DIRECT / INTEGRATED SENSOR ORIENTATION - PROS AND CONS

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ABSTRACT:

The direct geo-referencing of sensors based on a combination of relative kinematic GPS-positioning and inertial measurement units (IMU) has reached a high accuracy level and growing application. It includes the advantage of a very flexible use, independent upon control points which are only required for the system calibration and independent upon block or strip configurations. It is in use in areas with difficult access, as well as for standard applications. The direct georeferencing is a prerequisite for the economic use of small format digital images instead of standard aerial photos.

Projects with standard accuracy requirements can be handled without problems. Only some limitations may appear for the model setup; disturbing y-parallaxes cannot be avoided with the today dominating application of standard photographic aerial cameras. But an improvement of individual models or a whole block by a combined adjustment together with image coordinates of tie points can solve this problem. For large scale projects with higher accuracy requirements an integrated sensor orientation by a bundle block adjustment with the orientations as observations and a minimal number of control points is proposed.

An overview of the status of direct and integrated sensor orientation will be given.

1. INTRODUCTION

A basic geometric problem in photogrammetry is the determination of the sensor orientation. For analogue and digital frame cameras this can be made by resection for single images or relative and absolute orientation for a stereo model. In aerial applications we usually do have an image block and the common determination of the exterior orientation by block adjustment is more economic. The expensive and time consuming control point measurement can be reduced by a common bundle block adjustment with projection centres from relative kinematic GPS-positioning. This method of combined adjustment is today a standard solution, but it is economic only for larger blocks and it requires in addition to a small number of control points, the photo measurement of tie points and also a satisfying block configuration with usually additional crossing flight lines. For individual flight lines the use of projection centres for the block adjustment has only a limited advantage, it cannot control the lateral tilt. In addition an extrapolation out of the area of the control points should be avoided.

The direct and the integrated sensor orientation are able to solve several up to now existing problems of the sensor orientation and can speed up the projects. With a combination of relative kinematic GPS-positioning and an Inertial Measurement Unit (IMU), the projection centre position and the attitudes can be determined. This gives a wide range of flexibility like for example in coastal regions where only a small part of the images is covering land and the traditional tie of images are failing. Also no problems exist in forest, desert and mountainous areas where the automatic aerotriangulation has problems.

Under direct sensor orientation we do understand the determination of the exterior orientation just by the combination of IMU and relative kinematic GPS-positioning. Of course the determination of the attitude and shift relation of the IMU to the sensor system, the boresight misalignment, or a complete system calibration has to be made over a controlled reference area. A disadvantage of the direct sensor orientation is the missing reliability and also some problems with y-parallaxes of the model set up. This can be improved by a common adjustment of the directly determined exterior orientation together with image coordinates, which is named as integrated sensor orientation. With the integrated sensor orientation we still do have the advantage of an orientation without control points and also problems of the image tie do not lead to missing solutions.

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 centres to the ground. By this reason, the steps of computation have to be handled with more care.

The accuracy and also the reliability of the direct sensor orientation are depending upon the relation of the IMU to the sensor, the so called boresight misalignment. This has to be determined and respected. Of course it is an additional effort influencing the economic aspects. By this reason the required methods are critical for the wide acceptance of the direct georeferencing. For the determination of the boresight misalignment control points are required. Of course it is easier if always the same reference area, located close to the airport of the survey aircraft, will be used. But this requires a correct handling of the coordinate systems and also a system calibration including the inner orientation of the imaging sensor. In addition it is important how often the system has to be calibrated. On one side we do have the economic aspects, on the other side we do have the required accuracy and reliability, so a compromise between both is required which may be dependent upon the product specifications.

For the correct estimation of the pros and cons, the possibilities and requirements of the preparations have to be analysed because of their strong effect to the economic situation and the required additional handling time.

2. BORESIGHT MISALIGNMENT

The direct sensor orientation is based on a combination of an inertial measurement unit and relative kinematic GPS-positioning. Instead of the sometimes uses expression inertial navigation system (INS), the expression IMU is used because in this case the identical hardware for both applications will not be used for navigation, but only for the registration of the attitude and position data. The IMU attitude information and the position, which is based on a double integration of the acceleration, do have only good short time accuracy. By this reason the IMU has to be combined with the GPS-positioning which has an absolute accuracy. On the other hand GPS cycle slips can be determined by the IMU, so the combination of both lead to an optimal solution.

The orientation of the imaging sensor is requested, so the IMU has to be fixed to the sensor. The mounting can only be done approximately parallel to the system of sensor axis requiring a calibration of the relation IMU – sensor.

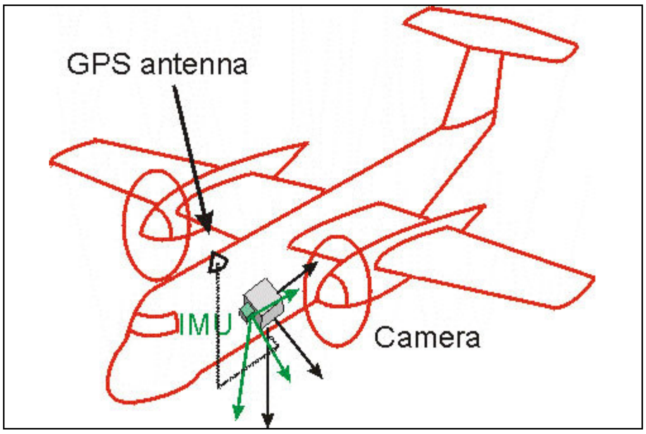

Figure 1. Relation camera – IMU – GPS antenna

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-attitude and position data with the exterior orientation of a controlled block adjustment. 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 GPS shifts cannot be separated from the position of the principal point if we do have only one flight direction.

If the reference block will be flown with the same altitude above ground like the project area, the determination of the boresight misalignment is sufficient. Discrepancies of the focal length will be compensated by the same flying height, but if the height is different, a system calibration is required.

3. SYSTEM CALIBRATION

The interior orientation is determined in laboratories under constant and homogenous temperature conditions. Under actual flight conditions, the temperature is different and we do have a not neglect able vertical temperature gradient in the optics causing a lens deformation. Meier (1978) has made a theoretical investigation of the resulting change of the focal length (table 1).
In general the values have been confirmed by empirical tests, but the values are just rough estimations which have to be checked under operational conditions. The same problem exists with the principal point location.

	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)

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 only exceeding the usual vertical accuracy of 0.01% of 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 of steep mountains.

Based on projection centres 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 the influence of the inner orientation from 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 has an effect linear depending upon it. So indirectly the inner orientation will 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.

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 two 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 flight for testing the results in the scale 1:5000. The targeted control points of the test field are available with 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 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. Intensive tests with 11 system calibrations have been made by the Finish Geodetic Institute and the National Land Survey of Finland (Honkavaara et al 2003) showing improvements of the focal length up to 45µm and significant changes of the principal point locations up to 40µm.

The discrepancy of the interior orientation parameters cannot be neglected. The knowledge of the actual focal length is important for a flight over the project area with a different flying height above ground like during the reference flight. The location of the principal point is also important if the flight direction will not be the same – like usual. But the location of the principal point can be determined with a reference flight only on one height level, flown with opposite directions.

4. INFLUENCE OF THE GROUND COORDINATE SYSTEM

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

The earth flattening by the net projections is deforming the geometric relations. All modern national net projections are conformal – over short distances the angular relations are not influenced by the projection. This only can be reached if the enlargement of the ΔY, which is caused by the convergence of the lines perpendicular to the reference meridian, will be compensated by a local enlargement of the ΔX (see figure 2). So we do have a local change of the projection scale independent upon the direction (formula 1).

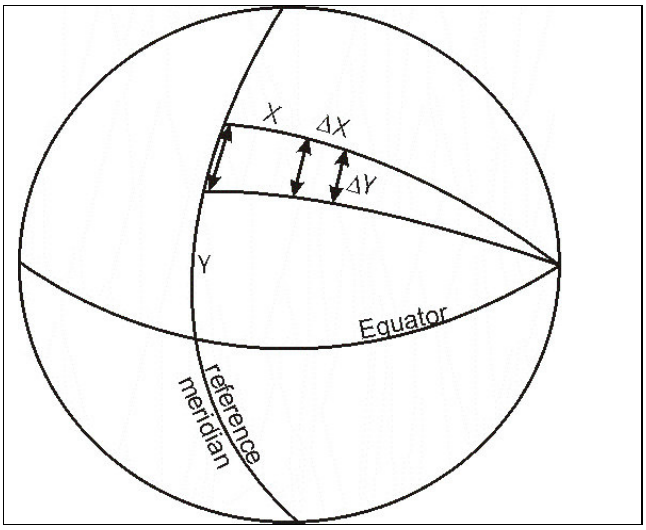

Figure 2. net projection

S0 = scale factor for reference 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

This local scale change is valid 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 leading to an affinity deformation of the three-dimensional coordinate system.

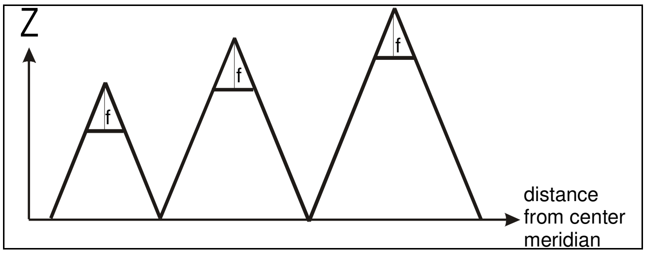

Figure 3. influence of the national net scale to the exterior orientation

Only one average scale for all three coordinate components will be determined by the image orientation. Caused by the limited Z-range the vertical control points usually have no or only a negligible influence to the model scale. 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 or 40cm difference for a flying height above ground of 1000m. The scale factor of UTM-coordinates goes up to 1.001 corresponding to 1m over 1000m.

The influence to the ground heights is usually within the accuracy range of the point determination. This is different for the projection centre. 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 centres for the image scale 1:5000 of 20cm and for the image scale 1:10000 of 40cm. If the boresight misalignment is determined with images of the same scale in the project area, the shift in the projection centre 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 3).

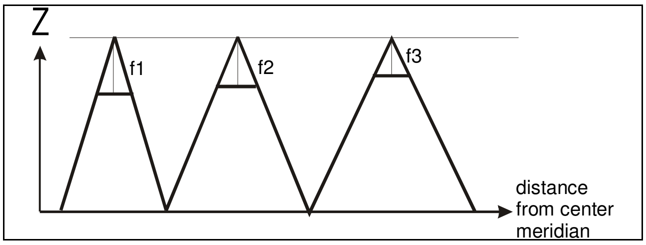

Figure 4. compensation of the scale difference between Z and X, Y by modified focal length

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

Distance from centre meridian	local scale in UTM	focal length (mm)		
		UTM with earth curvature	UTM with local scale correction	Tangential
4’	0.999 60	153.421	153.360	153.359
56’	0.999 64	153.416	153.360	153.359
1°56’	**0.999 75**	**153.398**	**153.360**	**153.359**
2°56’	0.999 96	153.368	153.360	153.359

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

With the data set of the OEEPE test “Integrated Sensor Orientation” (Heipke et al., 2000) a system calibration using the UTM and the tangential coordinate system has been made. For showing the influence of the reference block location, the ground coordinate system has been shifted by -2°, -1° and +1° longitude. In the UTM coordinate system a computation with just the earth curvature correction and a computation with additional local correction of the focal length has been made. Table 2 shows the result – if the local net scale will not be respected, the achieved focal length is linear depending upon the local scale of the UTM coordinate system. If this local scale will be respected, the focal length is independent upon the location of the reference block and it is with the exception of a negligible rounding error identical to the result achieved in the tangential coordinate system.

5. 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 originally 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 5, 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.

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 from –0.7” up to 4.6”. 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 in the OEEPE test area for the used 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 it can 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.

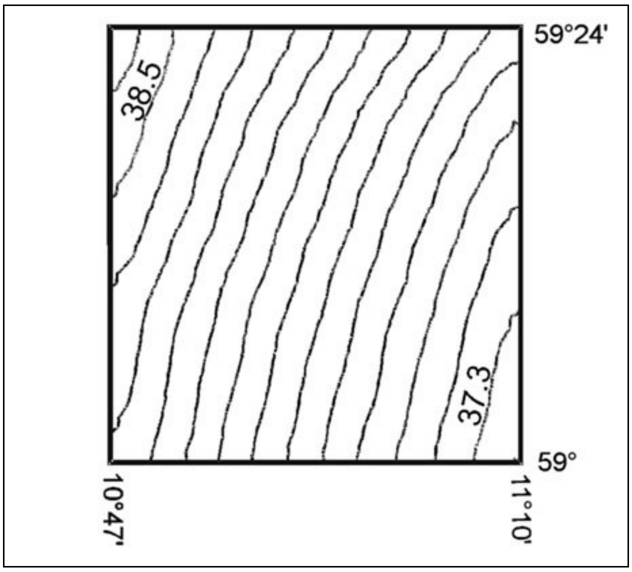

Figure 5. contour lines of the Geoid undulation in the OEEPE-test area

The geoid should be respected by the GPS-processing in the reference and the project area. Only the difference between the geoid in the GPS reference stations to the flight areas is influencing the result. The distance from the flight area to the local GPS reference station should not exceed 30km if the highest possible accuracy is required. In the above shown example (figure 5), the geoid undulation is changing over 30km up to 1m – this cannot be neglected. Datum problems are compensated by the GPS reference station.

6. STABILITY OF CALIBRATION

The stability of the geometric relation of the IMU to the imaging system and the stability of the inner orientation are important for the decision if a system calibration is required for any project or not or even if a calibration is required before and after any flight. Some investigations have been published by Hansa Luftbild (Dreesen 2001, Schroth 2003), the Institut Cartogràfic de Catalunya (Baron et al 2003), the University Stuttgart (Cramer et al 2002), the Finnish Geodetic Institute together with the National Land Survey of Finland (Honkavaara et al 2003), Applanix (Mostafa et al 2003) and the author (Jacobsen 2000).

The analogue photogrammetric cameras have not been constructed for the attachment of an IMU causing some of the stability problems. Also the inner orientation of the analogue cameras has only the stability required for the classical orientation. This is different for the new digital cameras like Z/I DMC, Vexcel Ultracam, Leica ADS40 and Applanix (Emerge) DSS. The construction has respected from the beginning the mount of an IMU-system. The line scanner ADS40 cannot be operated without. Today the use of analogue cameras is dominating, so most of the investigations are related to them.

The quality of the attitude information has reached a high level, so with some exceptions the problems of direct sensor orientation are located more in the position of the projection centre and the inner orientation. Especially the focal length has only limited long term stability. Honkavaara et al (2003) are reporting about a change of a wide angle focal length from 25µm to 43µm against the calibration certificate. The change of 43µm – 25µm = 18µm corresponds to 0.01% of the flying height and this is the usual accuracy of photogrammetric point detection. Cramer (2003) is showing problems of the vertical component of some long term investigations of Hansa Luftbild. Baron et al (2003) reports about a change of the focal length of 15µm within 24 days. An explanation for the change of the focal length can be found at Meier (1978). Theoretical investigations were leading to changes of the focal length caused by the vertical temperature gradient in the lens system based on the cold air outside and moderate temperature in the aircraft. Discrepancies of the focal length under flight conditions to the laboratory calibration up to 40µm have been seen often.

The shift parameters between IMU and the imaging sensor are changing from day to day. Of course this cannot be explained by a physical shift of one to each other, but the shift parameters are strongly correlated with the location of the principal point and in the flight direction with problems of the time synchronisation. A separation between the shifts caused by the GPS positioning and the principal point location is possible if the reference flight will be flown in two opposite directions. Due to strong correlation a separation of the principal point location in the flight direction and a time synchronisation is not possible, but it is also not required. Cramer (2003) is reporting about the results achieved by Hansa Luftbild showing a change of the shift parameters from day to day in the range of 10cm up to 20cm, but Hansa Luftbild made only reference flights in one direction, so a separation between the principal point location and other reasons is not possible. Honkavaara et al (2003) have identified changes of the principal point location up to 16µm for the same camera – this is more than the possible photogrammetric measurement accuracy of objects.

With the exception of the influence to the model set up for a stereo measurement, the accuracy of the attitude parameters is usually sufficient. But Dreesen (2001), Honkavaara et al (2003), Baron et al (2003) and Jacobsen (2000) have seen some sudden changes of attitude parameters from one day to the other even after longer time stability. Baron et al (2003) have identified sudden changes of the attitude relation in the range of 3' and this cannot be neglected for all applications.

7. ACCURACY AND RELIABILITY ASPECTS

If the mentioned problems are respected in the correct manner, the direct sensor orientation – the determination of the exterior orientation based on inertial data in combination with relative kinematic GPS positioning – has reached a high accuracy level sufficient for most applications. With large scale images, object point accuracies in the range of 20cm for all coordinate components can be reached, with a very careful handling even 10cm up to 20cm. This is sufficient for most of the applications. Still a problem may exist with the set up of models for manual stereo compilation. Often the rotation yaw or kappa is the week point causing not acceptable y-parallaxes in the stereo models.

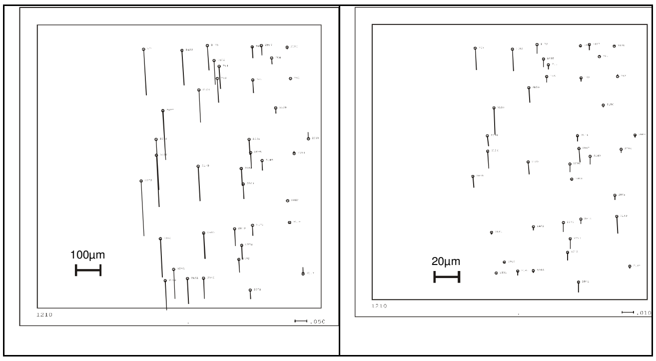

Figure 6. y-parallaxes in a stereo model of the OEEPE test

direct sensor orientation RMSpy=116µm

integrated sensor orientation RMSpy=13µm

An extreme case of problems with y-parallaxes in a stereo model set up by direct sensor orientation can be seen on the left hand side of figure 6; it corresponds to root mean square errors of the y-parallaxes of 116 µm (Jacobsen et al 2001). Values above 20µm do cause problems with the stereo impression of the floating mark. This can be solved by an integrated sensor orientation based on an adjustment of the exterior orientation determined by direct sensor orientation and image tie point. This bundle block adjustment with additional observations does not require control points. Based on the integrated sensor orientation the root mean square y-parallaxes of the mentioned model are reduced to 13µm. In the case of the both OEEPE test blocks, in the average the RMS y-parallaxes have been in the range of just 10µm – this is a usual value for model handling.

The integrated sensor orientation requires the determination of tie points, but today this is a standard procedure solved by automatic aero triangulation. Of course it improves also the reliability – the relative relation of the images is controlled by tie points. For operational blocks usually few check points are measured to be save for blunders in the data handling. Of course these check points can be used also for a combined adjustment which may solve also problems of shift values.

8. CONCLUSION

The direct and integrated sensor orientation reached an accuracy level sufficient for most applications. An important aspect is the quite higher flexibility of the block structure like for traditional block adjustment. Areas with missing object contrast like water surfaces, desert or forest can be bridged without problems. Even if few check points are used, their location can be somewhere within the project area – so special locations like block corners where the access to the ground may be difficult must not be used for their location. It is not a problem to map areas where the access is difficult or dangerous. The processing time can be reduced against traditional image orientation.

On the other side unreliable results are not accepted, so a procedure which is taking care about the reported problems has to be used. It became a common strategy to determine the boresight misalignment every flight day. Some companies have done it also before and after the photo flight. The reference flights should be done at least over a small test area with control points with opposite flight directions to control the principal point location. If the reference flight will be done with the same flying height above ground like used over the project area, the determination of the focal length is not required because the main effect is covered by the shift parameters. If different flying heights are used, a complete system calibration including also the focal length has to be made with two different flying heights. The influence of the map projection has to be taken into account – this can be made with a determination in an orthogonal coordinate system, like geocentric or tangential or with respecting the local net scale which also can be made by a local change of the focal length, but of course the refraction correction and in the case of a direct handling in the national coordinate system, the earth curvature correction has to be respected.

If the problems of the net projection and the focal length are respected, the reference area for the determination of the boresight misalignment must not be located in the area of the project. Of course the required GPS reference must be available, but this can be made also with worldwide differential GPS services like OmniStar, Skyquest Aviation or NavCom, reaching sub-meter accuracy. Still most companies are determining the boresight misalignment within the project area and with the same flying height, making the handling easier, but this may not be an economic solution for small projects.

In general it has to be mentioned that some experience and sufficient education is required for the handling of the direct sensor orientation. Often the first test fails because of some missing details. This may be the missing required flight figure for the initialisation of the inertial system or the use of very long straight flight lines which may be affected by inertial drifts. Extreme long flight lines should be interrupted by flight figures like a circle for avoiding problems with the inertial drift. Of course the handling has to be done more rigorous, respecting the geoid undulation and the characteristics of the used coordinate system. All these aspects are not reducing the large economic potential of the direct sensor orientation which may be improved by an integrated sensor orientation.

Some aspects of the limited stability of the boresight misalignment are caused by problems of the used analogue film cameras which have not been constructed for the mount of an IMU-system. This may be different for the new digital cameras with a stable imaging plane and a foreseen optimal IMU-mount, but up to now this has not been analysed in a sufficient long term manner.

The direct sensor orientation allows solutions different from standard applications with a high flexibility. The use of small format digital cameras is not economic if the orientation has to be determined by standard block adjustment. With the direct sensor orientation an economic use has been enabled.

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