# INFLUENCE OF SYSTEM CALIBRATION ON DIRECT SENSOR ORIENTATION

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**Abstract**

The determination of object coordinates based on direct or integrated sensor orientation is an extrapolation from the projection centers to the ground coordinate system. Like any extrapolation it is sensitive for random and systematic errors as well as for a not precise data handling.

The direct sensor orientation is based on the combination of an inertial measurement system and relative kinematics GPS. The GPS antenna, the IMU and the imaging sensor are located in different positions and the last two do have a different orientation. Therefore, the calibration of all sensors and the relation between the sensors is of vital importance a for precise ground positioning. The system calibration includes the determination of the boresight misalignment, the interior camera orientation and the GPS antenna offset. A strict mathematical model is required. The inner orientation of the used camera has to be determined under flight conditions. In this presentation, the influence of the system calibration to the direct sensor orientation is investigated based on a data set of the test “Integrated Sensor Orientation” of the European Organization for Experimental Photogrammetric Research (OEEPE). The influence of the system calibration and also a not precise data handling will be shown.

**Introduction**

The determination of image orientations, or more general the sensor orientation, is a crucial requirement for any kind of imagery. The image orientation in photogrammetry traditionally is solved indirectly by block adjustment. This indirect method cannot be used by scanners such as LIDAR, SAR sensors, CDD-line cameras and other line scanner systems. The direct determination of exterior orientation parameters of any sensor became possible by the combined use of inertial measurement units IMU and GPS. The integrated sensor orientation using in addition image coordinates of tie points is becoming more and more popular also for the traditional field where bundle orientation has been used before.

A system calibration is of vital importance for the accurate determination of object points based on the combined use of relative kinematic GPS and IMU. It is the first step of the direct or integrated sensor orientation. It includes the determination of the attitude relation and shifts between the IMU body frame and the imaging sensor (boresight misalignment), GPS antenna offsets and time synchronization errors as well as the interior camera orientation. The system calibration parameters can be classified in two groups; the calibration parameters of individual sensors and the relation between sensors (Skaloud, 1999). The calibration between sensors contains the GPS antenna offset, the determination of a displacement vector and attitude difference between the IMU body frame and the imaging sensor. The combined use of GPS and IMU is solving the problem of the IMU-drift supported by the absolute GPS-positioning and reverse it avoids GPS cycle slips supported by the IMU handled together by iterative Kalman Filtering (see for detail Schwarz at al, 1994). The calibrated focal length, the principal point and the radial symmetric lens distortion is traditionally determined by laboratory calibration. These interior orientation parameters do change under flight conditions caused by quite different temperature relations and a different air pressure. The direct sensor orientation is sensitive to the change of the sensor geometry because of the extrapolation from the projection center to the ground. The offset between the GPS antenna and the imaging sensor can be measured by conventional survey methods. The determination of the boresight misalignment is a more difficult task because the attitude relation between the IMU body frame and the imaging sensor cannot be measured directly. Thus, the boresight misalignment is determined by a comparison of the GPS / IMU derived image orientation with the results of a bundle block adjustment over a reference area with control points.

Also a correct mathematical model is required for the optimal solution. The influence of the system calibration and a not correct data handling to the direct sensor orientation is investigated by analyzing the data sets of the OEEPE test “Integrated Sensor Orientation”. It includes the material of two calibration and also project flights operated by different companies with also different IMU-units. This presentation is limited to photogrammetric cameras, but the system calibration procedure is similar also for other sensors (see Mostafa and Schwarz, 2001).

**Coordinate System**

Block adjustments and also the whole photogrammetric data handling is usually made in the national coordinate systems. They are not orthogonal systems and do not correspond to the correct mathematical model used in photogrammetry. The national coordinate systems are map projections and follow the curved earth. The difference between the curved earth and the correct mathematical model is causing mainly a deformation of the vertical coordinate component. It is usually compensated by an earth curvature correction of the image coordinates.

The national coordinate systems are mixed coordinate systems. The horizontal coordinates X and Y are belonging to the map projection, but vertical coordinates are usually orthometric heights and related to the geoid. The national coordinate systems do have a local scale factor for the compensation of the flattening as shown in Figure 1. The orthometric heights are independent upon the location within the national coordinate system and not influenced by scaling effects of the map projection. This causes an affinity deformation of the coordinate system. The modern national coordinate systems are conformal projections. In differential units, angular relations are not changed, that means the local scale is the same in all horizontal directions. The Mercator systems are fixing the scale in the reference meridian; Lambert systems are fixing the scale in a selected parallel of latitude and Hotine systems in an inclined direction. Perpendicular to the reference direction the coordinates are modified by a local scale to reach the conformal condition. In the reference meridian, UTM coordinates do have a scale factor $s_0$=0.9996. The local scale factor for other locations in UTM is computed by using the formula

$$s = s_0 \left( 1 + \frac{X^2}{2R^2} \right) \quad (1)$$

where $s_0$ is the scale factor of the reference meridian, $Y$ is the distance from the reference meridian, $R$ is the earth radius.

By traditional bundle block adjustment the image scale is based on control points. The vertical range of the control points is usually very limited in relation to the horizontal range, so the scale is determined by the horizontal control points. The vertical control points do have only a negligible influence to the scale. In the case of direct sensor orientation, the absolute orientation is based on directly determined projection centers and attitude data by GPS/IMU. The scale of the national net has an influence to the flying heights above ground and this influence is not negligible on direct sensor orientation (see Figure 2). The scaling effects do not exist, if the image orientation will be handled in an orthogonal coordinate system like geocentric or tangential. In this case, the orientation information has to be transformed into the national coordinate system for the handling of the model or the generation of orthoimages. Such a transformation of orientation data, from an orthogonal system to the national coordinate system will cause again the problems in the map projection or requires additional computation steps.

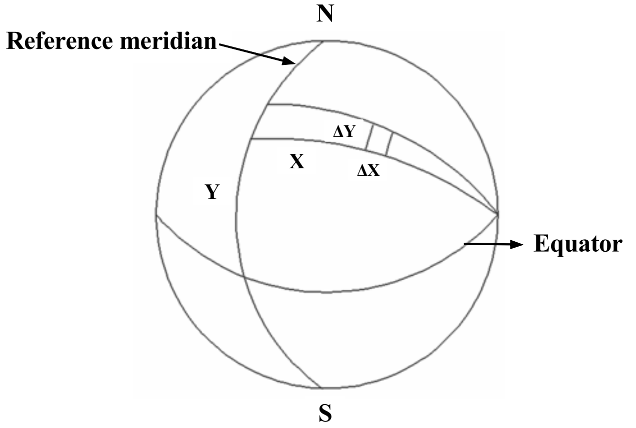


Figure 1. Scale factor in national net projection caused by convergence of the parallels

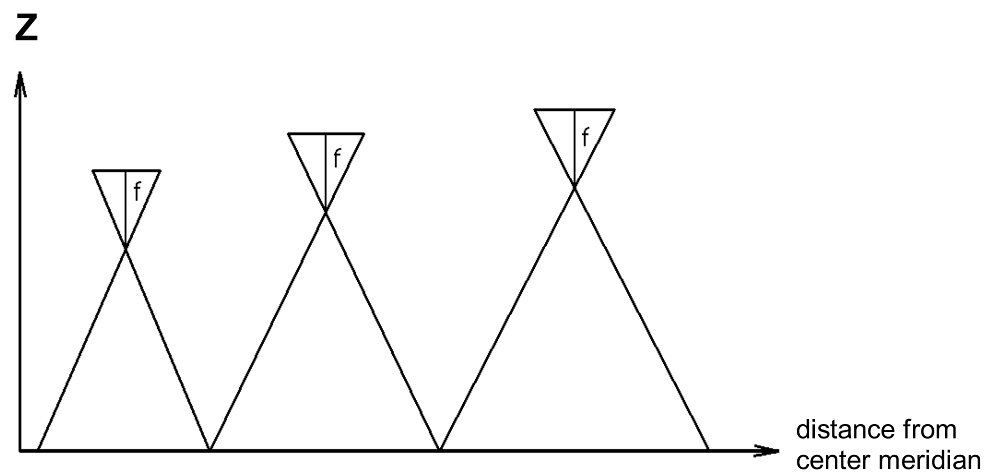


Figure 2. The influence of the national net scale to flying height on direct sensor orientation

The influence of the affinity model deformation can be compensated for nadir images with a modified focal length with the following relation: fc = f /local scale. This will compensate the difference between the horizontal and vertical scale in a sufficient manner. The used geometric configuration including the individually modified focal length has to be respected for the whole photogrammetric process up to the photogrammetric workstation.

**Camera Calibration**

As mentioned before, under actual flight conditions the focal length differs from the camera calibration certificate. The interior orientation is determined in laboratories under constant and homogenous temperature conditions. Under actual flight conditions, the temperature is different and we do have a not neglect able vertical temperature gradient causing a lens deformation. Meier (1978) investigated the focal length change of Zeiss cameras depending upon flying height and camera mounting. The change of the focal length as result of actual flight conditions is of mayor importance for direct sensor orientation since the focal length corresponds to a scale factor for the height. The situation is similar for the location of the principal point. Because of a limited vertical object range in a traditional bundle block adjustment, the scale is determined by horizontal control points and an error in the focal length is compensated by the flying height above ground. The focal length and location of the principal point cannot be determined by self calibration because of the extreme correlation between the flying height and the focal length. This is different if there is a stronger vertical variation of the control points, but it can be solved also with coordinates of the projection centers determined by relative kinematic GPS-positioning. The additional GPS-information introduces also an unknown additional vertical shift factor for the GPS positions and if we do have only one flying height, we cannot separate the GPS shift from the focal length. By this reason at least two different flying heights are required for a complete camera calibration together with the determination of the GPS shift (Jacobsen, 2001).

**Boresight Misalignment**

The offset vector from the GPS antenna to the camera projection center (entrance nodal point) can be measured by conventional survey methods. The IMU is fixed to the camera body and generates roll, pitch and yaw as attitude information of the IMU body frame together with the position by double integration of the acceleration. The system of camera axis will not be exactly parallel to IMU. Therefore, the boresight misalignment, the attitude and shift relationship between IMU body frame and camera, has to be determined.

A small test field equipped with control points is sufficient for the determination of the boresight misalignment. By traditional bundle block adjustment the exterior camera orientation can be adjusted. The attitude relations and shift values are determined by comparison of GPS / IMU derived attitude information and positions to the orientation data from bundle block adjustment. The reference block should contain at least two flight strips, flown in opposite directions to enable a separation of GPS shift values from the principal point location. The IMU attitude information and photogrammetric orientations can not be compared directly since the IMU attitude information is related to geographic north while the usual photogrammetric image orientations are related to grid north. The convergence of meridian has to be respected beside the other required transformations from roll, pitch, yaw to phi, omega, kappa (Jacobsen, 1999).

**Influence of System Calibration**

The influence of the different data handlings to the direct sensor orientation will be shown, using the data set of the OEEPE test "Integrated Sensor Orientation" (Heipke et al., 2000). The used test field in Frederikstad, Norway is about 5 x 6 $km^2$ and has 51 well distributed signalized control points with UTM/EUREF89 coordinates and ellipsoidal heights. The control point accuracy in test field is better than 0.01 m. The calibration flight in two different scales (1:5000 and 1:10 000) and the actual test flight in 1:5000 were carried out by Fotonor AS using a photogrammetric camera equipped with a wide angle lens, Ashtech GPS receiver and the Applanix POS/AV 510 system (see also Nilsen, 2002). The calibration flight arrangement and actual test flight patterns are shown in Figure 3 and Figure 4. In order to investigate the influence of the system calibration and the not precise data handling to the direct sensor orientation, different sets of the system calibration parameters were computed. The bundle block adjustment of the reference block with all images (1:5000 and 1:10000) has been made in the UTM coordinate system and the orthogonal tangential system. These approaches can be described as follow:

(a) the standard bundle block adjustment, with self calibration by additional parameters,
(b) GPS supported bundle block adjustment,
(c) GPS supported bundle block adjustment, with self calibration by additional parameters,
(d) GPS supported bundle block adjustment, using corrected interior orientation parameters,
(e) GPS supported bundle block adjustment, using corrected interior orientation parameters with self calibration by additional parameters.

The focal length (f = 153.344 mm) from calibration certificate was used for the first three approaches. In the UTM system, the focal length got a correction of $\Delta f$ = 0.039 mm and the principal points $\Delta x_0$ = -0,024 mm, $\Delta y_0$ = 0.001 mm using an adjustment with self calibration by additional parameters (c). For investigation of the coordinate system influence, the bundle block adjustments have been made in addition in a tangential coordinate system with corresponding parameters and an approach like in the national coordinate system. In the tangential coordinate system, the computed correction for the interior orientation are different with $\Delta f$ = 0.015 mm for focal length and $\Delta x_0$ = -0,025 mm, $\Delta y_0$ = 0.006 mm for the principal point (c). The corrected interior orientation was used for the last two bundle block adjustments (approaches d, e) to investigate the influence of interior orientation to the ground coordinates.

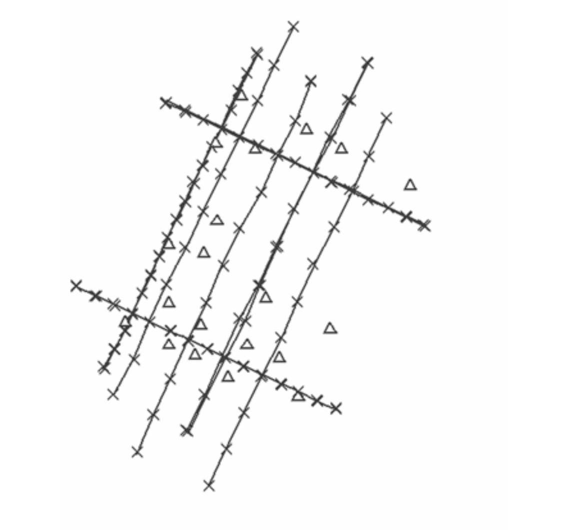

Figure 3. Calibration flight (1:5000+1:10000)

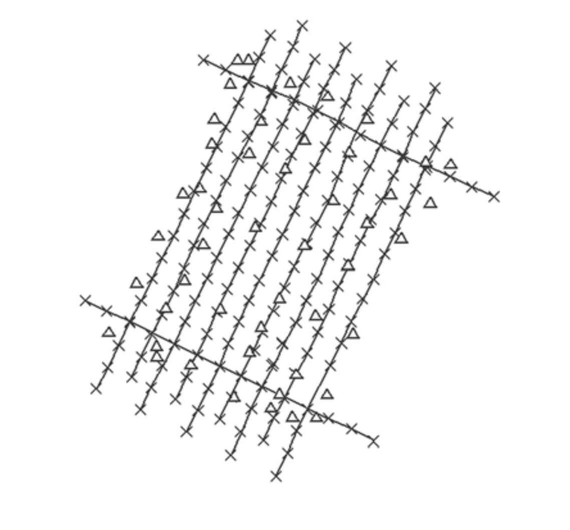

Figure 4. Test flight (1:5000)

The influence of interior orientation parameters determined by self calibration can be seen by the comparison of the results of approach (b) and approach (d) in Table 1. The object coordinates of signalized control points were adjusted and compared with the given reference coordinates. The bundle block adjustment results using the Hannover program system BLUH in the UTM and the tangential coordinate system are given in Table 1. The accuracy improvement shown by the root mean square of control point discrepancies, especially in Z at approach (d) is approximately corresponding to the influence of the changed focal length. When we compare the bundle block adjustment results in UTM and tangential coordinate system, the main differences are visible in approach (b). The root mean square difference of control points, especially in Z can be explained by the scaling effects of the UTM coordinate system. The differences of computed corrections for interior orientation parameters are also covering the average local scale factor in UTM. The standard bundle block adjustment results are approximately the same in UTM and the tangential system because of the limited size of the block and the same location of the calibration or reference block and the project block.

To investigate the influence of the local scale in the UTM coordinate system, the control points and the GPS/IMU-data have been transformed into 3 different locations with shift values of full degrees of longitude. The reference block is located in Frederikstad, Norway at East 10°56' North 59°11'.

| Approach | | number of control points | $\sigma_0$ [$\mu$ m] | RMS at control points [cm] | | |
|---|---|---|---|---|---|---|
| | | | | X | Y | Z |
| (a) (UTM) | reference | 20 | 4.97 | 1.4 | 1.0 | 1.0 |
| (a) (Tang.) | reference | 20 | 4.96 | 1.4 | 1.0 | 1.0 |
| (b) (UTM) | combined with GPS | 20 | 12.02 | 8.2 | 6.5 | 25.8 |
| (b) (Tang.) | combined with GPS | 20 | 8.93 | 3.0 | 2.6 | 10.4 |
| (c) (UTM) | GPS + add. parameters | 20 | 6.58 | 1.5 | 2.5 | 3.0 |
| (c) (Tang.) | GPS + add. parameters | 20 | 6.45 | 1.4 | 2.7 | 2.8 |
| (d) (UTM) | " + inner orientation | 20 | 8.74 | 2.7 | 1.8 | 8.4 |
| (d) (Tang.) | " + inner orientation | 20 | 7.70 | 1.6 | 1.4 | 4.3 |
| (e) (UTM) | using improved f | 20 | 5.97 | 2.6 | 2.3 | 3.2 |
| (e) (Tang.) | using improved f | 20 | 5.67 | 2.3 | 2.4 | 3.6 |

Table 1. Reference bundle block adjustment results in UTM and tangential coordinate system

The scale variation of the reference block and the shifted reference blocks are limited due to the location of the reference block in Norway at latitude of 59° 11'. At the equator, the local scale within a UTM coordinate system goes up to 1.0014. This would cause a vertical shift of the projection centers of 1.4m over 1000m flying height if the local scale would not be respected. The affinity 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 2). For the reference block shifted into 3 different locations, the corrected focal length was computed by bundle block adjustment with self calibration by additional parameters in the UTM and tangential coordinate system (see table 2).

| Distance from center meridian | local scale in UTM | focal length (mm) | | | |
|---|---|---|---|---|---|
| | | UTM | UTM with earth curvature | UTM with local scale correction | tangential system |
| 4' | 0.999 60 | 153.406 | 153.421 | 153.360 | 153.359 |
| 56' | 0.999 64 | 153.400 | 153.416 | 153.360 | 153.359 |
| **1° 56'** | **0.999 75** | **153.383** | **153.398** | **153.360** | **153.359** |
| 2° 56' | 0.999 96 | 153.353 | 153.368 | 153.360 | 153.359 |

Table 2. Focal length determined in reference blocks shifted into 3 different locations (1°56’ = original)

As expected, the determined focal length with or without earth curvature correction in table 2 is changed depending upon the scale of the map projection in the different location if the reference block has been adjusted with image coordinates improved by earth curvature correction and the local map scale is respected by an individual modification of the focal length within the bundle adjustment program. The same focal length was computed in all locations in the map coordinate system if the local scale has been respected and the mathematical correct tangential coordinate system. The difference of just 1 micron of the computed focal length is caused by some rounding effects. That means, a system calibration based on a reference block not at the location of the project area has to be handled in a tangential coordinate system, which takes a little more handling effort, or it can be adjusted in the national coordinate system if the local scale will be respected.

The image orientations determined by the calibration flights with different approaches are used for the determination of the boresight misalignment. The orientations from the reference adjustment were transformed into roll, pitch and yaw and used as reference for the determination of the attitude relations. For the shift values, the projection center coordinates determined by the reference adjustment are compared with the GPS/IMU derived projection centers. The discrepancies do show also the quality of the GPS/IMU positions in relation to the photogrammetric orientations. The GPS/IMU derived attitudes and positions of test flight were improved by the different sets of boresight misalignment. The improved attitude data were automatically converted into the photogrammetric definition of rotations. With the improved image orientations and manually measured image coordinates of the control points, used as independent check points, the ground coordinates of the check points were computed by common intersection (direct georeferencing). The object coordinates of check points were compared with the given reference coordinates. The used system calibration approaches, $\sigma_0$ of combined intersections and the RMS of differences at check points are given in table 3.

For the first two approaches shown in table 3, the boresight misalignment has been determined by standard bundle block adjustment and the interior orientation from the calibration certificate were used. The reached accuracy of direct georeferencing is not too much different for handling it in the UTM and the tangential coordinate system. The influence of the local scale cannot be seen here because the calibration and the project block do have the same location and they are limited in the size. In the third and fourth approach, the reference adjustment has been supported with GPS-projection center coordinates and the inner orientation has not been improved. The influence of the inner orientation can be seen in comparison to the last two cases (table 3 last 2 lines). The influence of the local scale to the map projection can be seen in comparing the results reached by handling in the UTM- with the tangential coordinate system. The last two combined intersections are based on improved inner orientations. The corrections for interior orientation are different in UTM and the tangential system due to the scaling effects of the UTM system. The improvements of the root mean square differences at check points in Z are approximately corresponding to the change of the focal length and do give us an idea about the influences of interior orientation to the direct sensor orientation.

| Approach | check points | $\sigma_0$ [$\mu$m] | RMS of differences at check points [cm] | | |
|---|---|---|---|---|---|
| | | | X | Y | Z |
| misalignment by standard bundle adjustment with calibrated focal length in UTM | 49 | 24.39 | 6.6 | 6.1 | 15.2 |
| misalignment by standard bundle adjustment with calibrated focal length in tangential coordinate system | 49 | 24.55 | 6.6 | 6.5 | 12.4 |
| misalignment by bundle adjustment supported by GPS projection centers with calibrated focal length in UTM | 49 | 21.20 | 7.1 | 4.9 | 28.5 |
| misalignment by bundle adjustment supported by GPS projection centers with calibrated focal length in tangential coordinate system | 49 | 21.20 | 7.1 | 5.0 | 12.2 |
| inner orientation by system calibration, computed in UTM with local scale | 49 | 20.06 | 6.6 | 4.0 | 8.6 |
| inner orientation by system calibration, computed in tangential coordinate system | 49 | 18.03 | 6.7 | 4.6 | 8.7 |

Table 3. Results of combined intersections computed in UTM and tangential coordinate system under different conditions

**Conclusions**

The direct sensor orientation is an extrapolation from the projection centers to the ground coordinate system. Because of this, it is sensitive for random and systematic errors as well as for a not precise data handling like any extrapolation. The system calibration, including the boresight misalignment and the inner orientation of the used camera, is of mayor importance for direct sensor orientation because any discrepancies between the assumed mathematical model and the true physical reality during image exposure causes not negligible errors in object space. Under flight conditions the interior is not identical to the laboratory calibration, so it has to be improved by the system calibration. If the reference block is located within the project area and the flying height is the same, the determination of interior orientation parameter in actual flight condition is not important since several systematic errors are compensated.

The mathematical model used in photogrammetry is based on an orthogonal coordinate system. The data handling can be done directly in the mathematic correct tangential coordinate system. In that case, a transformation from tangential coordinate system to the national coordinate systems is required for the model handling or the generation of the orthoimages. A data handling is possible without loss of accuracy directly in the national coordinate system if the image coordinates are improved by earth curvature correction and the local scale of the national net is respected by an individual modification of the focal length. The system calibration can be made in a different location, which means the reference block may be far away from the project area.

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