DEPENDENCIES AND PROBLEMS OF DIRECT SENSOR ORIENTATION

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ABSTRACT

The direct sensor orientation has reached a high accuracy level. This and also the fact that we do have an extrapolation from the projection centers to the ground, makes it necessary to take care about all sources of errors. It is not anymore possible to use a not orthogonal coordinate system like the national net. The national coordinate system is not just causing a scale error of the height by the local scale factor, it is also influenced by a change of the height-to-base-relation by the flattening of the curved earth. Also the inner orientation became more important - the temperature depending changes are not compensated like in the case of an exterior orientation with control points. Errors of the mathematical model can only be compensated if the determination of the boresight misalignment will be done under the same condition like the use of the direct sensor orientation. If the image scale will not be the same like during the determination of the boresight misalignment, the boresight misalignment has to be made with 2 different flying altitudes to enable the separation of the inner orientation from the shift values of the exterior orientation.

Even the today reached high accuracy level is not sufficient for the set up of the models. The partially not acceptable y-parallaxes can be reduced to the usual level by a combined adjustment with the direct sensor orientation and image coordinates of tie points; control points are not required.

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 camera calibration and the self calibration by additional parameters in a bundle block adjustment is a well investigated problem, which always has been handled in an ISPRS Working Group from 1976 – 1980. Nevertheless some of the results of the old investigations have not been respected up to now. For the handling of a bundle block adjustment this is not causing problems because several small errors can be compensated by the exterior orientation. This is not anymore the case with the direct sensor orientation, it cannot compensate discrepancies of the focal length with the flying height, if the boresight misalignment between the camera and the IMU has been determined in a different altitude.

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.

An up to now not solved problem is the stability of the calibration. It is not well known, how often a system calibration is required. Of course this is depending upon the flight conditions and the careful handling of the hardware components. If components are dismounted, after mounting again, the geometric relations may have changed.

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 camera (f=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 vertical temperature gradient 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 in which the camera has been 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 inner orientation. 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. But also here we do have a limitation, because the focal length may change depending upon the air temperature as mentioned before. So finally we are still limited to a three-dimensional interpolation which will lead to sufficient results if the conditions for projects, using the determined boresight calibration, are done under comparable conditions, that means also similar temperature as a function of the flying height. The use of the determined focal length also for other projects with an image scale outside the range which has been used for the determination, is still limited, but it is a better estimation of the real condition than the focal length from the calibration certificate. For the location of the principal point we do have a similar condition, but it is not depending upon temperature of the camera system.

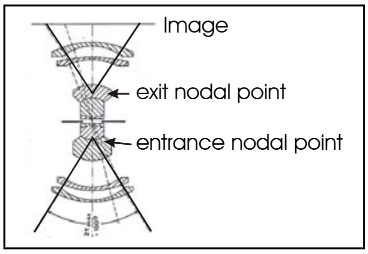


figure 1: definition of projection center

As mentioned, the whole process has to be handled very strictly. This includes also the pre-correction of all used values e.g. by refraction correction and the correct offset from the GPS-antenna to the entrance nodal point of the camera (figure 1) – the projection center in the object space. The rotation of the system camera + IMU against the aircraft is changing the offset, so it has to be recorded. This can be done with a separate gyro-system or in the case of the use of a gyro stabilised platform with a registration of the rotations.

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.

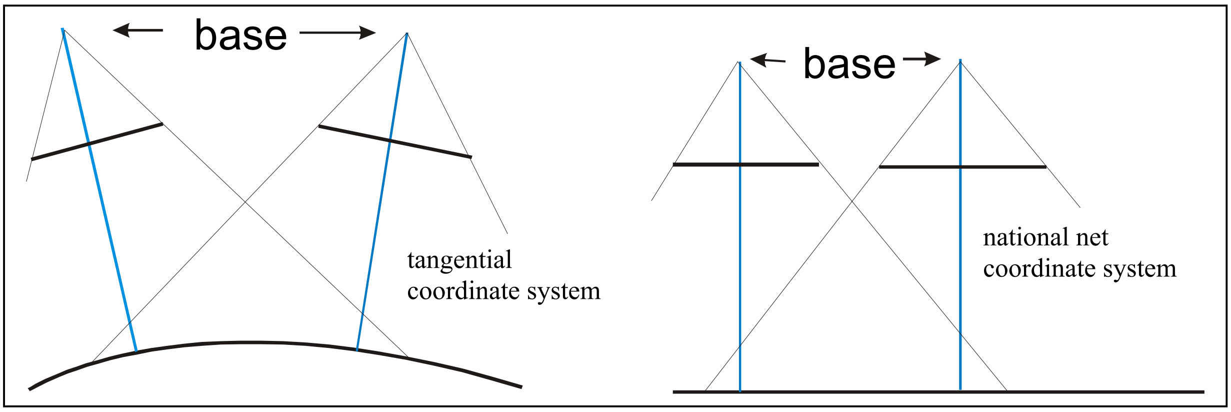


figure 2: influence of earth curvature correction

As it can be seen in figure 2, 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 a 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.

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

formula 2: influence of earth curvature correction

Δb = change of base by earth curvature correction
Δfe = change of the focal length for the compensation of the second order effect of the earth curvature correction
R = Earth radius

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 can 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 of a wide angle camera (f=153mm) by Δfe = 24µm.

Another effect is based on the map projection. UTM-coordinates do have in the center meridian a scale 1:0.9996. The scale of the reference bundle block adjustment is based on the horizontal control points, so the vertical component will be changed by this scale – a ΔZ of 100m is changed 0.04m or a flying height of 1500m is influenced by 0.6m.

The correct method for the reference bundle block adjustment and the following model handling is the computation in an orthogonal coordinate system. A tangential coordinate system to the earth ellipsoid has the advantage of a more simple weight variation between horizontal and vertical coordinates than a handling in the geocentric coordinate system. If the boresight misalignment including the inner orientation has been determined in an orthogonal system, these results are only valid for this. It is not possible to use such a misalignment for a model handling in the national coordinate system. Only few photogrammetric workstations are able to handle the relations in an orthogonal coordinate system together with a direct output of the results in the national net coordinate system. This is causing a complicate data handling. It is much more simple to have the data acquisition directly in the national net coordinates.

Finally it is not so complicate like in the first view, because also the direct sensor orientation is together with the boresight misalignment not an extrapolation from the projection centers to the ground, the whole system is based on the control points of the reference block and indirectly the points in the project area are determined based on this. If the boresight misalignment will be determined in the national net coordinate system, and the data handling in the project area will be done in the same way, the resulting ground coordinates do have approximately the same accuracy like in the mathematical strict solution, if the reference block has the same scale or scale range like the project area and the scale of the national net coordinates are similar. The mathematical strict handling has the advantage, that it is independent from the national coordinate system, it can be handled also for different net projections and it is much more free in relation to different image scales. But in general it is not easy to estimate all the second and third order effects, by this reason empirical investigations have to be 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.

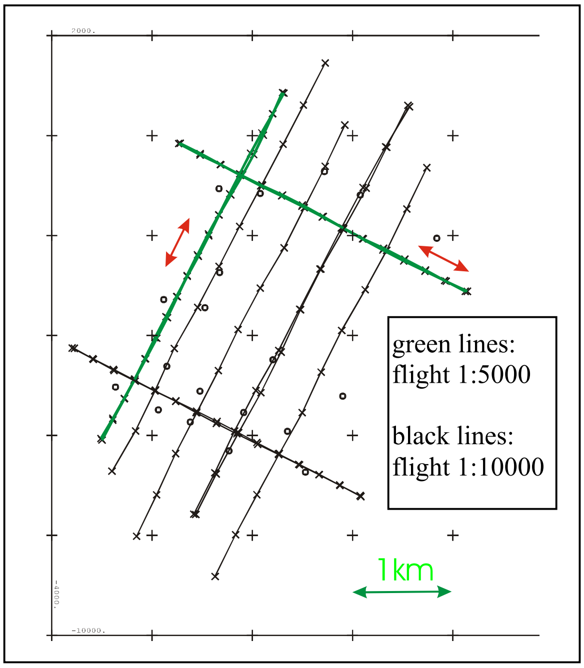


figure 3: calibration flight Friderikstad

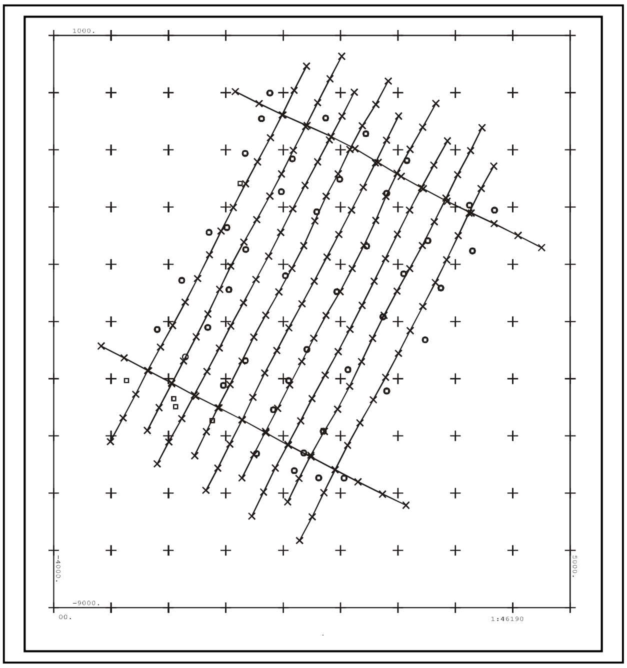


figure 4: test block

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 inner orientation, based on a bundle block adjustment with all images of the calibration flights, separately for company 1 and

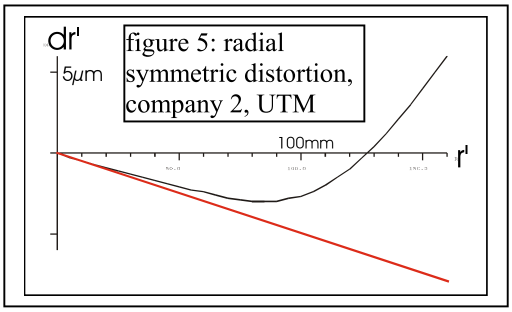


figure 5: radial symmetric distortion, company 2, UTM

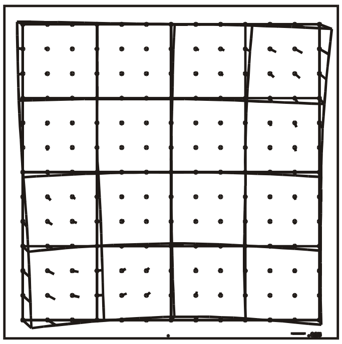
company 2. It has been computed in the tangential plane and directly in the UTM coordinate system. In the UTM coordinate system the adjustment has been made with and without earth curvature and refraction correction. The influence of the earth curvature and refraction to the image coordinates can be 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 5. 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 Δf =+5µm. For the image scale 1 : 10 000 the corresponding figures are –4µm, +15µm, resulting in Δf =+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.

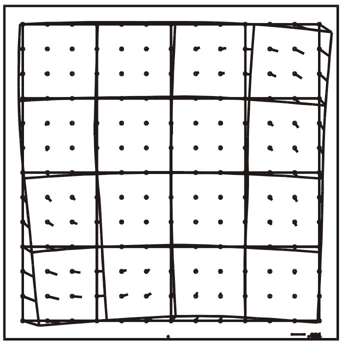
	company 1	company 2
	with self calibration by additional parameters	
tangential coordinate system	-41µm	+13µm
UTM without earth curvature and refraction correction	+20µm	+49µm
UTM with earth curvature and refraction correction	+ 5µm	+39µm
	without self calibration by additional parameters	
tangential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

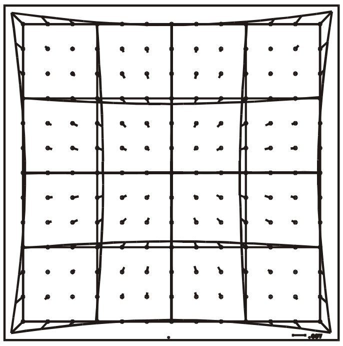
table 2: correction of focal length computed by bundle adjustment

The tendency of the focal length correction between company 1 and company 2 is the same for the different types of reference block adjustments. The absolute values are of course different – 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 6: "systematic image errors" tangential coordinate system

figure 7: "systematic image errors" UTM, without earth curvature correction

figure 8: "systematic image errors" difference between fig. 6 and 7

The systematic image errors, computed in the different coordinate systems, are similar like shown as example for company 2 in figures 6 and 7. The main difference between both is a radial symmetric effect like shown with enlarged vectors in figure 8.

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 free of error – 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.

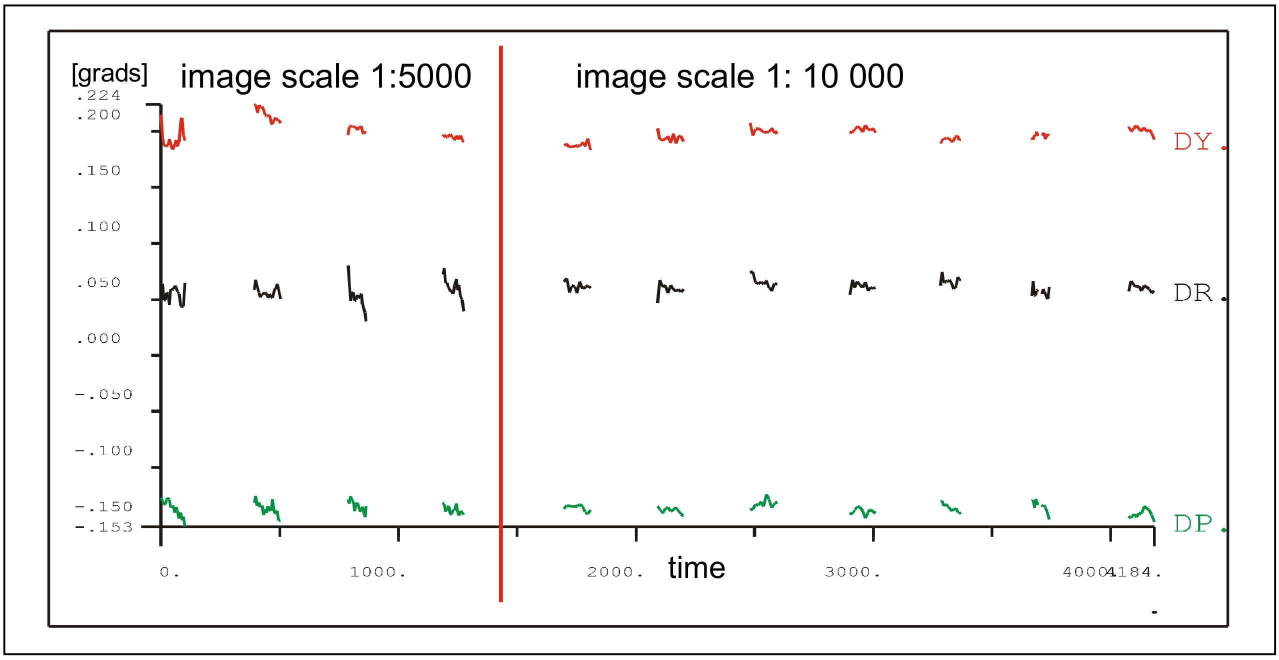


figure 9: attitude discrepancy photogrammetric orientation – IMU (company 2, UTM) as function of time

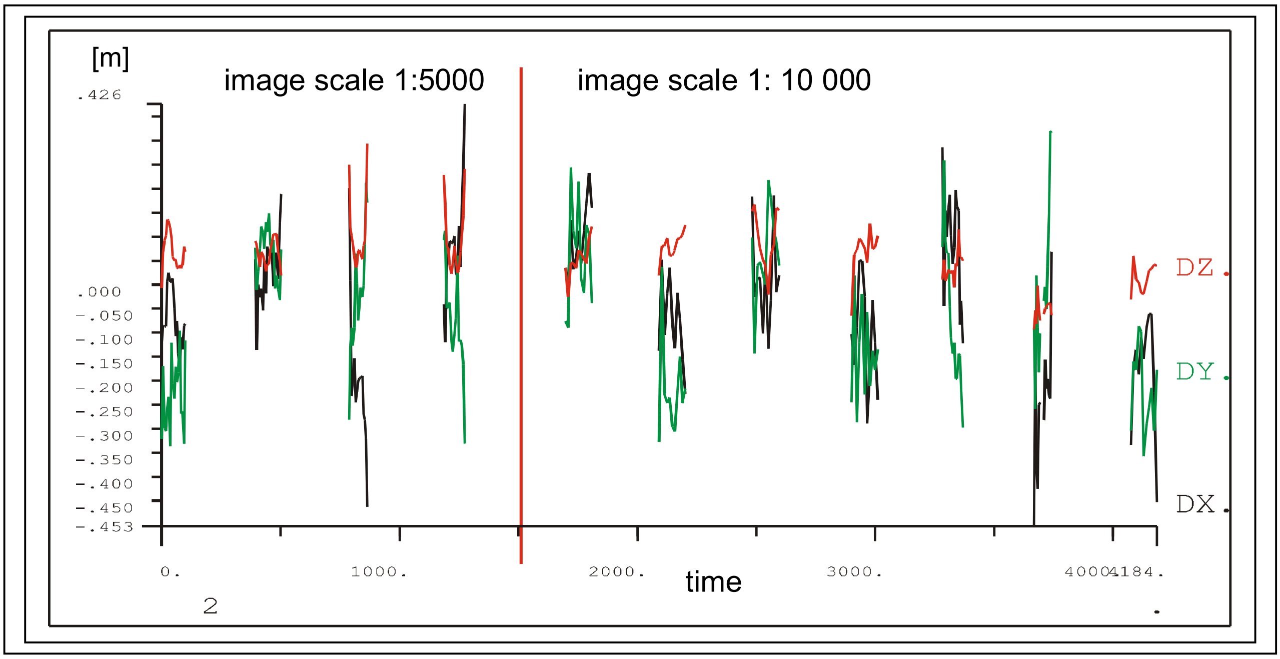


figure 10: discrepancy of projection center coordinates block adjustment – IMU (company 2, UTM)

In figure 9 and 10 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 coordinate system and 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.

	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

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 inner orientation 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	11.3cm	14.7cm	16.3cm	16.6cm	12.8cm	22.3cm	36.7µm
company 1, tangential	11.1cm	15.4cm	16.5cm	16.1cm	12.7cm	21.4cm	38.5µm
company 2, UTM	8.5cm	3.3cm	12.3cm	11.4cm	9.2cm	14.5cm	16.1µm
company 2, tangential	5.5cm	4.0cm	7.9cm	11.6cm	9.6cm	14.6cm	16.2µm

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 a major improvement of the more strict computation in the tangential coordinate system in relation to the direct handling in the national 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 11) 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 accuracy reached with the data of both companies are not indicating mayor differences 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.

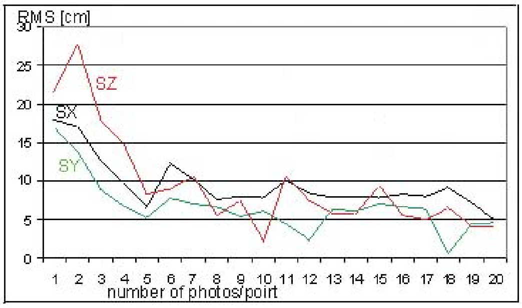


figure 11: accuracy of ground points determined by combined intersection based on direct sensor orientation as function of number of images per point (company 2)

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.

6. COMBINED ADJUSTMENT

As listed in table 4, the sigma0 of the combined intersection based on the direct sensor orientation is in the range of 16µm up to 38µm. This is still a good result, sufficient for several applications like the generation of orthophotos, but it may cause problems for the set-up of stereo models. As a rule of thumb, the y-parallax in a model should not exceed in maximum 30µm, the problems with the stereo view of the floating mark is starting at 20µm. Of course the sigma0 of the combined intersection is not identical to the root mean square y-parallax (Spy) of the model; the y-parallax is computed as difference of 2 coordinates. On the other hand, the orientation elements of neighboured images are correlated, so sigma0 only shows the tendency.

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 a combined 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	**Spy**	>10µm	>20µm	>30µm	Spy max	**Spy**	>10µm	Spy max
company 1	UTM	47	**46.6µm**	35	18	8	116.9µm	**9.0µm**	5	14.7µm
company 1	tangential	47	**46.3µm**	38	28	23	115.6µm	**8.7µm**	4	13.1µm
company 2	UTM	47	**21.6µm**	45	19	6	47.5µm	**9.8µm**	15	13.3µm
company 2	tangential	47	**21.7µm**	45	20	8	48.8µm	**9.4µm**	12	13.3µm

table 5: y-parallax of models and number of models exceeding specified limits

Table 5 shows the result of the root mean square y-parallax errors of the model set-up for the images included in the block for phase 2. Between Spy of the model set-up and sigma0 of the combined intersection based on the direct sensor orientation there is a relation between 1.2 and 1.3 (see also table 3). If the orientations are independent, there should be the relation of 1.4. As expected, no significant differences can be seen between handling in the UTM- and a tangential system. The main differences between both companies can be explained by the yaw, which is not so good for company 1 (see table 3). After 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 Spy for all models.

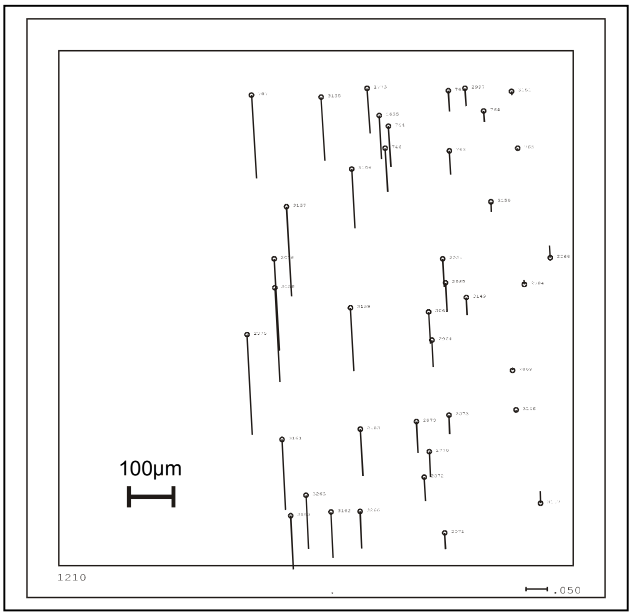


figure 12: y-parallaxes, model 1210/1211 company 1 for model orientation with direct sensor orientation

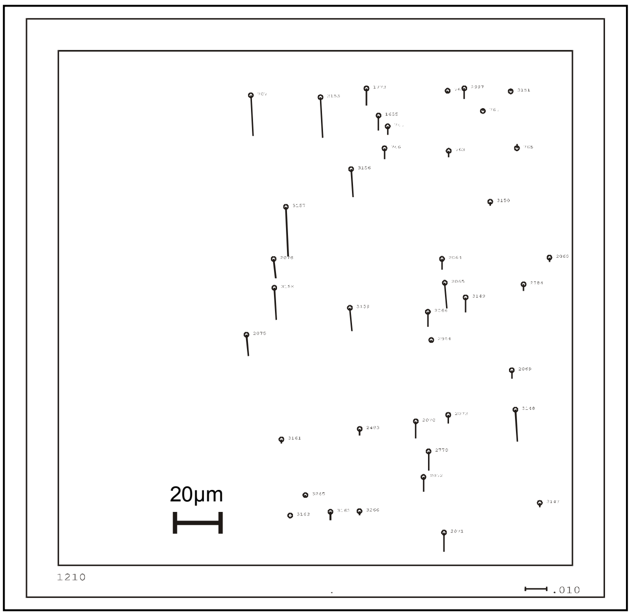


figure 13: y-parallaxes, model 1210/1211 company 1 for model orientation based on combined adjustment

Figure 12 and 13 are showing the y-parallaxes for the model 1210/1211 which has the largest values based on the direct sensor orientation for company 1. After improvement by the combined adjustment, in the whole model there are no more problems for the stereoscopic handling. In this case, the dominating effect of the yaw is obvious. Of course it is possible to reach a further improvement of the model orientation based on the combined adjustment by a larger weight for the image coordinates, but this is not justified for the complete solution.

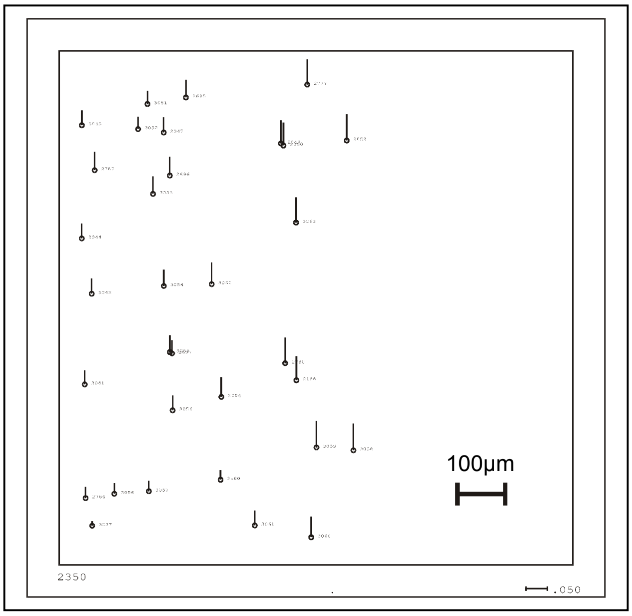


figure 14: y-parallaxes, model 2350/2351 company 2
for model orientation with direct sensor orientation

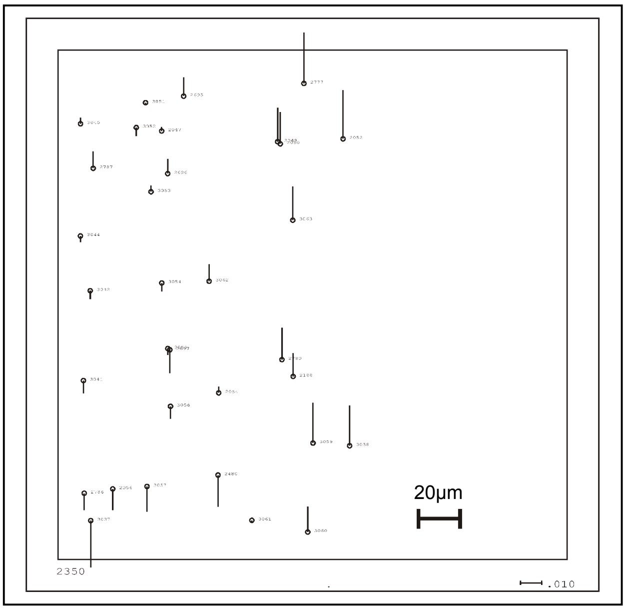


figure 15: y-parallaxes, model 2350/2351 company 2
for model orientation based on combined adjustment

The corresponding extreme case for company 2 is shown in figures 14 and 15. For company 2 the week point is more roll and pitch, visible also in the y-parallaxes based on the direct sensor orientation

		intersection with direct sensor orientation			intersection with combined adjustment		
		SX [cm]	SY [cm]	SZ [cm]	SX [cm]	SY [cm]	SZ [cm]
company 1	block, UTM	14.6	20.1	13.3	11.8	14.5	8.5
	strip, UTM	9.4	5.8	13.7	7.7	6.5	5.3
	block, tangential	13.6	20.0	15.9	11.4	15.5	8.3
	block, tangential	9.3	7.6	14.6	7.7	8.5	5.9
company 2	block, UTM	4.8	3.6	13.0	3.7	3.4	13.0
	strip, UTM	5.1	6.2	15.0	4.7	4.8	14.1
	block, tangential	8.1	3.7	13.8	3.2	1.1	9.5
	block, tangential	5.7	5.6	12.5	7.1	3.9	11.4

table 6: root mean square error at independent check points determined by combined intersection

Based on the combined adjustment of the direct sensor orientation together with image coordinates, but no control points, the random errors of the image orientations can be improved. Only the more local component of the systematic errors can also be improved, but not more. In table 6 on the left hand side the results of an intersection based on the direct sensor orientation determined in phase 1 are listed. These values are not the same like listed in table 3 because of a different selection of images for phase 2. By the comparison of the left hand part with the right hand part of table 6, the improvement of the ground coordinate accuracy by the combined adjustment can be seen. For company 2 there is only a small reduction of the root mean square differences for Z because of a dominating systematic influence.

The root mean square error at independent check points can be separated into the random and systematic component. As systematic component the mean value of the discrepancies has been used, the random component is the root mean square after shift by the systematic component. In general by the combined adjustment together with the image coordinates, the random part can be improved; for the systematic component control points are required, but they have not been used in phase 2 of the OEEPE-test.

		intersection with direct sensor orientation **random part**			*intersection with direct sensor orientation systematic part*			intersection based on combined adjustment **random part**			*intersection based on combined adjustment systematic part*		
		SXr	**SYr**	**SZr**	*sysX*	*sysY*	*sysZ*	**SXr**	**SYr**	**SZr**	*sysX*	*sysY*	*sysZ*
company 1	block UTM	**10.1**	**11.6**	**13.0**	*10.6*	*-16.3*	*-2.8*	**5.8**	**5.3**	**8.1**	*10.3*	*-13.5*	*-2.6*
	strip UTM	**6.4**	**3.2**	**13.4**	*6.9*	*-4.9*	*2.8*	**4.6**	**3.0**	**5.3**	*6.2*	*-5.8*	*0.4*
	block tang.	**9.7**	**10.8**	**15.2**	*9.5*	*-16.8*	*4.5*	**5.8**	**5.1**	**8.3**	*9.8*	*-14.6*	*-1.2*
	strip tang.	**6.3**	**3.3**	**13.8**	*6.8*	*-6.8*	*5.0*	**4.5**	**3.3**	**5.3**	*6.2*	*-7.8*	*2.5*
company 2	block UTM	**4.6**	**1.1**	**5.8**	*-1.4*	*-3.4*	*11.6*	**2.4**	**1.0**	**5.8**	*-2.8*	*-3.2*	*11.6*
	strip UTM	**4.6**	**5.5**	**8.1**	*-2.4*	*-2.9*	*12.7*	**4.7**	**3.8**	**6.7**	*-0.3*	*-3.0*	*12.5*
	block tang.	**7.9**	**3.2**	**6.7**	*-1.5*	*-1.9*	*12.0*	**2.4**	**1.0**	**5.6**	*2.1*	*-0.5*	*7.6*
	strip tang.	**4.7**	**5.6**	**8.2**	*3.4*	*0.3*	*9.4*	**4.7**	**3.9**	**6.8**	*5.5*	*0.2*	*9.1*

table 7: discrepancies at independent check points determined by combined intersection, separated into random and systematic component

Table 7 shows the improvement of the random component by the combined adjustment and also the only slightly changed systematic part. For company 1 for Z the random part is dominating and for company 2 the systematic part, by this reason there is a more strong improvement of the height by the combined adjustment for company 1. For X and Y in the case of company 1 the systematic part is not negligible and cannot be reduced, only the also not so small random horizontal components are causing also an improvement.

7. 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. The boresight misalignment should not be determined in the tangential plane coordinate system and used in the national net coordinate system or reverse, this is causing a loss of accuracy in any case.

The computation of the misalignment between the IMU and the photogrammetric camera has to include also the calibration of the inner orientation, which has a limited long term accuracy and is dependent upon the environmental conditions. The focal length and also the location of the principal point 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.

Only based on the direct sensor orientation, the y-parallaxes for stereo models are out of the tolerance level. A combined adjustment using the direct sensor orientation together with image coordinates of tie points is required for the computation of the settings for stereo models. In addition the random part of the direct sensor orientation will be reduced, leading to a further improvement of the ground coordinates determined by combined intersection.

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