# ASPECTS OF HANDLING IMAGE ORIENTATION BY DIRECT SENSOR ORIENTATION

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## ABSTRACT

The direct sensor orientation by Inertial Measurement Units (IMU) in connection with relative kinematic GPS-positioning is becoming more and more important. This new technology still includes some not well known problems which will be discussed.

The camera calibration is much more important than for the traditional image orientation which can compensate some errors by the exterior orientation. In addition to the camera calibration, the boresight misalignment between camera and IMU has to be defined. With a calibration flight in 2 different flying heights over an area with control points, the misalignment and some components of the camera calibration can be defined, but caused by the problem of the dependency of the focal length from the outside air temperature this will finally lead only to a 3-dimensional interpolation of the system orientation which is usable for practical application. This includes also the aspect of the handling of the sensor orientation in the national coordinate system or a real orthogonal coordinate system like a tangential coordinate system to the Earth ellipsoid. The system calibration determined in the national coordinate system will lead to a different focal length and different misalignment values than in the case of a handling in a real orthogonal coordinate system, but if the mapping will be done in the same coordinate system like the calibration, there is finally no influence of the used coordinate system to the accuracy of the ground coordinates.

The theoretical background of the system calibration will be explained and the practical results will be demonstrated with 2 precise test blocks.

### 1. INTRODUCTION

The determination of the image orientation is a basic requirement for every type of photogrammetric data acquisition. The traditional method by means of bundle block adjustment is time consuming and needs a sufficient number of ground control points. The combined adjustment together with projection center coordinates, determined by relative kinematic GPS-positioning is reducing the effort for the ground control but it is still based on image coordinates of tie and control points. The progress of the hard- and software components of inertial measuring units (IMU) during the last years, allows now a direct sensor orientation based on the combined use of IMU and GPS for several applications. The relation between the IMU and the photogrammetric camera (boresight misalignment) has to be determined with a traditional bundle block adjustment. During this process it is also possible to calibrate the camera under operational conditions. The inner orientation is much more important for the direct sensor orientation like for the traditional image orientation where for example a deviation of the focal length can be compensated with the flying height. The whole process of the direct sensor orientation is very sensitive against a not strict data handling, especially also the chosen coordinate system. The mathematical model, used in photogrammetry, is based on an orthogonal coordinate system. The national coordinate systems are not orthogonal because the coordinates are following the curved earth, nevertheless the data acquisition usually is based on it. In the traditional data handling, the lack of the mathematical model will be compensated by an earth curvature correction. The second order effects are nearly totally compensated by the absolute orientation.

In the case of the direct sensor orientation no absolute orientation based on control points will be done, the absolute orientation is based on the directly determined projection centers and the attitude data, that means, the evaluation of ground points is an extrapolation out of the level of reference. In the case of such an extrapolation, the whole solution must be more strict because errors are not compensated by the solution. Only indirectly we still do have an interpolation based on the ground points by the boresight misalignment which enables us to compensate or determine some geometric problems.

## 2. BACKGROUND

In the normal case of aerial photogrammetry (view vertical and perpendicular to the base) we do have the simple mathematical relation shown in formula 1.

$$X = \frac{h}{f} \bullet x' \qquad Y = \frac{h}{f} \bullet y' \qquad Z = \frac{b \bullet f}{px}$$

h = flying height above ground
f = focal length
x’, y’ = image coordinates
b = base (distance of projection centers)
px = x-parallax = x’ – x”

formula 1: ground coordinates for normal case

The relation h/f is identical to the image scale number. In the case of an absolute orientation with control points or a classical bundle block adjustment, the scale is determined by the horizontal control points, that means, an error in the focal length will be compensated by the flying height above ground. For the vertical component, the scale is indirectly included in the base, but a deviation of the focal length will directly have a linear influence to the height. So a discrepancy of the focal length will cause an affine deformation of the model with a correct scale in the X-Y-plane but a not correct scale in the vertical direction. For example an error of 15 µm of a wide angle focal length (153mm) will change the height of a point located 100m above the level of the control points by 15µm / 153mm • 100m = 10mm. This usually will not be recognised. On the other hand, a deviation of the focal length by 15µm will change the distance from the projection centers for a flying height of 1000m (image scale 1 : 6500) by 100mm or 0.1%, that means 10 times the usual vertical accuracy.

The focal length is determined by laboratory calibration under constant temperature condition. During photo flight a temperature change in the optics from the cold air to the warm aircraft cannot be avoided. H.-K. Meier (Meier 1978) has investigated this for the Zeiss cameras with the results shown in table 1.

| | pressurised cabin, cover glass | | lens in free atmosphere, constant temperature 7°C | | lens in free atmosphere temperature depending upon air | |
|---|---|---|---|---|---|---|
| flying height | 6 km | 14 km | 6 km | 14 km | 6 km | 14 km |
| wide angle camera f = 153mm | -20µm | -38µm | -36µm | -58µm | -47µm | -80µm |
| Normal angle camera f = 305mm | + 12µm | -17µm | -33µm | -28µm | -110µm | -172µm |

Table 1: change of focal length depending upon flying height and camera operation condition (Meier 1978)

The change of the focal length shown in table 1 depends upon the camera type, the camera operation conditions and the time period of the camera under same temperature condition. By this reason, the values cannot be used directly for a correction of the calibrated focal length. But of course the situation should be respected for the boresight calibration – before taking the photos, the camera should be under constant temperature conditions for a sufficient time.

A complete boresight information should include the attitude relation between the inertial measurement unit (IMU), the constant shifts in X, Y and Z and also the actual focal length. The focal length can be determined together with the other elements of the boresight misalignment, if a calibration flight will be done in different height levels. As mentioned before, the computed flying height is linear depending upon the focal length, so an additional information is required and these are the projection center coordinates computed by a Kalman filter of the IMU-data together with the relative kinematic GPS positions. A shift in Z is included in the boresight data. If only one flying height is available and the control points are approximately in the same height level, it is not possible to separate between a shift in Z and a change of the focal length, they are correlated by 100%. The change of the focal length Δf can be computed from the height shift ΔZ with the relation $\Delta f = \Delta Z \bullet f / Z$. If the boresight misalignment will be done in 2 different height levels, in both height levels the same height shift ΔZ is available, but the influence of Δf is different, so it can be separated. Finally Δf is depending upon the vertical difference of the both height levels used for the determination of the boresight misalignment.

The mathematical model, used in photogrammetry, is based on an orthogonal coordinate system. An orthogonal coordinate system we do have with geocentric coordinates, but the handling of geocentric coordinates, oriented against the equator, has some disadvantages, it is mixing the original height with the horizontal position, so it is better to transform it into a tangential coordinate system. For the data acquisition it is more easy to operate directly in the national than in the tangential coordinate system. Only few photogrammetric operation systems are including internally the transformation from the tangential to the national coordinate system. The traditional photogrammetry is respecting the earth curvature by an earth curvature correction of the image coordinates, but this compensates only a part.

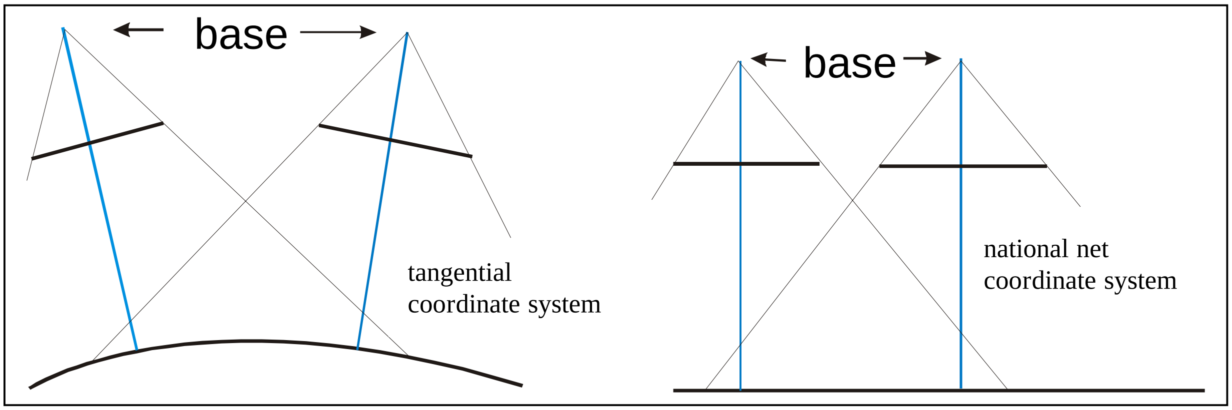


Figure 1: influence of earth curvature correction

As it can be seen in figure 1, the real geometry of the photo flight, shown on the left hand side, is changed by the earth curvature correction to the situation shown on the right hand side. By the traditional photogrammetric model orientation, based on control points, this leads to sufficient situation in X and Y. The influence of the map projection usually can be neglected within one model, it only has to be respected in the case of space images. The vertical component is influenced by the change of the base. Corresponding to formula 1, the height is linear depending upon the base. The base is reduced by the earth curvature correction to the base projected to the height level of the control points, that means the ground.

$$\Delta b = \frac{h}{R} \bullet b \qquad \Delta fe = \frac{h}{R} \bullet f$$

$\Delta b$ = change of base by earth curvature correction
$\Delta fe$ = change of the focal length for the compensation of the second order effect of the earth curvature correction
$R$ = Earth radius

formula 2: influence of earth curvature correction

The base reduced by the earth curvature correction is causing a scale change of the height. For a flying height of 1000m above ground, this will change the height of a point located 100m above the level of the control points by 16mm which usually will be neglected, but it is changing the computed flying height above ground by 160mm, which cannot be neglected for the direct sensor orientation. But it can be compensated by a change of the focal length by $\Delta fe = 24\mu m$.

If the boresight misalignment will be determined in the national coordinate system, the results are valid only under the same condition. In the case of calibration only in one flight level, the boresight is only correct for this height level. If the calibration is based on 2 different height levels, the focal length can be determined together with a shift and the results are valid for the range between both flying height levels and an extrapolation out of this is also possible. The rigorous solution is the calibration of the boresight in the tangential plane system. This is a general method which can be used independent upon the image scale, but it cannot be used directly for a data acquisition in the national coordinate system. It is not easy to estimate all the second and third order effects, by this reason an empirical investigation has been made.

## 3. USED DATA SET

The empirical investigations have been made with the data of the OEEPE-test “Integrated Sensor Orientation” (Heipke et al 2000). The test field in Frederikstad, Norway, has been flown by companies producing suitable GPS/IMU equipment, namely Applanix of Toronto, Canada, using their system POS/AV 510 and IGI mbH, Germany, with the system Aerocontrol II. Both companies, further named Company 1 and Company 2 without indication of the real companies, have made calibration flights in the image scales of approximately 1 : 5000 and 1: 10 000 and a block flight for testing the results in the scale 1 : 5000. The targeted control points of the test field are available with an accuracy below +/-1cm for all coordinate components.

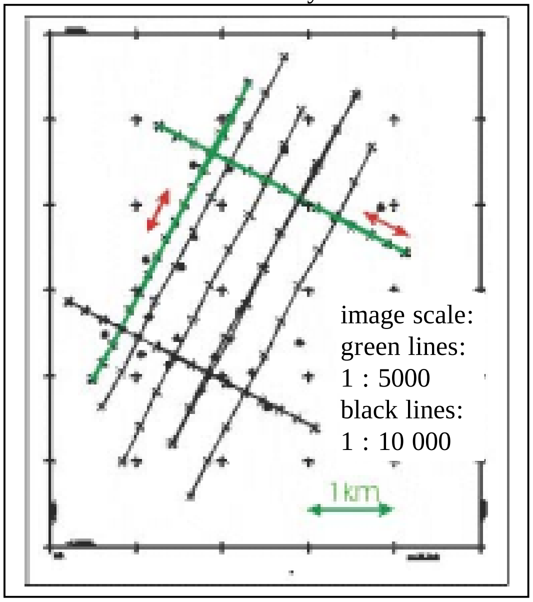


Figure 2: calibration flight Friderikstad

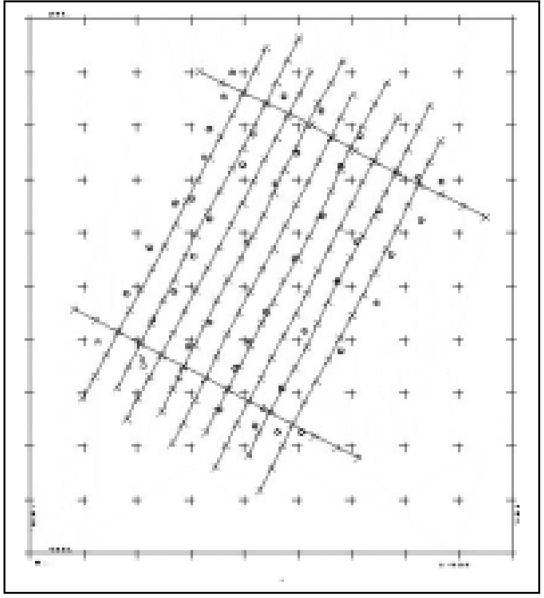


Figure 3: test block

The image coordinates have been measured with an analytical plotter Planicomp P1.

## 4. BORESIGHT MISALIGNMENT

The relation between the IMU and the camera (3 rotations, 3 shifts) have been determined together with the focal length, based on a bundle block adjustment with all images of the calibration flights, separately for Company 1 and Company 2. It has been computed in the tangential plane and directly in the UTM coordinate system. In the UTM coordinate system the adjustment has been made with and without earth curvature and refraction correction. The influence of the earth curvature and refraction to the image coordinates can be compensated also by self calibration with additional parameters, but the used Hannover program system BLUH is using, like common, for the compensation of the radial symmetric effect a zero crossing like shown in figure 4. For a radial distance of 146mm and the image scale 1:5000, the refraction correction is –2µm, the earth curvature correction +7µm, so the resulting effect is +5µm. For the image scale 1 : 10 000 the corresponding figures are –4µm, +15µm, resulting in +11µm. With pre-correction by earth curvature and refraction correction for Company 2, the radial symmetric distortion, determined by self calibration, has not exceeded 1µm, so the radial symmetric effect of the computation without pre-correction shows mainly the compensation of the Earth curvature. The influence to the focal length can be seen as vertical difference between the red line and the correction curve at a radial distance of 153mm. The difference of the focal length computed in the tangential and the UTM-system (see table 2) of 10µm and 7µm for Company 2 and 15µm and 6µm for Company 1 can be explained by this.

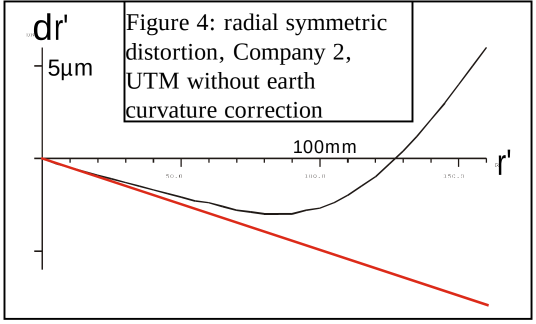


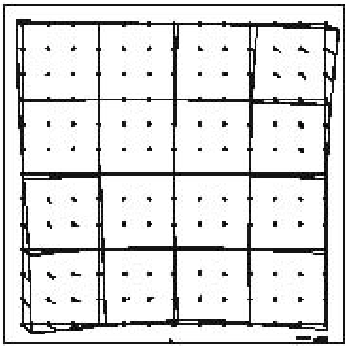
Figure 4: radial symmetric distortion, Company 2, UTM without earth curvature correction

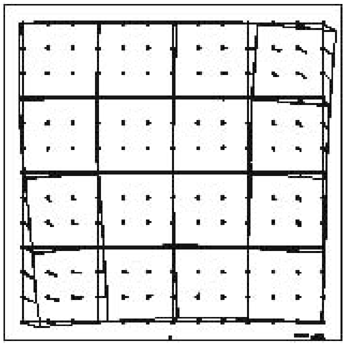
|  | Company 1 | Company 2 |
|---|---|---|
|  | **with self calibration by additional parameters** |  |
| tangential coordinate system | -41µm | +13µm |
| UTM without earth curvature and refraction correction | +20µm | +49µm |
| UTM with earth curvature and refraction correction | + 5µm | +39µm |
|  | **without self calibration by additional parameters** |  |
| tangential coordinate system | +4µm | +1µm |
| UTM without earth curvature and refraction correction | +18µm | +43µm |
| UTM with earth curvature and refraction correction | +24µm | +50µm |

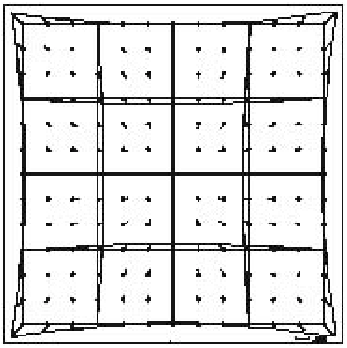
Table 2: correction of focal length computed by bundle adjustment

The tendency of the focal length correction between Company 1 and Company 2 is the same between the different types of reference block adjustment. The absolute values are different of course– this is dependent upon the changes of the focal length against the laboratory calibration.

The variation against the simplified theory, mentioned before, may be explained by the effect of systematic image errors.In general, table 2 shows also the dependency of the inner orientation to the self calibration. The additional parameters are correlated with the focal length if this is used as unknown in the adjustment. Especially the radial symmetric distortion is affecting the focal length like mentioned before. In general it is not possible to have only an isolated view to the focal length, it has to be seen together with the "systematic image errors" as a system calibration.







largest vector 25µm 21µm 7 µm

Company 2

Figure 5: "systematic image errors" Figure 6: "systematic image errors" Figure 7: "systematic image errors"
tangential coordinate system UTM, without earth curvature correction difference between Fig. 5 and 6

The systematic image errors, computed in the different coordinate systems, are similar like shown as example for Company 2 in Figures 5 and 6. The main difference between both is radial symmetric effect like shown with enlarged vectors in figure 7.

The differences between the computed focal length have to be seen also together with the shift for the Z-components in the misalignment, both are highly correlated. The location of the principal point is more or less independent from the different types of computation, it is varying only few microns.

The image orientations determined by the calibration flights with the improved focal length, but without influence of the direct sensor orientation information, are used as reference for the determination of the misalignment. The attitude misalignment has to be computed in the IMU-system pitch, roll and yaw with yaw as primary rotation. The difference between the transformed photogrammetric orientation and the IMU-data is the boresight misalignment. The individual discrepancies are indicating the quality of the IMU-data and the photogrammetric orientation. The photogrammetric orientation is also not error free – the projection center coordinates X0 and Y0 are highly correlated to phi and omega or transformed to pitch and roll (Jacobsen 1999). In the case of narrow angle images, like taken by the digital camera Kodak DCS460, it is not possible to determine the attitude and the shift parameters for the misalignment, the shift values have to be set to 0.0 for a correct determination of the attitude data. This problem does not exist for standard aerial cameras, but the accuracy of the IMU attitude data is today on a level that it should not be neglected.

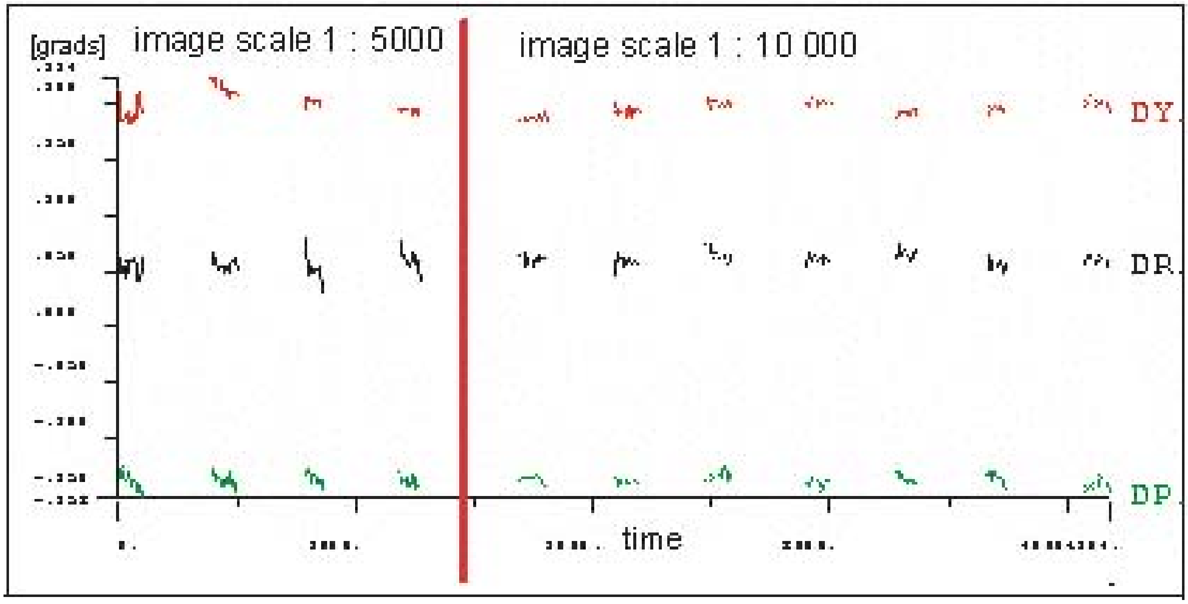


Figure 8: attitude discrepancy photogrammetric orientation – IMU (Company 2, UTM) as function of time

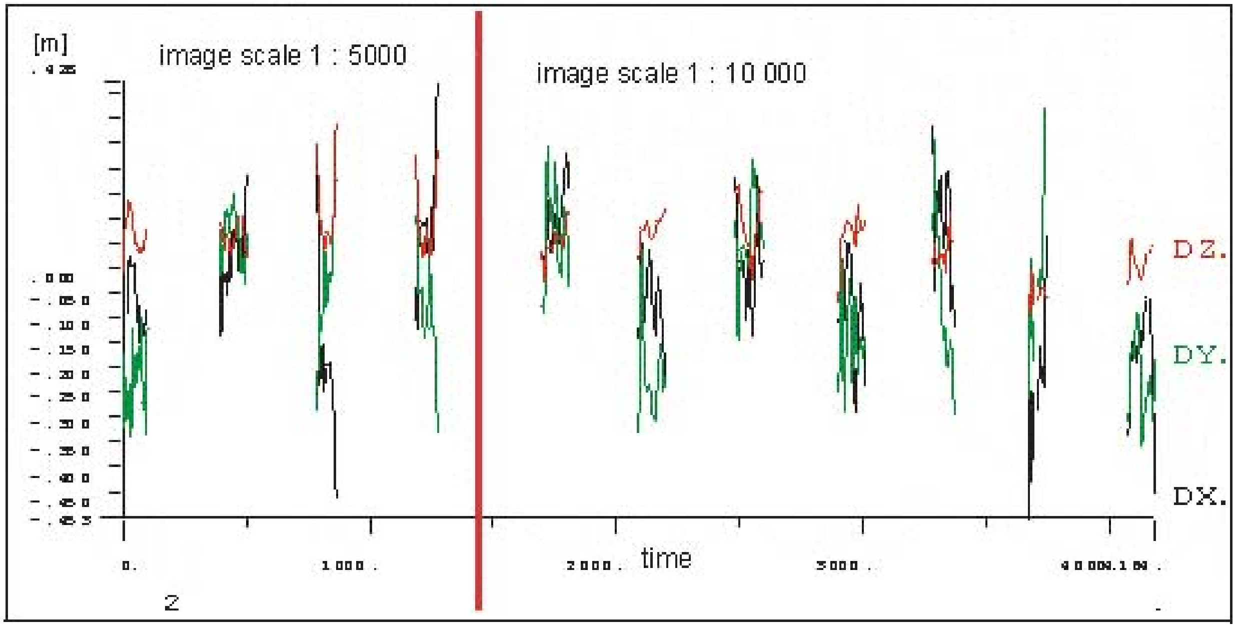


Figure 9: discrepancy of projection center coordinates block adjustment – IMU (Company 2, UTM)

| | pitch | roll | yaw | X0 | Y0 | Z0 |
|---|---|---|---|---|---|---|
| Company 1 UTM | 0.0038° | 0.0035° | 0.0102° | 6.7cm | 8.1cm | 7.6cm |
| Company 1 tangential | 0.0029° | 0.0039° | 0.0106° | 6.8cm | 7.8cm | 6.9cm |
| Company 2 UTM | 0.0067° | 0.0046° | 0.0077° | 15.4cm | 15.5cm | 5.6cm |
| Company 2 tangential | 0.0055° | 0.0059° | 0.0078° | 12.1cm | 13.6cm | 2.5cm |

Table 3: mean square discrepancies of orientation by BLUH against IMU after misalignment correction

In figure 8 and 9 the discrepancies of the image orientations determined by bundle block adjustment with program system BLUH against the IMU can be seen. These results are very similar for the data handling in the national net coordinate system to the data handling in a tangential plane coordinate system, the values are only shifted. This is reflected also in table 3, showing the mean square discrepancies of the image orientations determined by bundle block adjustment against the IMU + GPS after shift correction. The shifts are the boresight misalignment. No general discrepancies can be seen between the results in the UTM and the tangential coordinate system and also between both companies. The attitude data are very constant over the time and flight strips. The projection centers are still changing slightly from flight strip to flight strip, but in both cases the results are not improved by a linear function of the time.

The small differences of the results, based on the data of both companies, can be explained also by the used hardware components, for example in one case a not up to date dry tuned gyro has been used, which would not be done today again. The more complicate data acquisition in the tangential plane seems not be justified, but these figures are just the first indication for this.

## 5. COMBINED INTERSECTION

The next step of investigation can be made by a combined intersection based on the direct sensor orientation, that means, the IMU-data improved by the boresight misalignment and converted to the photogrammetric definition of the rotations, together with the actual focal length adjusted together with the misalignment. The ground coordinates, computed by combined intersection can be checked against the control points, used for the reference adjustment, but also the ground coordinates of all tie points determined by the reference block adjustment just based on control points.

| | RMS at control points | | | RMS at ground points | | | σo intersection |
|---|---|---|---|---|---|---|---|
| | RMS Xcp | RMS Ycp | RMS Zcp | RMS X | RMS Y | RMS Z | |
| Company 1, UTM | 8.2cm | 6.9cm | 9.8cm | 16.6cm | 12.8cm | 22.3cm | 22.0µm |
| Company 1, tangential | 8.1cm | 6.7cm | 9.7cm | 16.1cm | 12.7cm | 21.4cm | 22.6µm |
| Company 2, UTM | 8.7cm | 5.8cm | 12.4cm | 11.4cm | 9.2cm | 14.5cm | 23.3µm |
| Company 2, tangential | 7.9cm | 6.3cm | 12.8cm | 11.6cm | 9.6cm | 14.6cm | 24.2µm |

Table 4: discrepancies at ground points determined by combined intersection based on direct sensor orientation

Also the results of the combined intersection (table 4) of the reference block do not indicate an improvement of the more strict computation in the tangential coordinate system in relation to the direct handling in the national net coordinate system – here the UTM-system. The discrepancies at the independent control points are smaller than at the not totally independent ground points of the reference adjustment – this can be explained with the number of images per point (figure 10) and the location. The ground points are located in the average in 6.8 photos, the control points in 13 photos. In addition some ground points are located outside the area of the control points, where also the reference adjustment is not so accurate. The accuracies reached with the data of both companies are not indicating any difference of the quality of direct sensor orientation – in the case of company 1 several points with poor photogrammetric accuracy, far out of the range of the control points, are included.

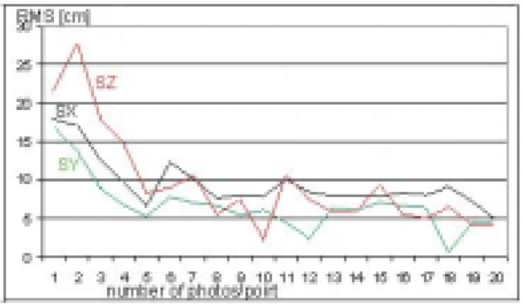


Figure 10: accuracy of ground points determined by combined intersection based on direct sensor orientation as function of number of images per point (Company 2)

black line: RMSX
green line: RMSY
red line: RMSZ

If the boresight misalignment determined in the wrong coordinate system will be used, the standard deviations are approximately 50% higher.

An independent check of the investigations of course requires an independent data set. This is not totally the case for the OEEPE-test, because the test block has the same location like the reference blocks and the time interval between both is limited, nevertheless, independent photos are available. The block has been handled in the similar way. The misalignment of the reference block has been used for the correction of the block area. The block data are belonging to the 2nd phase of the OEEPE-test and the data have not been distributed to the participants of the test. By this reason, the results cannot be published now by members of the pilot center. But nevertheless the same general tendency of the results can be mentioned. For the block, the relations are the same like for the calibration flights. The ground coordinates determined by common intersection do have the same accuracy in the tangential coordinate system like in the national net coordinate system.

## CONCLUSION

The accuracy of the direct sensor orientation has been improved to a level where it can be used for several applications. The data acquisition is more simple directly in the national net coordinate system like in a tangential plane coordinate system which corresponds to the mathematical model. Investigations have demonstrated that in spite of the not strict solution, it is possible to handle the problem of the direct sensor orientation also directly in the national net coordinate system. But the handling has to be done consequently, including also the determination of the boresight misalignment. No loss of accuracy could be seen in the case of the investigated limited area with large image scales. Only if the boresight misalignment will be determined in the tangential plane coordinate system and will be used in the national net coordinate system or reverse, a loss of accuracy cannot be avoided.

The computation of the misalignment between the IMU and the photogrammetric camera has to include also the calibration of the focal length, which has a limited long term accuracy and is dependent upon the environmental conditions. The focal length can only be determined if the calibration flight includes photos taken from different flying heights. If the focal length will not be adjusted, the use of the boresight misalignment is limited to the flying height of the calibration flight.

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