ON THE USE OF DIRECT GEOREFERENCING IN AIRBORNE PHOTOGRAMMETRY

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Key words: GPS/inertial, airborne, photogrammetry, direct georeferencing

ABSTRACT

With the availability of high-end integrated GPS/inertial systems the direct georeferencing of airborne imaging sensors becomes feasible even for highest accuracy demands. Such integrated systems provide the only way for an efficient orientation of the upcoming airborne digital line scanning sensors. Nevertheless, the use of GPS/inertial systems in combination with classical analogue aerial cameras is advantageous, too. To investigate the performance of direct orientation measurements in photogrammetric environments extensive flight tests were done at the Institute for Photogrammetry (ifp) in 1998 and 2000 using two commercially available integrated GPS/inertial systems (Applanix POS/AV 510 DG, IGI AEROcontrol IId) in combination with standard analogue aerial cameras (Z/I Imaging RMK-Top15). To compare the quality of the two systems the tests were flown over the same test area under similar flight conditions. Within these tests, traditional aerial triangulation (AT) provides independent data for the orientation parameters. Comparing the indirectly determined orientation parameters from AT to the values from GPS/inertial data processing first estimations on the quality of the directly measured orientation parameters are possible. The overall system performance is estimated from re-determined object points that are compared to their given reference coordinates. For this final accuracy test not only the quality of GPS/inertial orientations but the image block geometry – resulting in varying image overlaps – and the quality and stability of the imaging sensor is of major concern and discussed in detail. Using an optimal overall system calibration the accuracy of direct georeferencing can compete to the well known quality establishing the traditional indirect method of AT for image orientation. Finally, possible applications of GPS/inertial systems in the airborne photogrammetric environment are given.

1 INTRODUCTION

Photogrammetry in general deals with the three dimensional object reconstruction from two dimensional imagery. In practical aerial photogrammetry these images are mainly captured using classical film based airborne cameras. Nonetheless, main focus was laid on the development of digital airborne sensors in the last years to finally close the fully digital photogrammetric

processing chain. Since digital photogrammetric work stations are available for a while and introduced in practice, the image data acquisition is the only gap in the fully digital photogrammetric work flow. Based on the experiences with first experimental digital camera systems like the Digital Photogrammetric Assembly DPA from DASA (Kaltenecker, Müller & Hofman, 1994), the Wide Angle Airborne Camera WAAC (Sandau & Eckert 1996) and the High Resolution Stereo Camera HRSC (Wewel, Scholten, Neukum & Albertz 1998) both developed by the DLR, the first commercial airborne line scanner Airborne Digital Sensor ADS 40 was developed by LH-Systems and presented in summer 2000 (Sandau et al. 2000). In contrary to the push-broom line approach applied by the systems mentioned before, parallel tests were done using smaller format CCD frame sensor configurations (Thom & Souchon 1999, Toth 1999) and now Z/I Imaging is the first commercial company working on the development of an airborne system based on the combination of several CCD frame sensors to provide a large format camera that can compete to the standard analogue frame sensors. This so-called Digital Modular Camera DMC will be launched on the market in 2001 (Hinz, Dörstel & Heier 2000). Despite of the digital data recording providing significant advantages for example time and cost savings – no film development and scanning is necessary – and higher radiometric accuracy and resolution resulting in additional photo flight days, the major goal of the digital sensors is the acquisition of pan-chromatic and multi-spectral imagery simultaneously. This functionality will open up a completely new market segment for airborne remote sensing applications. Due to the expanded spectral capabilities many applications for example in agriculture, forestry and disaster management will efficiently use the new digital sensor data. From market forecasts there will be a significant growth of commercial applications in this market segment whereas the traditional government and civil mapping applications will stagnate or even shrink (Heier 1999). The applications in this new market segment have different requirements by means of classical map production that are characterized by two major points: 1. Since most of the applications are dependent on very actual information there is a high need for a fast, flexible and efficient data acquisition and processing chain. 2. The requirements on the spatial resolution and accuracy are somewhere between the very stringent demands from traditional photogrammetric large scale mapping or applications in cadastral or infrastructure planning and on the other side limited from the high resolution satellite sensors. Since airborne applications are in strong competition to the high resolution satellites airborne sensor always have to beat their competitors with better spatial resolution resulting in higher accuracy.
This short overview illustrates the future situation on airborne photogrammetric image market and the different types of sensors that are available for the data acquisition. Dependent on the aspired application analogue or digital sensors and direct or indirect method of georeferencing will be advantageous. Against this background the two different methods for image georeferencing are discussed in the following.

2 GEOREFERENCING OF IMAGE DATA

The georeferencing is one essential pre-requisite for the whole image data evaluation work flow. The general problem is described like follows: Since no knowledge on the image position and orientation during time of exposure is available immediately after the image recording process, the image vector is pointing to an arbitrary point in object space. Only if the position (X_0, Y_0, Z_0) and orientation (ω,φ,κ) of the sensor is known – the six exterior orientation elements – the uncorrected image vector is transformed to the corrected georeferenced position and the relation between the local image coordinate system and the global object coordinate frame used for the data evaluation is solved. In general two different methods are possible for this orientation task.

Although the standard approach of indirect sensor orientation using aerial triangulation is well known this method is revisited shortly. The indirect approach is based on ground control points, the measurements of their corresponding image coordinates and the connection of neighbouring images via tie points. With the knowledge of the sensor geometry (interior orientation of the camera) the aspired exterior orientations are estimated as one group of unknowns in an adjustment procedure. Additional to the orientation parameters, the unknown object point coordinates and if necessary additional self-calibration terms are determined. This self-calibration is done to fit the physical process of image formation on the assumed mathematical model of central perspective based on the collinearity equations. Dependent on the implemented approach physical significant parameters (Brown 1971) or simple orthogonal polynomials (Ebner 1976, Grün 1978) are estimated during self-calibration to correct for remaining systematic errors. Since there are strong correlations between the different unknowns, the estimated values of exterior orientation are optimal values only in the sense of object reconstruction but compensate for all types of remaining systematic errors and thus might be different from the true physical parameters of exterior orientation (see e.g. (Schenk 1999), (Cramer, Stallmann & Haala 2000)). This is of no concern in the AT process, because there is no need for the knowledge of the true physical orientation parameters and the correlation did not affect the object point accuracy, but this situation changes when direct georeferencing using integrated GPS/inertial systems is applied.
Within the direct approach the GPS/inertial components provide measurements of the true physical position and orientation of the sensors. In contrary to the classical aerial triangulation the exterior orientation parameters are determined completely independent to the sensor to be oriented, therefore this direct method is flexible and can be used for any kind of sensor. On the other hand, since the position and orientation sensors (GPS antenna, IMU) are displaced from the camera to be oriented, the time and spatial eccentricity and especially the misalignment or boresight alignment between IMU and camera coordinate frame has to be determined and corrected before using the GPS/inertial exterior orientations for sensor orientation. The requirements on this calibration between GPS/inertial and camera components are very high, since small errors here will cause large errors in object point determination. Additionally, the interior geometry of the camera is of major importance. The integrated GPS/inertial system now provides true physical position and orientation parameters and the physical image formation process has to be known very precisely, since remaining non-modelled systematic errors affect the quality of georeferencing. The analysis of the empirical test data will investigate the influence on system calibration on the quality of georeferencing. For more details on the general concept of direct georeferencing and GPS/inertial data integration using recursive Kalman filtering the reader is referred to literature (e.g. Skaloud 1999, Skaloud, Cramer & Schwarz 1996, Schwarz et al. 1993).

3 EMPIRICAL ACCURACY TEST

3.1 Sensor configuration

As already mentioned in the beginning of this paper two different commercial GPS/inertial systems were tested under similar airborne environments. During the first campaign in December 1998 the POS/AV 510 DG – formerly called POS/DG 310 – from Applanix, Canada (Reid & Lithopoulos 1998) was flown, about 15 months later in June 2000 a similar test was done using the AEROcontrol IId system from IGI, Germany. Since both systems are the only two commercial systems for high-end direct georeferencing applications available on the world market in the moment, these accuracy investigations are very interesting for the users community. The general integration and sensor concept of the systems is quite similar. The GPS/inertial data integration is based on a loosely coupled decentralized Kalman filter approach, where the differential GPS phase data processing is done first and the obtained DGPS positions and velocities serve as update information for the later inertial data processing. For the GPS data evaluation the GrafNav software package (Waypoint Consulting, Canada) is used, for the final data filtering both companies provide their own Kalman filter software embedded in a user-friendly graphical user interface. The later data processing is done using the commercial software tools only to compare the off-the-shelf system quality directly. The only difference from a hardware point of view is the IMU: Since the inertial unit installed in the POS/AV 510 DG (Litton LR86 unit, meanwhile replaced by Applanix AIMU) is based on dry-tuned gyros, the AEROcontrol unit (IGI IMU-2d) utilizes fibre-optical gyros. This different sensor technology results in small differences in their technical specifications.

3.2 Test flight design

Testing the accuracy performance of high-end integrated GPS/inertial systems in dynamic environments is not an easy task, since independent references for the exterior orientations are necessary for the quality checks. One possibility in airborne applications is combining the system with an imaging sensor flying over a well prepared photogrammetric test site, where the indirect method of AT is used to determine independent values for the comparisons. Applying this method for the accuracy tests two things have to be taken into account: First, as it was pointed out before, the exterior orientations from AT are only estimated values affected by any uncorrected systematic errors and might be different from the physical orientation parameters. Second, the theoretical accuracy of the orientation parameters is dependent on the image block geometry and the image scale (for positioning information of the camera perspective centre). Using the results from AT as independent reference the accuracy should be preferable 5-10 times better than the expected accuracy from GPS/inertial. This cannot be guaranteed for high-end integrated systems where the accuracy potential is in the range of 10cm for positioning and 10”-20” for the attitudes. Therefore, the analysis of the differences at the camera air stations is interpreted as first estimation of the accuracy potential from GPS/inertial only, the overall performance is obtained from re-determined object points using direct georeferencing and their comparison to their given reference coordinates.

In our case the ifp test field Vaihingen/Enz about 25km north-west of Stuttgart/Germany was prepared for the accuracy investigations. This test site covers an area of about 30km² with more than 80 signalized points determined from static GPS surveys and standard photogrammetric AT. Since the accuracy of these object points is about 5cm and better, they are used as references for the overall system accuracy check. The location of the reference points is optimized for two different image flights with different flying height and image scale. The medium scale flight covers the whole test site and is flown in cross-pattern at a flying height of 2000m above ground. During the three long (east-west) and three cross (north-south) strips altogether 36 images are captured. The large image scale block is flown in the eastern part of the area and consists of two north-south strips (h_g=1000m) only, providing 16 independent values for camera air stations. Since a wide-angle camera was used in both test campaigns the different flying heights result in image scales of 1:13000 and 1:6000, respectively.

To enlarge flying time and number of images the two different blocks were flown several times. The corresponding flight trajectories of the two different test flights are depicted in Figure 1 and Figure 2, respectively. During the Applanix test (December 1998) each of the two different image blocks was captured twice. Due to the long aircraft transition flight an in-air alignment was performed immediately before entering the first 1:6000 image scale block (16 images). After this the two identical 1:13000 blocks (72 images) were flown and the campaign was finished with the second 1:6000 flight (16 images). Overall, 104 images were captured in a period of 1.5h. Within the second mission in June 2000 using the IGI system the 1:13000 scale block was flown three times (108 images) followed by the large scale block (16 images), resulting in about 2h photo flight and 124 recorded images. Since this mission started at an airport about 60km away from the test area no in air-alignment but a short static alignment on the tarmac was performed. For both test flights redundant GPS receivers were set up in the test area and close to the test area (25km distance). During the first mission additional receivers were installed in varying distance up to 380km to investigate the influence of baseline length on the quality of GPS/inertial orientation parameters and the accuracy of direct georeferencing. These results are published in (Cramer, Stallmann & Haala 2000, Cramer 1999). In this paper only the results based on the evaluations using the reference stations located in the test area are given.

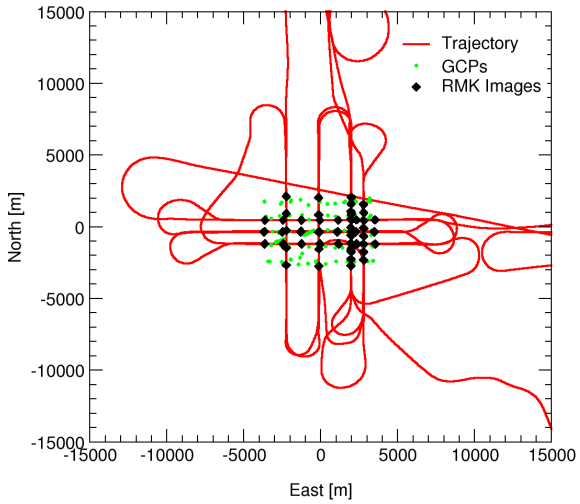


Figure 1: POS/AV 510 DG test flight, flight date 17.12.1998.

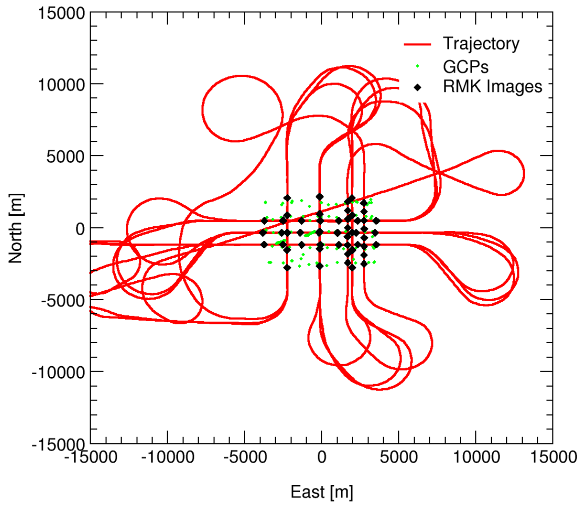


Figure 2: AEROcontrol IId test flight, flight date 09.06.2000.

3.3 Quality of GPS/inertial exterior orientation elements

General remarks Using the traditional method of AT the recorded photogrammetric images are orientated providing independent values for the exterior orientation elements. Since the estimated values for position and orientation of the camera station from AT are highly correlated – for example a sensor motion in flight direction can be compensated by a different pitch angle –, two different AT versions are calculated for the quality comparisons. The first AT is based only on the ground control points and is used to check the performance of GPS/inertial positioning. For the GPS/inertial attitude accuracy investigation a second AT is necessary where the ground control points and additionally the GPS/inertial positions are introduced as absolute observations of the camera stations to de-correlate the influence of position and attitude. Another important aspect to be mentioned is the correct transformation between the different reference frames before starting the accuracy investigations, since photogrammetry and GPS/inertial exterior orientations are related to different coordinate systems. In general, the photogrammetric data processing is based on a local three dimensional cartesian reference frame. Normally, the ground control coordinates used in the AT are given in a national mapping frame (e.g. Gauss-Krüger coordinates defined on the Bessel ellipsoid) that is a non-cartesian coordinate frame normally. Therefore, the influence of earth curvature is corrected in the image coordinate measurements to establish the cartesian coordinate frame before starting the photogrammetric AT. On the other hand the coordinate frame of GPS/inertial navigation is different to the national mapping frame. The positions and orientations are determined in the navigation frame which is most often the GPS WGS84 reference frame, since GPS is the main sensor for updating the integrated system and consequently positions and velocities are determined in geocentric or geographic coordinates on the WGS84 ellipsoid. Therefore, the datum shift between the WGS84 and the national coordinate frame and the appropriate map projection has to be applied. Additionally, since GPS/inertial integration provides ellipsoidal heights normally, the geoid correction is necessary before the directly measured positions are comparable to the values from AT. The transformation of the three GPS/inertial navigation angles roll, pitch and yaw is even more demanding. The GPS/inertial angles are obtained from a rotation matrix that relates the so-called body frame coordinate system defined by the internal axes of the inertial unit to the local cartesian topocentric coordinate frame, whose x-axis is pointing to geographic north, z-axis is pointing down following the local plumb line and y-axis is completing the orthogonal right handed frame. Since this local topocentric system is following the motion of the carrier and its origin is moving with time, the resulting variations in the north direction and the plumb line have to be considered to transform the navigation angles into photogrammetric attitudes ω, φ, κ. Although the commercial software packages provide transformations to make the different systems compatible all accuracy investigations in our case were done in a local cartesian topocentric coordinate frame related to the WGS84 ellipsoid in order to avoid any inaccuracies from coordinate transformations and especially from datum shift. Finally, the spatial and time eccentricity (including the correction of the boresight angles) has to be considered for the quality tests.

Quality of GPS/inertial positioning The comparison between the orientation parameters obtained from AT and the directly measured GPS/inertial orientations gives a first estimation of the expected accuracy potential. Since the theoretical accuracy of the perspective centre coordinates from AT is scale dependent the accuracy checks are done for each image scale, separately. Unfortunately, at the time this paper was written the data processing of the second test flight was not fully completed, hence for this case only first preliminary accuracy investigations based on 36 images from the second flown 1:13000 block are available and given in this paper. For the POS/AV 510 DG test flight the accuracy of all 72 images from the 1:13000 blocks and the 32 large scale images 1:6000 is presented. The resulting GPS/inertial positioning accuracy is given in Table 1.

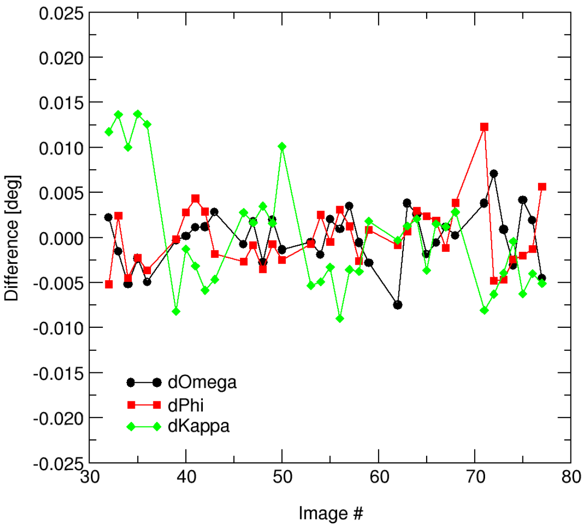
The table shows the typical results for this kind of investigation. Since the theoretical accuracy of the perspective centre coordinates from AT is dependent on image scale the values obtained from statistical analysis of the differences from large scale imagery are approximately a factor of two better compared to the 1:13000 imagery. Especially for the medium scale imagery the error of the independent values from AT plays a significant role in the difference – in other words, the values from AT could not be used as reference –, therefore only the results from the 1:6000 image blocks should be interpreted as GPS/inertial positioning accuracy. From this differences the obtained STD are below 10cm which one could expect for airborne kinematic environments. In the vertical coordinates from POS/AV 510 DG a significant offset correlated with image scale and flying height is clearly visible. This error is most likely due to systematic errors in the

Image block	Statistical value	**POS/AV 510 DG** [cm]			**AEROcontrol IId** [cm]		
		East	North	Vert.	East	North	Vert.
6000	RMS	9.7	6.9	12.7	n.a.	n.a.	n.a.
	Max.Dev.	18.2	17.9	16.9	n.a.	n.a.	n.a.
	Mean	-4.8	-1.5	12.5	n.a.	n.a.	n.a.
	STD	8.4	6.8	2.4	n.a.	n.a.	n.a.
13000	RMS	14.6	16.5	33.4	13.2	11.8	6.7
	Max.Dev.	44.2	39.0	52.1	29.9	27.3	15.6
	Mean	1.6	0.4	32.8	2.2	-2.4	1.9
	STD	14.5	16.4	6.1	13.0	11.6	6.4

Table 1, Absolute accuracy of GPS/inertial positioning compared to AT.

positions from AT that are used for the comparison which underlines the problems using indirectly determined exterior orientations as references for the GPS/inertial quality investigation. As pointed out earlier the estimated orientations from AT are quite sensible on the used parameters in the adjustment and highly correlated. Uncorrected systematic errors are directly projected into the estimated orientation parameters. In this case, the vertical offset might be due to any scale dependent errors influencing the vertical component of the estimated camera stations. Most easily such an offset can be explained by uncorrected influences of refraction or inconsistencies between the focal length from lab calibration – used in the bundle adjustment – and the true physical focal length during data acquisition. In contrary to the results from the 1998 test no systematic height offset is present in the AEROcontrol position differences from 1:13000 imagery. This can be interpreted as a sufficient agreement between the assumed parameters and the true physical environment during data acquisition. Nevertheless, further investigation will show whether this situation remains the same especially for the position differences from large scale imagery.

Quality of GPS/inertial attitude determination Before starting the analysis of GPS/inertial attitude performance the directly measured orientations have to be calibrated on the image coordinate frame. This calibration is not an easy task – dependent on the chosen images from AT the boresight angles are estimated slightly different. To achieve an optimal boresight calibration for both test flights all images were used for the estimation of the misalignment between IMU sensor frame and camera coordinate frame. Therefore the boresight alignment should be optimal for the test data and the analysis of the attitude differences will define an upper accuracy bound what one can expect in case of optimal misalignment calibration. The resulting differences between attitude angles from AT and GPS/inertial are shown exemplarily for one 1:13000 image block in Figure 3 and 4. The fully analysis of POS/AV 510 DG attitude differences from all 104 camera stations can be seen in (Cramer 1999). For the POS/AV 510 DG system the RMS values from the depicted 36 images are about 11”, 13” and 23” for ω, φ and κ respectively. Analyzing all 104 images the corresponding values are 11”, 10” and 19”. The maximum attitude deviations did not exceed 0.008deg, 0.012deg and 0.013deg. No time dependent errors are visible for the whole photo flight which confirms that GPS updates significantly eliminated the systematic inertial errors. In Figure 4 the corresponding attitude differences from the 36 evaluated images of the second test campaign using the AEROcontrol system are shown. The accuracy of ω and φ-angle is slightly better compared to the results from POS/AV 510 DG. RMS values of 8” are obtained for ω and φ, respectively.



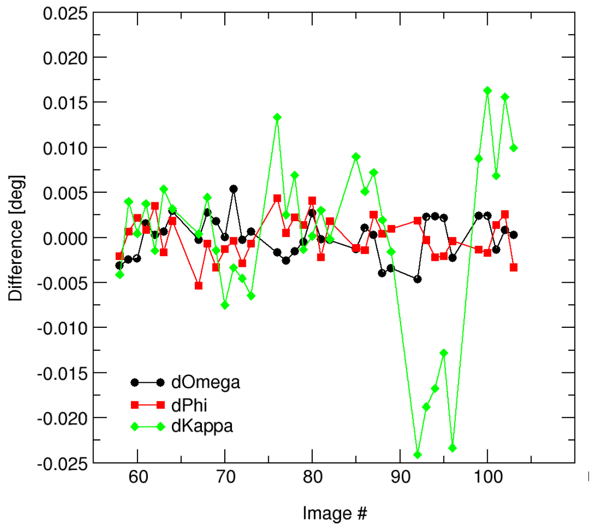


Figure 3: Variations of POS/AV 510 DG attitudes compared to AT.

Figure 4: Variations of AEROcontrol IId attitudes compared to AT.

The κ-angle performs worse. The RMS is about 34", with maximum deviations of approximately 0.025deg. These values are caused by significant larger deviations at the images # 92 – 96. The images correspond to one single north-south flight line located the centre of the test area. Since the image block geometry is very stable in the centre of an image block providing good estimations for the orientation angles from AT, the larger differences at these camera stations are due to remaining systematic in the AEROcontrol orientation elements. The reason for these errors is under current investigation.

4 PERFORMANCE OF DIRECT GEOREFERENCING

As mentioned before the analysis of the differences at camera air stations based on the exterior orientations from AT gives a first rough estimation on the accuracy potential of the tested integrated systems. The overall accuracy control is only possible when object points obtained from direct georeferencing are compared to their pre-determined reference coordinates. Furthermore, the final accuracy on the ground is the most important thing in image data evaluation. In our case, only the images from 2000m flying height are considered since the influence of orientation errors is correlated with flying height and remaining errors would be more clearly visible for the medium scale images. Two different approaches for the determination of object points will be presented in the following: The first one is based on the imagery from the 1:13000 image blocks separately, providing a high image overlap and strong block configuration with a maximum of 15-folded points. In this case the large number of image rays used for the object point determination results in very high redundancy. Therefore, this method should give an estimation on the maximum accuracy that is achievable from image blocks with strong geometry. The second method for object point determination is based on a strip-wise processing, where only the images of one flight line are considered for object point determination. In this case only three image rays (maximum) are available for each point. The results of single flight lines (7 or 5 images each), exemplarily chosen from each data set are presented in Table 2 together with the results from the block-wise approach utilizing 36 images flown in cross pattern each. For a more detailed analysis of the results of direct georeferencing using the POS/AV 510 DG system the reader is referred to (Cramer, Stallmann & Haala 2000).

System	Images	Checkpoints	East [cm]		North [cm]		Vertical [cm]	
			RMS	Max.Dev.	RMS	Max.Dev.	RMS	Max.Dev.
POS/AV 510 DG	36	135	6.4	20.0	9.0	31.9	15.7	37.1
	36	133	9.0	24.9	8.2	30.5	15.0	63.0
	7	84	15.0	30.8	13.9	47.3	23.9	63.7
	7	95	7.1	22.8	16.1	35.2	25.2	59.0
	7	92	9.9	37.6	21.1	70.8	24.9	91.5
AEROcontrol IId	36	84	7.5	19.3	12.1	37.8	12.1	34.4
	7	50	12.8	24.1	9.7	27.9	18.7	55.4
	7	49	8.5	21.0	8.4	18.4	17.2	43.2
	7	51	15.0	36.1	16.7	35.0	24.3	66.2
	5	31	14.3	27.4	26.2	62.4	16.6	54.7

Table 2, Accuracy of direct georeferencing (1:13000 imagery, h_g=2000m).

The results from Table 2 underline the positive influence of numerous image rays used for object point determination. The higher redundancy compensates for small errors in the orientation elements. The resulting accuracy in object space is very close to the theoretical accuracy to be expected from AT. There is almost no significant difference between the performance of both systems visible. One thing has to be mentioned for the direct georeferencing using POS/AV 510 DG orientation elements: To compensate for the significant vertical offset that was detected at the camera air stations of the first test flight the interior orientation of the camera is slightly modified compared to the values from lab calibration. The focal length was corrected by 20µm which eliminates the scale dependent systematic vertical error. Focussing on the strip-wise direct georeferencing resulting in a weaker block geometry the accuracy of direct georeferencing is slightly worse. Normally, the horizontal RMS values are within 10-20cm, the vertical RMS between 20-30cm. In addition to the reduced number of image rays, a portion of this deterioration is caused by sub-optimality in the boresight angles, since the boresight alignment angles were estimated from all images and therefore are not optimal for only a small part of the block. In the final row of Table 2 the object point differences obtained from the images # 92 – 96 is shown. As depicted in Figure 4 the larger differences in κ-angle mainly affect the north coordinates. The RMS value of almost 30cm is significantly larger compared to the remaining horizontal accuracy.

5 DIRECT VERSUS INDIRECT GEOREFERENCING

Within the accuracy tests described before classical AT was only used to provide independent values for the accuracy investigation of the different GPS/inertial systems. In this section of the paper the results of direct georeferencing are directly compared to the accuracy from traditional indirect image orientation using standard AT. To simulate photogrammetric production environments a sub block consisting of two east-west strips (scale 1:13000) with standard photogrammetric overlap was chosen exemplarily from the image data of the first test flight in 1998. For system calibration (boresight alignment) the estimated angles from all 72 medium scale images are applied. This is quite similar to the later use of GPS/inertial systems in a production environment where the calibration site is different to the aspired mission area. For this following investigation the GPS/inertial orientation parameters are obtained from the POS/AV 510 DG system. In the first step a standard AT is calculated using 9 well distributed ground control points (CoP). As given in Table 3 the σ_0 a posteriori is about 4.8µm without additional self-calibration terms (Version 1). Due to a systematic 15cm offset in height, the RMS of the vertical coordinates obtained from 122 empirical check point (ChP) differences is significant worse compared to the horizontal components and reaches 20cm with maximum deviations of 57cm. Introducing additional self-calibration parameters (radial lens distortion and decentering distortion) the adjustment process is improved. The empirical maximum deviations did not exceed 22cm and 35cm for the horizontal and vertical coordinates, respectively. This refinement of object point accuracy shows the important role of self-calibration to compensate for systematic effects caused by differences between the mathematical model and the true physical situation even only photogrammetric measurements are used. Comparing the results from indirect image orientation to the empirical object point accuracy from direct georeferencing without any ground control (Version 2) the results are worse about a factor of two. Since the GPS/inertial exterior orientations are used as direct measurements of the true physical position and orientation of the camera, the σ_0 of about 10µm indicates remaining discrepancies between the image observations and the orientation parameters. The non-optimal determined system calibration for the misalignment and the uncorrected image distortions provoke errors in object space. To overcome these systematic errors two different approaches are possible: The first one is based on the measurement of all environmental aspects like temperature or pressure to guarantee an optimal transfer of the system calibration from the calibration site to the mission area. Since this approach is very demanding from operational aspects and the success is not investigated and proven till now the second possibility might be advantageous: For the optimal correction of systematic errors and other calibration terms the AT with additional self-calibration functionality is re-introduced again. To perform this combined GPS/inertial AT approach a bundle adjustment program developed at the Institute for Photogrammetry (ifp) was used, where the directly measured exterior orientations are introduced as very high accurate observations of the camera air stations. In this particular case the standard deviation is assumed to be 5cm and 0.001deg for position and attitude, respectively. Since there is enough information from image space (130 tie points available) additional unknowns are estimated. In Version 4 three additional unknowns for the refinement of the boresight angles are introduced which improves σ_0 and the accuracy in height and north component. Adding additional self-calibration parameters (Version 5) the resulting RMS values are about 5cm and 9cm for the horizontal and 13cm for the height component. These values are very close to the AT accuracy, although the maximum differences are slightly bigger compared to AT resulting in larger RMS values. This is mainly due to the fact, that for the combined GPS/ inertial AT approach only one control point is used, which is located in the centre of the block. Therefore, extrapolation to the borders of the block is necessary.

Approach		CoP	ChP	σ_0 [µm]	RMS Object Coordinates [cm]		
					East	North	Vertical
1	AT	9	122	4.79	5.6	6.2	20.3
2	AT + SC	9	122	4.24	4.5	6.3	12.1
3	DG	0	131	10.80	8.8	11.9	17.8
4	DG + AT with SC	1	130	5.16	8.7	8.7	15.8
5		1	130	4.46	5.2	9.2	13.3

Table 3, Quality of indirect vs. direct georeferencing (GPS/inertial exterior orientation parameters from POS/AV 510 DG).

6 CONCLUSION AND OUTLOOK

The two empirical tests have shown that the direct georeferencing of standard analogue photogrammetric cameras using commercial high-end integrated GPS/inertial systems provides an accuracy (RMS) of 1-2dm for the horizontal components and 2-3dm for the vertical coordinate. This accuracy is obtained under standard photogrammetric flight conditions without any ground control. Since both test flights are very well controlled the obtained results are representative and should be reproducible for the future use in a production environment. The values mentioned above are valid even for the evaluation of single flight lines, which are somehow critical from standard photogrammetric data processing. Transferring the obtained accuracy to accuracy numbers traditionally used in photogrammetry, the horizontal accuracy corresponds to 10µm in image space and the vertical accuracy is about 0.1‰ of the flying height assuming an image scale of 1:13000 and a corresponding flying height of 2000m above ground. Although this accuracy is about a factor of two worse compared to the accuracy theoretically obtained in photogrammetric aerial triangulation, this performance is sufficient for almost all of the future applications in photogrammetry, in especially on the background of the new digital airborne sensors with their multi-spectral data acquisition capability for airborne remote sensing applications. As described in Section 1 of this paper the bulk of applications in future photogrammetry will be in this market segment. Thus, the direct method of image orientation will provide significant advantages with respect to very high flexibility and fast and efficient data evaluation. From this point, direct georeferencing based on high quality integrated GPS/inertial systems will gain in importance and become the standard approach for the orientation of digital imagery, at least for the remote sensing applications.

The major problem limiting the overall accuracy of georeferencing is the influence of uncorrected systematic errors. This is a general problem and therefore not only restricted on direct georeferencing using GPS/inertial systems in combination with imaging sensors. Even for the classical approach of indirect image orientation non-modelled systematic errors are limiting the performance of object point determination. This was shown in Table 3 for a standard medium scale photogrammetric block where standard AT without self-calibration provides insufficient results in height component. Only when the additional correction terms for self-calibration are considered the aspired maximum vertical accuracy of 0.05‰ of flying height is achieved. Therefore, the calibration problem is an inherent necessity for both approaches of georeferencing. The only difference is, that for direct georeferencing this later on-line calibration is not possible traditionally. In case there is some sub-optimality in the overall system calibration – the reason for this sub-optimality is of no importance and might be due to errors in the boresight angles, spatial offsets or systematic errors in imagery – re-introducing the high quality directly measured position and orientations elements in some sort of reduced AT again allows the subsequent refinement of the system calibration. Within this re-introduction of AT even highest accuracy demands in the range of 10cm could be fulfilled with reduced effort in AT. Additionally, since almost optimal measurements of exterior orientation parameters are available from GPS/inertial only a very small number of ground control points is necessary. As depicted in Table 3 the use of one control point will increase the accuracy significantly. For aspects of reliability at least one check point should be available in each mission area. This one control point is sufficient for the subsequent refinement of system calibration. From photogrammetric point of view, a very few number of control points should be available even in remote areas, otherwise no redundancy is existent and the georeferencing is not controllable: A situation that should be avoided strictly!

To conclude finally the following remarks should be mentioned:

- Direct georeferencing is an excellent tool for fast and flexible sensor orientation.
- The GPS/inertial technology is mature for the practical use.
- Integrated GPS/inertial systems will become a standard tool for airborne sensor orientation. The acceptance of this technology will be pushed by the growing distribution of the new digital airborne sensors.

The future work has to be focussed on the overall system calibration. From a practical point of view optimal calibration procedures have to be defined. Especially for the boresight alignment the exterior orientations from AT are essential and therefore recommendations for an optimal design for the calibration block are necessary. Additionally the stability of system calibration over longer time periods and the quality of the calibration transfer from the calibration site to the mission area has to be investigated. Finally, as one major point, aspects on reliability have to be considered. The system reliability is very important for example for orthoimage production where digital terrain models are available. Using direct georeferencing for such applications the requirements on standard photogrammetric image overlap can be reduced to an absolutely minimum to minimize flying time and number of imagery. Since this scenario relies on the GPS/inertial exterior orientations totally, undetected errors in the integrated system would prevent the successful image evaluation. Therefore the quality of the different hardware components has to be checked permanently, preferable during data acquisition using the real-time capability of Kalman filtering to allow fast interaction. If possible, a redundant data acquisition should be aspired, at least for the GPS reference stations. With multiple reference stations a multi-station GPS processing will be possible which will increase the accuracy and reliability of GPS data as the main update information and will influence the resulting integrated system performance. From this point of view the use of centralized or adaptive Kalman filtering is very promising.

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