CALIBRATION ASPECTS IN DIRECT GEOREFERENCING OF FRAME IMAGERY

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ABSTRACT:

The determination of the exterior orientation by a combination of an inertial measurement system (IMU) with relative kinematic GPS-positioning – the direct georeferencing - has a growing number of applications for standard photogrammetric projects. One mayor problem is the determination of the relation between the camera and the IMU - the boresight misalignment. The rigorous mathematical model requires the computation and use of it in an orthogonal coordinate system like a tangential system in relation to the earth ellipsoid. But the final data acquisition usually shall be made directly in the national coordinate system. The procedure to use the boresight misalignment without loss of accuracy in the national coordinate system in any location will be explained. Results of the stability of the misalignment over the time will be shown.

If the results of the boresight calibration shall be used for different image scales, also the inner orientation has to be determined together with the boresight misalignment. This has to be done with 2 different flying heights over a calibration site.

Another problem is the limited accuracy of the model set up, today the direct sensor orientation is often not accurate enough to guarantee a model set up without a disturbing size of the y-parallaxes. This can be solved with a combined adjustment of the direct sensor orientation together with image coordinates of tie points, but without control points.

1. INTRODUCTION

The determination of the exterior orientation for frame cameras is possible by the traditional method of resection, model orientation or block adjustment. For not individual images or models, the bundle block adjustment is the standard method because it is reducing the required number of control points against the individual model orientation. With coordinates of the projection centers determined by relative kinematic GPS-positioning as additional observations, the number of control points can be further reduced. This method of combined bundle block adjustment is today also a standard solution, but it requires image coordinates of tie points and also a satisfying block configuration. For individual flight lines, the advantage of the combined adjustment with projection centers is limited, it cannot control the lateral tilt. In addition an extrapolation out of the area of the control points should be avoided.

With direct georeferencing by a combined use of the GPS-data together with inertial measurements, the whole process of the image orientation can be speed up and it can be used for any type of image configuration. It has no problems in areas with problems of the tie of images like in coastal regions where only a small part of the images is covering land.

The usual block adjustment is in general an interpolation within the area of the control points. This is different for the direct georeferencing which is an extrapolation from the projection centers to the ground. By this reason, the steps of computation have to be handled with more care for the direct sensor orientation.

2. BORESIGHT MISALIGNMENT

The direct georeferencing is based on the attitude data determined by an inertial measuring unit (IMU) and relative kinematic GPS-positioning. The inertial data will be used only for the determination of the attitude values and differences in the position and not for navigation. By this reason the expression IMU will be used instead of inertial navigation system (INS). 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 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.

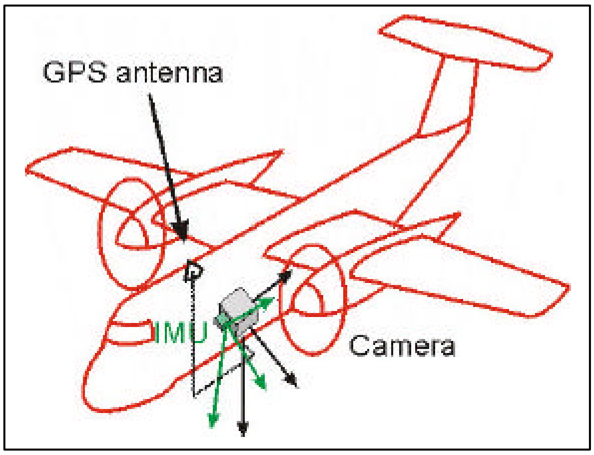

Figure 1: relation camera – IMU – GPS antenna

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.

The direct georeferencing has reached an accuracy level where also the image orientations of a block adjustment are not accurate enough in any case. Especially the first and the last image of a flight strip, only partially covered by image points, should not be used as reference.

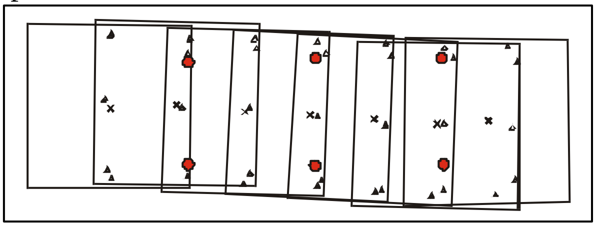

Figure 2: typical flight strip as for the determination of the boresight misalignment

Figure 2 shows such a typical flight strip for the determination of the boresight misaligment. The first and the last image are only partially covered by image points, in addition they are mainly outside the area of the control points. By both reasons they should not be used as reference.

3. INNER ORIENTATION

The inner orientation of aerial cameras usually will be determined by laboratory calibration. The conditions in the laboratory are not the same like during the flight. In the flying altitude usually the outside air is more cold like the aircraft, causing a deformation of the lenses. Meier (1978) has made a theoretical investigation of the resulting change of the focal length (table 1).

	lens in free atmosphere	
flying height	6km	14km
wide angle camera f=152mm	-47 µm	-80 µm
normal angle camera f=305mm	-110 µm	-172 µm

table 1: change of the focal length depending upon the flying altitude (Meier 1978)

In general the values have been confirmed by empirical tests but it is just a rough estimation which has to be checked under operational conditions. The same problem exists with the principal point.

An error of 47µm for a focal length of 153mm is changing a flying height of 1530m above ground (image scale 1 : 10 000) by 0.47m. This is important for the direct georeferencing but not so much for a usual image orientation by block adjustment with control points as reference. In the case of a flat area such a deviation of the focal length has no influence to the ground points and for an undulating terrain with 100m difference in height against the control points the influence is limited to 3cm in Z. Or reverse, the influence to Z is exceeding the usual vertical accuracy of 0.01% the flying height above ground if the height difference against the control points is larger than 30% of the flying height. Such relative height differences only will be reached under extreme cases osteep mountains.

Based on projection centers determined by relative kinematic GPS-positioning, a correction for the focal length can be computed as well as the location of the principal point. But we have to expect also constant errors of the GPS-values and caused by the extreme correlation, it is not possible to separate between the influence of the inner orientation and constant errors of the GPS-values if we do have only one flying altitude. For a complete calibration under flight conditions it is necessary to have at least 2 quite different flying altitudes with GPS-values for both. The constant GPS-errors are the same for both flying altitudes, but the inner orientation is linear depending upon it. So indirectly the inner orientation can be determined based on the difference in the flying altitudes of both flight levels.

Corresponding to the investigation of Meier (1978), the focal length will not be the same for both flying heights. So by theory a third flying altitude would be required for the determination of a linear change of the focal length as a function of the flying height. But this is not necessary for operational projects. The common adjustment of GPS-shift values and the inner orientation corresponds to a three-dimensional interpolation which is sufficient for different flying altitudes.

If the boresight calibration will be made with the same image scale like the flight over the project area, a separate determination of the inner orientation based on two flying altitudes is not required, the constant shift values will also compensate errors in the focal length – indirectly we will have the same situation like for a block adjustment with control points.

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 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.

The focal length was introduced as unknown during the computation of the boresight misalignment. Depending upon the data set and the type of computation, based on the both flying heights, there have been significant corrections to the focal length from –41µm up to +50µm. Also the location of the principal point could not be neglected.

4. INFLUENCE OF THE NATIONAL COORDINATE SYSTEM

The national coordinate systems are flattening the earth. This is deforming the geometric relations. 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 3). 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 has always the scale factor 1.0.

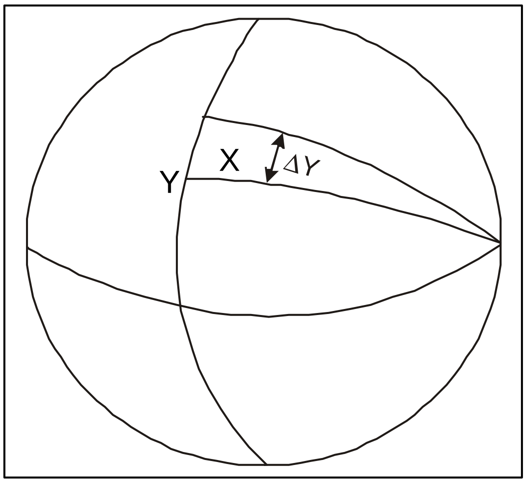

Figure 3: net projection

The usual photogrammetric data handling does not take care about the different 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.

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

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

Formula 1: local scale of transverse Mercator system

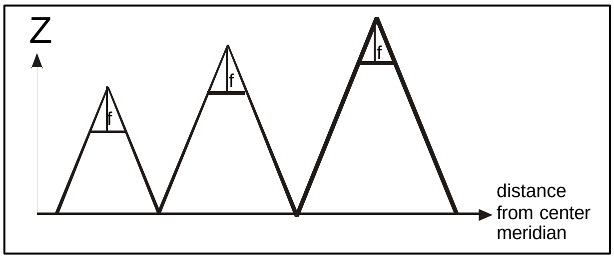

Figure 4: influence of the national net scale to the exterior orientation

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.

The influence to the ground heights is usually within the accuracy range of the point determination. This is different for the projection center. For the OEEPE-test on “integrated sensor orientation” 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 shift of the projection centers for the image scale 1:5000 of 20cm and for the image scale 1:10000 of 40cm. If the misalignment is determined with images of the same scale in the project area, the shift in the projection center is compensated by the Z-shift. This is different if the determination of the misalignment will be done in a location with a different distance from the reference meridian or with a different image scale (see figure 4).

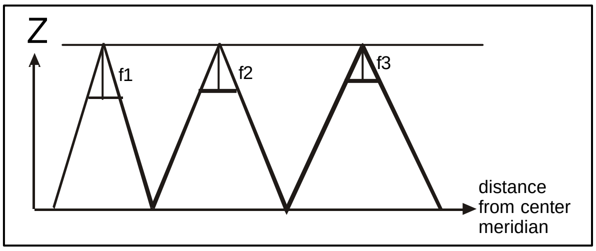

Figure 5: compensation of the scale difference between Z and X,Y by modified focal length

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 5). The transfer of the so determined orientations to analytical or digital photogrammetric work stations has to respect the used geometric configuration.

The influence of the earth curvature to the geometric solution usually will be compensated by an earth curvature correction of the image coordinates.

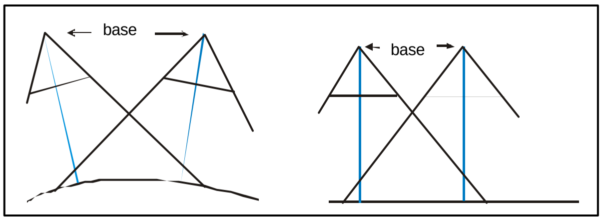

Figure 6: change of base to height relation by earth curvature correction

The flattening of the earth is also changing the base to height relation which is directly influencing the vertical scale (see figure 6). For the OEEPE-test data set with the image scale 1 : 10000, the influence can be compensated by a change of the focal length by 37µm.

All these problems do not exist if the photogrammetric data handling will be done in a tangential 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.

5. TRANSFORMATION FROM TANGENTIAL COORDINATE SYSTEM

The orientation data from an inertial measurement unit (IMU) is available at first in the roll, pitch, yaw-system. Yaw is the primary rotation and it is related to geographic north and not like the usual photogrammetric orientations to grid north. The difference between both is the convergence of meridian. Corresponding to the sequence of rotation of the roll, pitch, yaw-system the rotation matrix has to be computed and this has to be multiplied with a rotation matrix including the influence of the convergence of meridian. From this rotation matrix the photogrammetric orientations in the phi, omega, kappa-system can be computed.

The geocentric coordinate system is orthogonal, but it is not favourable for the data handling – the original horizontal and the vertical coordinate components are mixed and it is difficult to use the correct weights for different accuracy in the original coordinate components. By this reason it is better to handle the data in a tangential system to the earth ellipsoid. The transformations from the national coordinate system should be made over geographic coordinates, geocentric coordinates to tangential coordinates. In geographic coordinates the orientations are related to geographic north, that means the phi, omega, kappa-system has to be rotated by the convergence of meridian. From geographic to geocentric coordinates a rotation by geographic longitude and latitude is required. The next step to the tangential coordinate system has to be done in relation to the geographic longitude and latitude of the tangential point and in the tangential system it has to be related to grid north and the local normal of the earth ellipsoid. In the same way the transformation can be made backwards.

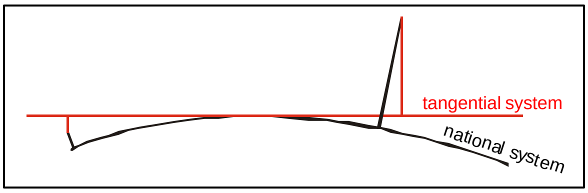

Figure 7: tangential coordinate system

In the tangential system (see figure 7) the described problems are not existing. The earth curvature is respected by the coordinate system and so no net projection is required. In this system the misalignment can be determined with any image scale and in any location and used for the correction of the orientations determined by direct sensor orientation. There is only the problem of the dependency of the focal length from the temperature and the limited accuracy of the knowledge about the actual focal length as described before. If the same image scale will be used for the calibration and for the project area a possible error of the focal length will be compensated by the shift in the misalignment.

The model handling usually will not be made in the tangential system because this requires a transformation of the achieved vector data to the national coordinate system and also in the case of a map update a transformation of old vector data to the tangential system. There is a lack of programs for the transformation of the quite different vector data. By this reason the data acquisition usually will be made directly in the national coordinate system.

For checking purposes, image orientations have been computed with the OEEPE-test data (image scale 1 : 10000, f = 153.357mm) in the tangential coordinate system. For a better check, based on these orientations an error free data set (image orientation, focal length, image and ground coordinates) has been generated in the tangential system. A combined intersection in the tangential system resulted in a σo = 0.5µm and mean square errors at the ground coordinates of SX=0.2cm, SY=0.2cm and SZ=0.4cm. These discrepancies can be explained by rounding errors. A standard transformation of the error free data set into UTM (range of X: 106.4km – 115km from center meridian) without any correction resulted in σo = 27.9µm and mean square errors at the ground coordinates of SX=1.0cm, SY=0.9cm and SZ=31.3cm. That means, the neglected, but required corrections do have only a limited influence to the horizontal accuracy but a strong influence to the height. A combined intersection in the UTM-system with a corrected focal length corresponding to the local scale of the national net (f=153.394 instead of f=153.357) resulted in SX=0.3cm, SY=0.2cm and SZ=7.0cm. This step has reduced the systematic errors in Z from 31.1cm to 6.2cm. Still better results have been achieved just with a standard earth curvature correction - σo, SX and SY are down to results corresponding to the reference intersection in the tangential system and also the discrepancies in Z are quite better. There is only a remaining systematic error in Z of 3.0cm. This remaining shift in Z could be reduced by a change of the focal length corresponding to the average local scale of the UTM-system (formula 1 → scale factor 0.999745) changing the focal length from 153.357 into 153.396. The remaining discrepancies at the ground coordinates are now very close to the reference values in the tangential system. The remaining mean square discrepancies in Z are corresponding to mean square discrepancies in the x-parallax of 0.9µm or 0.7µm in each image. At first this is below any critical value, but it can be explained also by the different steps of computations – the image coordinates in this case only have been stored in full microns.

A detailed analysis of the remaining discrepancies shows a small tilt of the block area. The distance from the reference meridian is in the range of 106.4km up to 115km corresponding to a local scale from 0.999740 up to 0.999763. The difference in the scale leads to a change of the flying height above ground of 3.5cm which can be seen in a tilt of the block. By this reason also a combined intersection with the Hannover program BLUH using an individual correction of the focal length depending upon the local scale of the UTM-system has been made. This improved the mean square differences of the Z-component to 1.2cm together with a remaining systematic error of 0.9cm and after removing the systematic effect, to 0.9cm. The variation of the individual focal length is 3µm from west to east. The negligible discrepancies do not show any more a tilt of the block. The mean square discrepancies in Z are corresponding to a x-parallax of 0.6µm or for each image 0.4µm, that means they are in a range of not avoidable rounding errors.

6. INFLUENCE OF GEOID AND DEVIATION OF NORMAL

The national height values are related to the geoid. GPS and the combination of GPS and IMU are at first geocentric values, which have to be transformed to geographic values. At first the height values are related to the earth ellipse (e.g. WGS 84). These height values have to be improved by the geoid undulation. As visible in figure 8, the European quasigeoid EGG97 in the OEEPE-test area is mainly a tilted plane (Denker 1998). The geoid undulation in the shown area goes from 37.20m up to 38.66m. The mean square differences against a tilted plane are just +/-2.2cm.

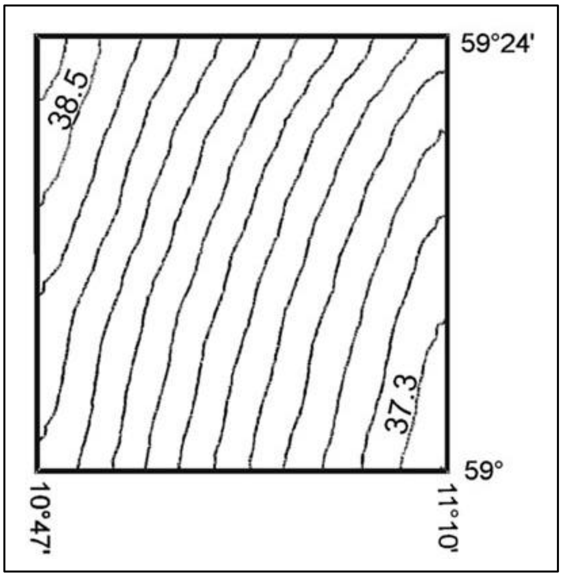

Figure 8: contour lines of the Geoid undulation in the OEEPE-test area

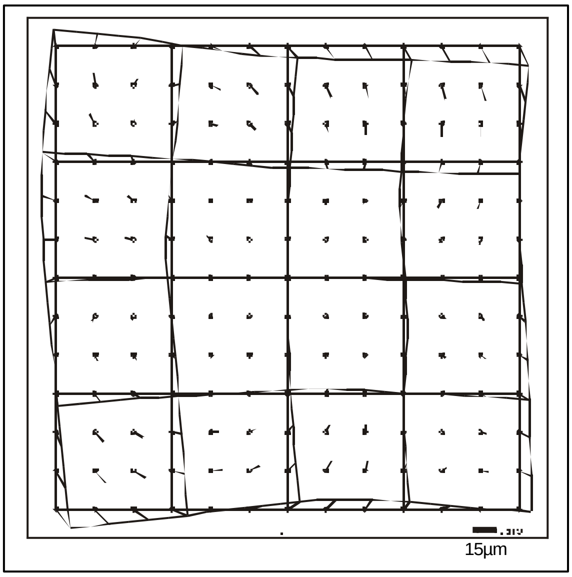

Figure 9: systematic image errors

Corresponding to the surface of the geoid, the normal has a deviation in east-west-direction from 8” up to 12” and in the north-south-direction –0.7” up to 4.6”. For the location of the images it is still smaller with 10.9” up to 12” in the east-west-direction and –1.8” up to –2.7” in the north-south-direction. The deviation of the normal is directly influencing the roll and pitch values. This is causing a shift of the location of the determined ground points for the image scale 1 : 5000 with a flying height of 750m above ground of 4cm up to 4.4cm in east-west direction and 0.7cm up to 1.0cm in the north-south-direction. Such a size should be respected, but ca be compensated by the shift values of the misalignment if the calibration site is not far away. After such a shift the final effect to the determined ground points is just in the range of few mm.

7. INFLUENCE OF SYSTEMATIC IMAGE ERRORS

The real geometry of aerial photos is not identical to the mathematical model of perspective images. Even if this is a lack of the mathematical model, the difference is named “systematic image errors” and determined by self calibration with additional parameters.

In the case of the OEEPE test data set, the number of images used for the determination of the misalignment is large enough for a save self calibration. In the used program system BLUH, the individual additional parameters are checked by statistical tests and only the significant parameters are finally used if they do not have too large correlation. The influence of the systematic image errors was like usual (see example shown in figure 9).

The self calibration is influencing the exterior orientation. If the reference adjustment will be made with self calibration, the same systematic image errors have to be used as a pre-correction of the image coordinates in the project area itself. This has been made with the OEEPE-test data set. A comparison without using self calibration from the beginning has shown only unimportant differences between both methods. The small discrepancies of the results are not astonishing, systematic image errors usually do have only a limited influence to a single model. Only the sum up of systematic errors in a block adjustment with a limited number of control points is causing a deformation of the block. Such a sum up of systematic image errors is not existing in the case of a direct sensor orientation.

8. STABILITY OF THE BORESIGHT MISALIGNMENT

The long time stability of the boresight misalignment is an open question. One limitation of the stability is coming from the fact, that the aerial cameras have not been constructed for the attachement of an IMU. This has been changed for the new high resolution digital cameras LHS ADS40 and Z/I DMC. Another fact is coming from the rough flight conditions and the mount of the IMU outside of the cameras where they are exposed to mechanical disturbance. Of course the stability is also depending upon the required accuracy. If the highest accuracy is required, a daily check of the boresight misalignment is recommended. Without check, at least one ground point in the project area should be used for reasons of reliability.

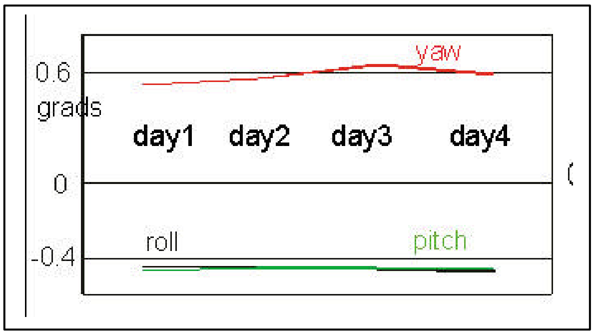

Figure 10: stability of boresight misalignment – block Leipzig

In a project in Germany, flown in 1998 with not the today newest IMU, the boresight misalignement has been checked during 4 flight days before and after the flight over the project area. The discrepancies before and after the flight over the project area have been not significant, but they gave the full reliability about the situation. This was different for the situation over the 4 days. Here the yaw (corresponding to kappa), which is usually the most sensitive element, changed significantly (figure 10).
Hansa Luftbild (Dreesen 2001) made during a large project a check during every flight day over a periode of 42 days showing two times a sudden change (figure 11).

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, it can be accepted for some orthoimage projects, but not for every project with higher accuracy requirements.

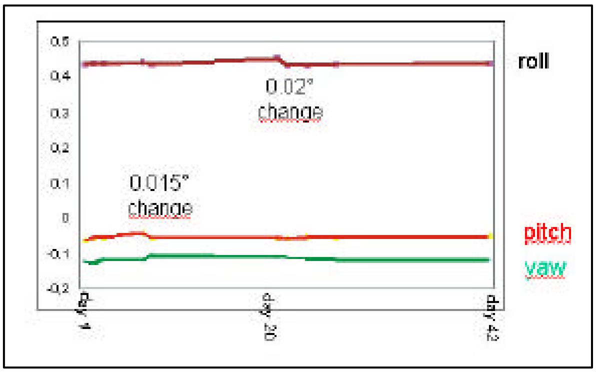

Figure 11: stability of boresight misalignment – results from Hansa Luftbild

9. MODEL SETUP

The sigma0 of a combined intersection with corresponding image coordinates, based on the direct sensor orientation is in the case of the OEEPE data set 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, 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 with 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.

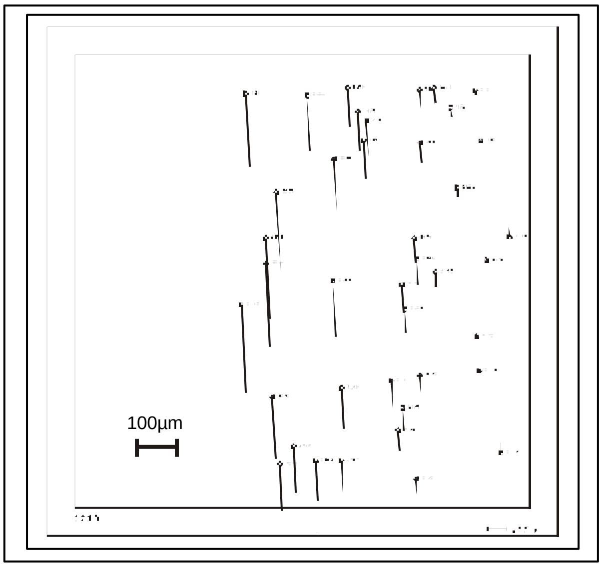

Figure 12: y-parallaxes after model set up – extreme case

Figure 12 is showing an extreme case of y-parallaxes of a model set up based on direct sensor orientation. After improvement by a combined adjustment, using the direct sensor orientation and corresponding image coordinates, but no control points, in the whole model there are no more problems for the stereoscopic handling. In this case, the dominating effect of the yaw is obvious. For the OEEPE test data set the mean square y-parallax has been reduced from 20µm to 46µm by a combined adjustment down to 9µm, with extreme values up to 14µm. That means after combined adjustment, the problem with the y-parallaxes was solved.

CONCLUSION

The direct georeferencing based on a combination of relative kinematic GPS positioning and IMU has reached a very high accuracy level which is suficient for most of the applications. With an image scale 1:5000, the accuracy of ground coordinates based on such orientations can be in the range of 10cm to 20cm for all coordinate components. Corresponding to this high accuracy level, all steps of the determination must be handled in a rigorous manner. This starts with the determination of the boresight misalignment including also the inner orientation of the used camera. If the image scale used during determination of the boresight misalignment is not the same like during the flight over the project area, the inner orientation has to be determined based on two different flying heights. The separation of the principal point location from GPS shift values requires images with opposite flight direction for the boresight calibration.
The photogrammetric data handling has to respect the local scale of the net projection – without taking care about the local scale, the direct georeferencing will cause a hight shift if the data are handled in the national coordinate system. Without change of the used programs, this can be made by a change of the focal length for close to vertical images. If in addition the image coordinates are improved by the standard earth curvature correction, for aerial images the influence of the flattening of the earth to the national coordinate system and the different scales in the horizontal and vertical direction are compensated. Based on such corrections the misalignment of an IMU can be determined in a different location and also with a different image scale like the project area.
Geoid undulations have to be respected for the computation of the national heights. In areas with a sufficient knowledge of the geoid, the deviation of the normal should be respected. If this will not be done, even in larger blocks it's influence is mainly covered by the horizontal shift values of the misalignment, so only a not important influence to the final ground coordinates will be seen.

The self calibration by additional parameters is not so important for the direct geo-referencing because there is no sum up of systematic errors like in a block with only few control points. In addition in an operational application, the reference blocks for the determination of the misalignment are usually small and do not allow a detailed determination of the systematic image errors.

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