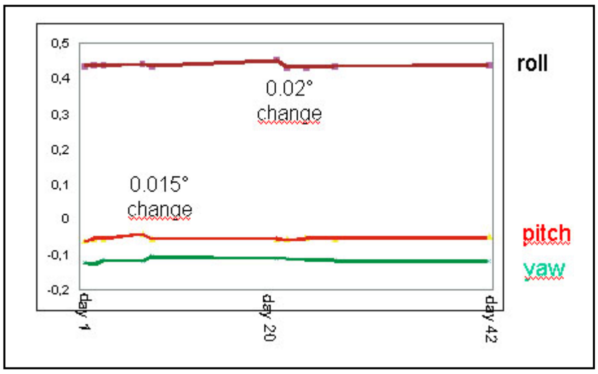

Figure 4: stability of boresight misalignment – results from Hansa Luftbild

4. Coordinate System

The correct handling of the reference block adjustment with the determination of the boresight misalignment and also the handling of the photogrammetric models of the project area based on the orientation determined by direct sensor orientation, should be done in a coordinate system corresponding to the correct mathematical model. Most bundle block programs and also most digital and analytical photogrammetric workstations are based on an orthogonal coordinate system. The geocentric coordinates are orthogonal but they do have the disadvantage that the original horizontal and vertical coordinates are mixed and it is not easy to interpret the discrepancies at the control points. By this reason, a tangential coordinate system is preferred. The handling of the block adjustment and also the determination of the image orientations can be done without any problem in the tangential coordinate system, but the final results of the model handling or the creation of orthoimages should be done in the national coordinate system. A transformation of the image orientation from the tangential to the national coordinate system can be done without any problems and without loss of accuracy, but this requires an additional step of computation which may be avoided, in addition the transformation of a GIS sometimes is not easy.

		σo [µm]	SX [cm]	SY [cm]	SZ [cm]	shift Z [cm]	SZ without shift [cm]
1	error free reference in tangential system	0.5	0.2	0.2	0.4	0.0	0.4
2	standard transformation to UTM without correction	27.9	1.0	0.9	31.3	31.1	3.5
3	UTM + correction of focal length	1.7	1.0	0.8	7.0	6.2	3.3
4	UTM + earth curvature correction	0.4	0.3	0.2	3.2	3.0	1.1
5	UTM + earth curvature + unique focal length	0.4	0.3	0.2	1.5	1.0	1.1
6	UTM + earth curvature + individual focal length	0.4	0.3	0.2	1.2	0.8	0.9

Table 1: combined intersection based on an error free data set in the tangential system, transformed to or computed in UTM , handled with different corrections; image scale 1:10000, f = 153mm (OEEPE test block)

For checking purposes, the reference bundle block and also the image orientations of the OEEPE test block project area have been determined in a tangential coordinate system. The image orientations and the ground coordinates of the project area have been transformed into the UTM-system. In addition the ground coordinates have been computed also directly in the UTM-system using the transformed orientations. For a more easy comparison, the used image coordinates of the project area have been corrected to an error free system.

The combined intersection of the error free reference in the tangential coordinate system is influenced by negligible rounding errors. If the image orientations are transformed to the UTM-system and the orientations are used without any correction, this is mainly influencing the height, dominated by a constant shift (line 2 of table 1). The result of the correct data handling shown in line 6 is very close to the original in the tangential coordinate system. The negligible loss of accuracy in Z, corresponding to a standard deviation of the x-parallax of 0.7µm, can be explained by rounding errors of the required transformations and image coordinate corrections. More or less identical results are achieved if the boresight misalignment will be determined directly in the UTM-system with the listed corrections.

If the reference area is located in the project area and the same flying height will be used, the different corrections will not have any influence if the data are handled for the determination of the boresight misalignment in the same manner like for the model handling. The only exception is the influence of the scale change by the map projection within the project area. If the scale change is not respected, it is causing a tilt in the West – East direction. At the reference meridian there is no tilt, at a distance of 150km from the reference meridian the tilt is 4cm / 10km and at a distance of 250km from the reference meridian the tilt is 9cm / 10km. Such a tilt of the block can be seen in figure 5 which is corresponding to line 5 of table 1. If any corrections are done correctly like in the case of line 6 of table 1, no more tilt can be seen. If the change of the UTM-projection scale will be compensated by the focal length, in the example of the OEEPE test block the variation of the focal length is reaching 4 µm over the 8km in West – East direction like shown in figure 5.

A complete system calibration includes also the inner geometry of the cameras presented by the "systematic image errors", showing the differences between the mathematic model of a perspective camera and the real camera geometry. If the self calibration by additional parameters will be used for the determination of the boresight misalignment at the reference block, the resulting systematic image errors have to be used also as a correction for the images in the project block. The usual photogrammetric workstations do not have the possibility of such corrections but it is possible to resample digital images by these corrections like it is possible with the Hannover program IMGEO. The use of the self calibration can only be recommended if the flight over the project area will be done under the same conditions like over the reference area. The flights have to be done at the same day and also with the same film cartridge. A change of the film cartridge has a strong influence to the systematic image errors and there is also no long time stability of the systematic effects. By this reason, the self calibration by additional parameters should be used only under special conditions for the direct sensor orientation. If the self calibration will be used, it is still more important to take care about the correlation between the different unknowns. Correlation values exceeding 0.95 should be avoided and the corresponding additional parameters should not be used.

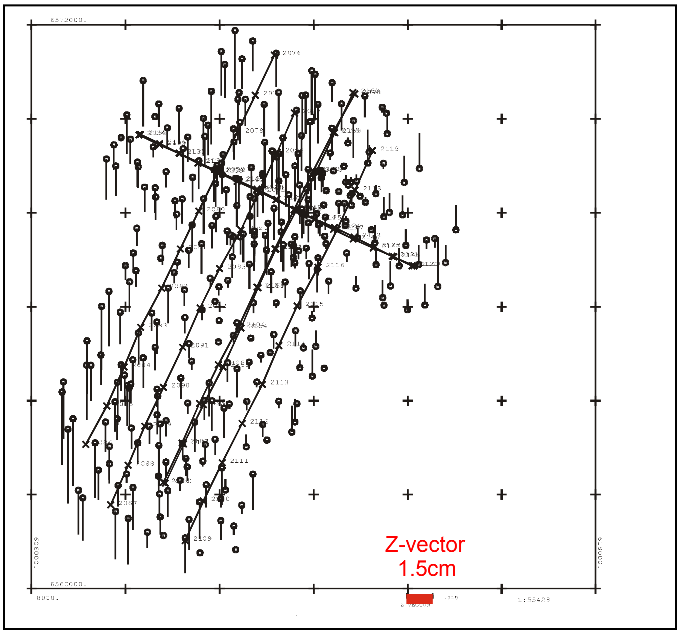

Figure 5: remaining Z-discrepancies of a combined intersection in the UTM-system with image coordinates improved by earth curvature correction and a unique change of the focal length by the mean scale of the UTM-system in the block

5. Model Setup

The exterior orientation determined by direct sensor orientation has reached a high accuracy level. With the data of the OEEPE-test block an accuracy of 10 – 20cm for the ground coordinates (X, Y, Z) based on this has been reached (Heipke et al 2001) – sufficient for several applications. In the OEEPE test “Integrated Sensor Orientation” test flights have been made by 2 companies with image scales 1 : 5000 and 1 : 10 000. The relative accuracy is not far away from the absolute accuracy, causing problems with the model set up. As a rule of thumb, the y-parallax in a model should not exceed in maximum 30µm, problems with the stereo view of the floating mark are starting at 20µm.

Another problem of the direct sensor orientation is the missing reliability, it can be checked only with the fitting of the final results like orthophotos and to some check points. Like the situation of the model set-up this can be improved by an integrated adjustment based on the direct sensor orientation together with image coordinates of tie points, not using control points. In addition, of course also the coordinates of the object points determined with image orientations from a combined adjustment will be more precise than just based on the direct sensor orientation.

	direct sensor orientation						**combined adjustment**		
	models	**RMSpy**	>10 µm	>20 µm	>30 µm	Spy max	**RMSpy**	>10 µm	Spy max
comp. 1	47	**46.6**	35	18	8	116.9	**9.0**	5	14.7
comp. 2	47	**21.6**	45	19	6	47.5	**9.8**	15	13.3

table 2: RMSE y-parallax [µm] of models and number of models exceeding specified limits, OEEPE test block

Table 2 shows the result of the root mean square y-parallax as RMSpy of the model set-up of an OEEPE test block sub-area. The main differences between the results based on data from both companies can be explained by the yaw, which is not so good for company 1. After the combined adjustment, there is no more problem with the model set-up and for both companies the results can be accepted for all models, visible also by the maximal RMSpy for all models. In addition, the integrated sensor orientation has improved the ground coordinates slightly against the result of an intersection with the orientation data from the direct sensor orientation.

Conclusion

The determination of the boresight misalignment for the direct sensor orientation has to be done together with a system calibration including the focal length and the principal point of the used camera. This is only possible with at least two quite different flying heights over the reference area. Only if the same image scale will be used for the project area like also the reference area, the determination of the inner orientation of the camera is not required. A self calibration by additional parameters can improve the final results only under special conditions.

The mathematical model used by most bundle block programs and also the photogrammetric workstations is based on an orthogonal coordinate system. The handling of the data in a tangential coordinate system can be done, but the final results are required in the national coordinate systems. It is possible to handle the calibration together with the data acquisition in the photogrammetric models directly in the national coordinate system if the image coordinates are improved by the earth curvature correction and if the focal length are fitted individually to the local scale of the national coordinate systems. This will not cause a loss of accuracy.

The problems with the y-parallaxes occurring during model set up can be solved by a combined bundle block adjustment or a model handling using tie points together with the orientation data from the direct sensor orientation. This also includes a reliability check.

References

[1] ARINC 705 (2001): http://www.arinc.com/cgi-bin/store/arinc

[2] Bäumker, M., Heimes, F,J. (2001): New Calibration and Computation Method for Direct Georeferencing of Image and Scanner Data using the Position and Angular Data of an Hybrid Inertial Navigation System, OEEPE Workshop "Integrated Sensor Orientation", Hannover 2001, on CD

[3] Dreesen, F. (2001): Erfahrung mit der direkten Georeferenzierung in der Praxis, Hansa Luftbild Symposium, Münster 2001

[4] Heipke, C., Jacobsen, K., Wegmann, H., Andersen, O., Nilsen, B. (2000): Integrated Sensor Orientation – an OEEPE-Test, IAPRS, Vol. XXXIII, Amsterdam 2000

[5] Heipke, C., Jacobsen, K., Wegmann, H.(2001): The OEEPE-Test on Integrated Sensor Orientation – Analysis of Results, OEEPE-Workshop Integrated Sensor Orientation, Hannover Sept. 2001

[6] Jacobsen, K. (2001): Aspects of Handling Image Orientation by Direct Sensor Orientation, ASPRS annual convention St. Louis 2001, on CD

[7] Meier, H.-K. (1978): The Effect of Environmental Conditions on Distortion, Calibrated Focal Length and Focus of Aerial Survey Cameras, ISP Symposium, Tokyo 1978