DIRECT GEOREFERENCING USING GPS/INERTIAL EXTERIOR ORIENTATIONS FOR PHOTOGRAMMETRIC APPLICATIONS

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ABSTRACT

One crucial point during the application of direct georeferencing is the accuracy and reliability of directly measured orientation parameters using integrated GPS/inertial systems in an operational photogrammetric airborne environment. In order to investigate the potential of direct georeferencing for standard photogrammetric applications the accuracy of a commercially available GPS/inertial system (Applanix POS/DG 310) is evaluated. For that purpose a well controlled airborne test comparing the results from standard bundle adjustment and point determination by direct georeferencing is described. Within this test special focus is given on the quality of the GPS/inertial exterior orientation using several master stations with varying baseline length up to 380km. Additionally, the influence of variable image overlap on the resulting object coordinates is investigated. Although very consistent and high accuracy in object space is proved using direct georeferencing, the tests show the great importance of proper calibration between GPS/inertial and camera components. From this point of view, the integration of the GPS/inertial exterior orientations in a combined aerial triangulation provides the most flexible approach and is recommended for highest photogrammetric accuracy demands.

1 INTRODUCTION

The determination of the exterior orientation parameters (e.g. position X_0, Y_0, Z_0 and attitude ω, φ, κ of an image at the time of exposure) is an essential pre-requisite for the evaluation of imagery based on any type of data from terrestrial, airborne or satellite platforms. Traditionally, in photogrammetry this orientation task is solved indirectly using the well-known method of aerial triangulation (AT). Although aerial triangulation was essentially improved and expanded to so-called automated aerial triangulation (AAT) in the last years (e.g. Schenk (1997)), the orientation process still suffers from a large amount of interactive editing and supervision of highly skilled operators. This is especially due to the high computational effort that is necessary for automatic tie point measurement. A reliable matching of tie points is necessary to determine the exterior orientation of each image correctly. With the availability of integrated GPS/inertial systems this situation changes. GPS offers high absolute accuracy position and velocity information. The short term noise is dependent on the data quality and observation approach. In contrast to this, inertial systems provide very high relative accuracy for position, velocity and attitude information, but the absolute accuracy decreases dependent on run-time if the system is working in stand-alone mode and no external update measurements are available. Since GPS and inertial systems are of complementary error behaviour, their optimal integration allows fully exterior orientation determination with improved overall accuracy and at higher reliability compared to the stand-alone units. Hence, this integration has already been proposed since a couple of years. Meanwhile integrated GPS/inertial systems are commercially available and commonly used for the operational processing of digital airborne line sensor data. Nevertheless, a GPS/inertial component is advantageous for the orientation of standard frame sensors like photogrammetric cameras, too. The potential of integrated GPS/inertial systems for photogrammetric applications is investigated in this paper in more detail. Within the following section the two different approaches of georeferencing of image data are described. Although the process of standard AT is quite familiar, some time is spend on the revisitation of its main characteristics, which are important for the later direct georeferencing. For the estimation of the empirical accuracy potential of direct georeferencing the commercially available POS/DG310 GPS/inertial system developed by Applanix Corp. Markham/ON Canada (Lithopoulos (1999)) was tested in conjunction with a standard photogrammetric aerial camera. The results of this photo flight carried out over a well-surveyed test field close to Stuttgart, Germany are given in Section 3. Finally, the results are summarized and a short outlook on the potential use of direct georeferencing for photogrammetric applications is given.

2 PRINCIPLES OF GEOREFERENCING

2.1 Indirect method

Up to now the indirect image orientation is the favoured approach for the orientation of traditional image based frame sensors (e.g. photogrammetric cameras). Within this approach the exterior orientation of each image is treated as unknown and estimated in a bundle adjustment process. This is the only way to determine the sensor position and orientation if no additional orientation sensors are used during the flight and only rough estimations of the exterior orientation of the imaging sensor, e.g. from flight mission planning, are available. Using the indirect method of image orientation, the six unknown orientation parameters are estimated from a number of ground control points and their corresponding image coordinates. For the evaluation of multiple images, this orientation determination is solved by aerial triangulation, where adjacent images are connected by measuring homologous points. Enforcing intersection constraints between multiple images, a reduced number of ground control points is sufficient to estimate the parameters of exterior orientation. Assuming the standard model of central perspective the georeferencing is based on the photogrammetric collinearity equation (e.g. Kraus (1994)). This equation defines the mathematical model for the physical process of image formation. The model relates the image coordinates to the object coordinate system, where the camera geometry itself is given by the parameters of interior orientation (principal point, focal length of the imaging sensor), and the camera station with respect to the global object coordinate frame is described by the time dependent parameters of exterior orientation.

Usually, the interior orientation is measured via laboratory calibration and assumed to be a known quantity for the bundle adjustment process. Nevertheless, to refine the model and to obtain highest object point accuracy, additional self-calibration parameters are introduced into the bundle adjustment. Ebner (1976) and Grün (1978) for example proposed additional orthogonal polynomials to overcome remaining systematic errors caused by effects like non-flatness in the focal plane, non-modeled lens distortions or anomalies in refraction. In the approach given by Brown (1971) physical meaningful error terms are estimated using appropriate coefficients to describe the changes in the geometric values of interior orientation and additional parameters like scale, shear, radial and decentering distortions. The expanded bundle adjustment with self-calibration is a very effective method to compensate systematic errors and is widely spread for highest accuracy applications. Therefore, using AT for image orientation not only the exterior orientations for each image are estimated as unknown parameters but also the coordinates of new object points and - if necessary - additional parameters for camera self-calibration are determined simultaneously in a closed solution.

Since the exterior orientations are estimated as free unknown parameters and can be strongly correlated with some of the used self-calibration terms, the estimated values might be different from the actual true physical position and orientation during exposure. To derive the influence of varying parameters in AT on the exterior orientations and the object point coordinates, different parameter are introduced in the bundle adjustment and the corresponding empirical object point accuracy is calculated in comparison to given reference values. For these investigations a photogrammetric image block (wide-angle, image scale 1:13000) consisting of three long strips (7 images each) with 60% forward/side overlap is analyzed. Using nine ground control points located at the border and in the centre of the block the coordinates of 122 well distributed and signalized object points are calculated and compared to given reference coordinates to determine the empirical accuracy. Overall, eight different bundle adjustments are computed using two different sets of interior orientation parameters and four different approaches for self-calibration. Details about the used parameters for the bundle adjustments are given in Table 1. For the first four runs the interior orientation from lab calibration is used. In Versions 5 - 8 the correct values are manually falsified by errors of about $\delta c = 20\mu m$ for the camera focal length and $\delta x'_0 = 10\mu m$, $\delta y'_0 = -5\mu m$ for the principal point coordinates. Concerning the influence of self-calibration, two adjustments (Version 1, 5) are done without any additional parameters, first. For the following versions the three geometric parameters of interior orientation are added (Version 2, 6). Since only the correction of focal length is significantly estimated, the principal point coordinates are eliminated for the final adjustment run. After this the full parameter set proposed by Brown (1971) (Version 3, 7) and finally the 12 parameter polynomial approach defined by Ebner (1976) is applied in Version 4 and 8. Similar to Version 2 and 6, only the significant parameters are used in the final adjustment. As it can be seen from the results given in the table, the estimated σ_0 a posteriori values are consistent and in the range of 4.2 - 4.7µm. Although the approaches for self-calibration are quite different, there is no major effect on the empirical accuracy in object space. The additional errors introduced on the interior orientation parameters for Versions 5 - 8 are of almost no influence on the obtained object point accuracy. The horizontal accuracy from check point analysis is in the range of 4 - 7cm for all runs. For the vertical accuracy some differences are visible. Using the subset of Brown's parameters for self-calibration the remaining systematic effects in height are modeled and the accuracy could be improved. Since the different variations used for the bundle adjustment are of minor effects on the object points, their influence is strongly correlated on the estimated exterior orientation parameters. To evaluate these variations, the different estimated orientation parameters from AT are compared, where the results of Version 3 provide the reference orientations and object coordinates. The statistics of the obtained differences (RMS values) are listed in Table 2. The influence on the estimated orientations is clearly visible. Depending on the used self-calibration terms, the

Ver.	Interior Orientation	Self-calibration Parameters	σ_0 [µm]	RMS Check Points [m]		
				ΔX	ΔY	ΔZ
1	lab calibration	no self-calibration	4.64	0.049	0.057	0.222
2	lab calibration	focal length Δc	4.61	0.045	0.057	0.214
3	lab calibration	Brown: 4 sign. par.: a, K_1, K_2, P_1	4.18	0.036	0.059	0.097
4	lab calibration	Ebner: 4 sign. par.: b_2, b_4, b_7, b_8	4.28	0.037	0.066	0.128
5	δc, $\delta x'_0$, $\delta y'_0$	no self-calibration	4.65	0.048	0.057	0.224
6	δc, $\delta x'_0$, $\delta y'_0$	focal length Δc	4.61	0.045	0.056	0.216
7	δc, $\delta x'_0$, $\delta y'_0$	Brown: 4 sign. par. a, K_1, K_2, P_1	4.18	0.036	0.059	0.098
8	δc, $\delta x'_0$, $\delta y'_0$	Ebner: 3 sign. par.: b_4, b_7, b_8	4.29	0.048	0.072	0.129

Table 1, Variations of object point coordinates using different parameter sets for AT

Version Diff.	RMS EO Position [m]			RMS EO Attitude [10^{-3} deg]			RMS Adjusted Object Points [m]		
	ΔX_0	ΔY_0	ΔZ_0	Δω	Δφ	Δκ	ΔX	ΔY	ΔZ
1 - 3	0.37	0.16	0.41	4.10	10.31	0.65	0.03	0.03	0.21
2 - 3	0.48	0.37	9.21	7.28	12.69	0.61	0.03	0.03	0.20
4 - 3	0.16	0.10	0.41	2.70	5.15	0.63	0.02	0.06	0.11
5 - 3	0.43	0.18	0.18	4.07	10.23	0.68	0.03	0.03	0.21
6 - 3	0.53	0.36	9.41	7.34	12.73	0.65	0.03	0.03	0.20
7 - 3	0.13	0.07	0.26	0.21	0.35	0.07	< 0.01	< 0.01	< 0.01
8 - 3	0.29	0.15	0.15	2.74	5.17	0.76	0.03	0.06	0.11

Table 2, Variations of estimated exterior orientations using different parameter sets for AT

RMS values of the orientation parameters are between 10cm - 10m for position and 0.001 - 0.010deg for the attitude values. These large variations are due to the strong correlation between some of the calibration terms and the exterior orientations. For example, in Difference 2-3 and 6-3 the estimated focal length correction Δc of about $7 \cdot 10^{-4}$m is directly projected into the Z_0 coordinate of the perspective centre. Due to the 100% correlation between Δc and Z_0 the perspective centres are shifted by approximately 9m. This shift corresponds to the estimated focal length correction multiplied with image scale. Similar effects can be seen on the horizontal coordinates of the perspective centres where the errors $\delta x'_0$, $\delta y'_0$ in the principal point coordinates provoke shifts of about 10cm for X_0 and 5cm for the Y_0 component. Nevertheless, the influence of orientation variations on the coordinates of the adjusted object points is quite small. This again confirms the results from the empirical accuracy analysis given in Table 1.

These results reaffirm photogrammetric bundle adjustment as a very robust method for object point determination. Although the assumed values for interior orientation parameters might be erroneous and the used calibration terms are sub-optimal and maybe also erroneous in some cases, the calculated object coordinates are relatively consistent. Due to the adjustment criterion the residuals of the observations are minimized and the bundles are optimally fitted to the given control points. Hence, uncorrected systematic effects are totally shifted into the estimated orientation parameters. For traditional indirect georeferencing this effect is less important because the accuracy of object point determination is of main interest. The estimated orientation parameters do not necessarily agree with the physical position and orientation of the camera during image exposure. They are optimal estimations for the photogrammetric reconstruction process, but they are physically wrong because they absorb all remaining systematic errors. Talking about direct georeferencing this situation changes and the true physical camera position and orientation becomes of prime importance.

2.2 Direct method

With the availability of integrated GPS/inertial systems the direct measurement of the full exterior orientation of any sensor during data recording became possible. This direct measurement of the orientation parameters is the fundamental difference compared to the traditional indirect approach. Using appropriate GPS and inertial sensor components and processing their data in an optimal filtering approach the orientation parameters are determined with very high absolute accuracy. This direct measurement of orientation simplifies the image orientation process significantly, even though AT was essentially improved and expanded to so-called GPS-supported AT and automated aerial triangulation in the last years. Although the reduction of ground control is not of major issue any more - using GPS controlled AT for photogrammetric image blocks ground control is only necessary to solve for the datum parameters in principle - the process still suffers from a large amount of interactive editing and control. This is especially due to the high computational effort that is necessary for automatic tie point measurement and the subsequent gross error detection. Another drawback is the specific block geometry required for AT. This becomes of major interest for non-standard applications, like the supervision of long, straight and narrow surface objects like power lines or traffic routes, in case of so-called pin-point photogrammetry, where only a few images are required to cover a very small surface area, or for orthoimage production, where in general no overlapping image recording is necessary. In such applications the geometric boundary conditions on block design are very uneconomical for the evaluation process. Additionally, for digital line sensor technology (e.g. airborne line scanners, laser scanners) direct georeferencing provides the only solution for the operational and economical data processing. Since the exterior orientations are required with very high frequency for each scan line, the indirect sensor orientation is almost impossible due to the very large number of required ground control points.

If directly measured orientation elements are utilized for sensor orientation, the mathematical model has to be adopted for this application. Since the orientation sensors are physically displaced from the sensor to be oriented, additional correction terms are introduced (e.g. Skaloud et.al. (1996)). Assuming an integrated GPS/inertial system in combination with an imaging sensor the physical shifts between inertial system and GPS-antenna on the one hand and the perspective centre of the camera on the other hand are corrected by lever arms defined in the local aircraft body frame. For each system installation these specific lever arms have to be determined using conventional terrestrial survey methods. The attitudes provided by the integrated GPS/inertial system are related on the inertial body frame coordinate axes. Thus an additional misalignment matrix has to be taken into account to transfer the measured attitudes to the imaging sensor frame. Since the misalignment angles between IMU and camera frame are not directly observable via conventional techniques they have to be determined indirectly in an appropriate calibration procedure. This attitude transfer is a quite demanding task because reference orientations of superior accuracy are necessary for precise alignment. Although traditional AT provides independent attitude information with high theoretical accuracy, the estimated values are affected by remaining systematic and do not agree with the true physical orientation as it was demonstrated in the section before. Nevertheless, photogrammetry provides the only method for determining the misalignment angles in a kinematic airborne environment and the attitude differences between the exterior orientations estimated from AT and GPS/inertial at - preferable - several camera stations have to be used for the misorientation calibration. The quality of the misalignment calibration is strongly dependent on the budget of non modeled systematic errors in the bundle adjustment. The calibrated misalignment angles should remain constant as far as there are no relative movements between the two sensor components. After correcting the GPS/inertial exterior orientations by the translational offsets and the misalignment angles, the reduced orientations are interpolated on the exposure times of the imaging sensor to overcome the time offset between the different sensors.

3 EMPIRICAL ACCURACY TEST

3.1 Test flight design

In order to evaluate the performance of the tested GPS/inertial system POS/DG310 from Applanix for the direct measurement of exterior orientation, a photo flight was carried out over a well surveyed test field (extension 7km x 5km) close to Stuttgart in December 1998. During the test flight several GPS receivers with different baseline lengths from 0-380km were used as reference stations to check the influence of varying baselines on the performance of the GPS/inertial orientation parameters. Aerial imagery was captured at a flying height of 1000m and 2000m above ground, resulting in two different image scales of 1:6000 and 1:13000. The large scale imagery is located in the eastern part of the test site. Two strips, each consisting of eight images, were acquired. The 1:13000 block covered the whole test area by three long image strips and three cross strips. Both blocks were captured twice in order to enlarge the flying time. Overall, 72 (scale 1:13000) and 32 (scale 1:6000) images were captured in a time period of 1.5h. Altogether, 142 control points with theoretical standard deviations better than five centimetres were available for the accuracy checks. Additionally, AT provides independent values for the exterior orientations directly measured. Although the orientations from AT are affected with remaining systematic errors as pointed out before, they are suitable for first estimations on the expected accuracy potential of the GPS/inertial system (Section 3.3). To estimate the order of accuracy of the complete sensor system object points are directly georeferenced from GPS/inertial orientations and compared to their pre-surveyed coordinates (Section 3.4).

3.2 GPS/inertial data processing

The integration of the GPS/inertial raw data was done using the Applanix POSPac software (Scherzinger (1997)). Within the data evaluation, the GPS phase solution trajectory (position, velocity) is determined using a standard GPS software package first. In a second step the results from GPS data processing are used as update information to perform an optimal integration with the IMU measurements using a Kalman filter approach. Afterwards a smoothing computes a blended solution from the data obtained in the previous step. The initial alignment of the IMU is obtained from the in-air alignment capability of the system. After processing, position, velocity and attitude data from GPS/inertial are continuously available for the complete trajectory with a data rate at 50Hz. Utilizing the recorded trigger times the camera air stations are interpolated into the 50Hz trajectory solution. In order to relate orientation and camera module, the spatial and rotational offsets between the different sensor components are applied. To obtain optimal misalignment calibration two sets of misalignment angles were estimated from all imagery of each image scale, separately. The detailed description of the test flight, the data processing, the misalignment calibration and the internal accuracy checks of the different GPS/inertial trajectory solutions depending on the varying baseline lengths can be found in Cramer (1999).

3.3 External quality of GPS/inertial exterior orientations

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 and two different misalignment corrections are applied, the accuracy checks are done for each image scale, separately. In Table 3 the accuracy (RMS) calculated from all differences at 72 and 32 camera stations for the 1:13000 and 1:6000 imagery is given for four different GPS/inertial trajectory solutions with varying distances to the test site. The results show remarkable consistency. Although the baseline length differs from 25-380km distance, the horizontal accuracy of the coordinates of the perspective centres is within 15-20cm and 10-15cm for the 1:13000 and 1:6000 images. Focussing on the attitude differences, the results are even more consistent. The RMS is within the 10arc sec level for $\Delta\omega$, $\Delta\varphi$ and about 15-20arc sec for $\Delta\kappa$. Nevertheless, some systematic errors are clearly visible in the vertical components of the perspective centres. The vertical accuracy is significant worse compared to the horizontal values. For the 1:6000 images the RMS is between 10-20cm, for the 1:13000 imagery the variations are between 20-50cm. Although the vertical RMS values are slightly different dependent on the GPS/inertial trajectory solution, the ratio RMS_{6000} vs. RMS_{13000} is almost constant, except for the 380km basis which performs little different due to the very long baseline distance and the influence of e.g. uncorrected atmospheric effects. The mean ratio of 0.46 corresponds exactly to the ratio between the two image scales. This systematic is most likely due to errors in the photogrammetric reference positions. As pointed out in Section 2.1 the estimated orientations are quite sensible on the used parameters in AT. Remaining systematic effects are directly projected into the estimated orientation parameters. In this case, the vertical offset might be due to any scale depend errors influencing the vertical component of the estimated camera stations. Most easily such an offset can be explained by erroneous focal length used in the bundle adjustment. In our case the scale dependent systematic is modeled improving the used focal length by a factor of about 20µm. Applying this correction to the interior orientation parameters of the camera, the vertical accuracy is improved to the level of the horizontal RMS values.

GPS/inertial solution	Image scale m_b	RMS EO Position [m]			RMS EO Attitude [10^{-3} deg]		
		ΔX_0	ΔY_0	ΔZ_0	$\Delta\omega$	$\Delta\varphi$	$\Delta\kappa$
S2	13000	15.1	17.5	30.8	3.2	3.0	5.9
25 km	6000	9.9	7.1	13.5	3.0	2.0	3.9
F	13000	14.5	16.9	48.1	3.2	3.0	6.1
120 km	6000	10.4	6.9	22.2	3.0	2.0	4.1
B	13000	16.0	16.9	36.9	3.2	3.1	6.1
230 km	6000	17.9	6.7	18.2	3.1	2.0	4.1
H	13000	14.8	16.9	23.9	3.2	3.0	6.1
380 km	6000	13.5	8.6	6.1	3.0	2.0	4.4

Table 3, Accuracy of GPS/inertial exterior orientation parameters compared to AT

3.4 Direct georeferencing

To estimate the accuracy of direct georeferencing, known object points are re-determined from image coordinate measurements and compared to their given reference coordinates. Since observations from image space as well as the directly measured orientations from GPS/inertial are necessary for this accuracy investigation, the resulting differences in object space represent the overall accuracy of direct georeferencing for the sensor system consisting of the imaging part and the orientation module. Additionally, this accuracy check gives more reliable results since the check point coordinates provide truly independent reference values, which are not affected by remaining systematic errors like in the estimated camera stations described before. To check the quality of direct georeferencing, the influence of varying image overlap (number of image rays that can be used for the point determination in object space) and the influence of different baseline length are treated separately. The quality checks were done using the 1:13000 imagery since the influence of orientation errors on object point determination is correlated with the flying height and therefore any remaining errors in the GPS/inertial orientations are more clearly visible for smaller image scales from larger flying heights.

3.4.1 Variable image overlap. To check the influence of variable image overlap on the resulting object point accuracy, the GPS/inertial trajectory calculated from the 25km distance baseline solution was used. The achieved accuracy (RMS) in object space from check point analysis is given in Table 4. Several different versions are calculated to investigate the influence of multiple image rays used for the point determination. In Version 1 all 72 images (two blocks flown in cross pattern) with up to 22-30 folded points were considered. The intersection for object point determination was done using the interior camera orientation parameters from lab calibration. Analyzing the obtained differences from the reference check point coordinates the horizontal accuracy is in the 1dm level, but the vertical component is worse due to a significant shift in the vertical Z-axis. The size of this systematic offset is about 25cm which corresponds more or less to the 30cm offset in the vertical coordinates of the perspective centre detected earlier (Table 3). Again, the incorrect assumption on the camera focal length is directly propagated into the accuracy of object point determination. The accuracy in the vertical component significantly improves applying the corrected interior orientation parameters for object point determination. Now, the accuracy in height is about 12cm (RMS) and the maximum deviations did not exceed 40cm in all coordinates (Version 2). For the east/north components the RMS values are well below 10cm. To further re-confirm the results of direct georeferencing only one single 1:13000 image block is processed separately (Version 3). From 36 images and 133 re-computed check points similar RMS values for the horizontal and vertical accuracy are obtained, although the image overlap was reduced by a factor of two. Nevertheless, the maximum deviations are bigger than before. This is due to the fact, that only 15-folded image points (max.) could be used for point determination. To simulate the standard photogrammetric data situation (photogrammetric block consisting of several parallel strips with standard 60% / 30% image overlap) the number of images is further reduced. In Version 4 only three north-south strips, in Version 5 only two east-west strips are used for point determination. Using standard block geometry the maximum number of image overlap is reduced to six which again deteriorates the obtained accuracy. Now, the horizontal accuracy is within 10-15cm, the vertical accuracy about 20cm which shows the positive effect on high image overlap and strong block geometry. This effect becomes more clearly when single image strips are considered where 2-3 image rays are available for intersection only (Versions 6-8). As mentioned before this scenario is quite interesting for the surveying of linear objects like power lines or traffic routes. The maximum deviations rise up to 30-90cm and the RMS values are deteriorated up to 20cm in X, Y and 25cm in height, consequently. Again, the reduced number of image rays influences the object point accuracy. Additonally, since the misalignment angles are estimated from all 72 images of the 1:13000 scale and not from the images considered in the different versions only, remaining systematic errors are present in the exterior orientations. Besides the influence of uncorrected distortions in the imagery, these misalignment errors will cause some portion of the errors budget for direct georeferencing in object space. Considering e.g. the single flight line (Version 7), the difference between the optimal misalignment angles calibrated from all images and from only 7 images within this strip reaches about $1.2\cdot10^{-3}$deg and $1.5\cdot10^{-3}$deg for the ω- and κ-angle. This will introduce significant shifts in object space of about 5cm from a flying height of 2000m above ground.

Version		Images	Check-points	RMS Object Coordinates [cm]		
				East	North	Vertical
1	cross	72	142	7.3	9.0	26.7
2	cross	72	142	5.0	7.0	12.1
3	cross	36	133	9.0	8.2	15.0
4	parallel	15	126	14.3	10.3	23.4
5	parallel	14	138	8.8	11.9	17.8
6	single	7	84	15.0	13.9	23.9
7	single	7	95	7.1	16.1	25.2
8	single	7	92	9.9	21.1	24.9

Table 4, Accuracy of direct georeferencing using varying block configurations (GPS/inertial results from 25km baseline)

3.4.2 Variable baseline length. A special feature of this test flight are the different GPS/inertial trajectories obtained from multiple base stations in varying distances to the test site. Since the baseline length is of major interest for photogrammetric applications, where the distance between master and rover station might be very long especially in remote areas, the georeferencing was repeated using the orientation data from the four GPS/inertial trajectory solutions mentioned before. To simulate standard photogrammetric conditions the investigations were done using sub blocks consisting of parallel strips with standard overlap again. Three north-south strips and two east-west strips with 15 and 14 images and 131 and 126 check points were

Block	GPS/inertial solution		RMS Object Coordinates [cm]		
			East	North	Vertical
3 north-south strips	S	*25 km*	14.3	10.3	23.4
	F	*120 km*	13.4	9.9	19.7
	B	*230 km*	13.3	10.3	20.1
	H	*380 km*	13.9	10.3	20.9
2 east-west strips	S	*25 km*	8.8	11.9	17.8
	F	*120 km*	10.7	12.1	18.6
	B	*230 km*	17.2	14.0	18.0
	H	*380 km*	11.3	15.0	24.6

Table 5, Accuracy of direct georeferencing using varying baseline length (standard photogrammetric overlap conditions) combined as test blocks. Again, the improved focal length of the camera was used for intersection. The obtained results are given in Table 5. Similar to the accuracy from the comparison at the camera air stations the accuracy on the ground is quite consistent for all baseline solutions. There is almost no dependency on base station distance visible. The mean accuracy obtained from all baselines is about 14.1cm and 10.6cm (east), 10.1cm and 12.8cm (north) and 22.8cm and 19.3cm (vertical) for the first and second block configuration, respectively. Although these results are quite promising especially for the long baselines, they might be different for different test conditions and have to be re-confirmed by additional investigations.

3.5 Combined GPS/inertial AT

The accuracy tests have shown the potential of direct georeferencing using the Applanix high-end integrated GPS/inertial system in a standard photogrammetric environment. Assuming an image block with very strong block geometry due to high image overlaps the accuracy of object determination is close to the accuracy of photogrammetric point determination. From Kraus (1994) the theoretical accuracy of object point determination from AT is expected to be within $\sigma_{X,Y}$ = 5cm for horizontal and σ_Z = 10cm for vertical components. Nevertheless, the proper system calibration is an issue of major importance and is absolutely necessary for highest accuracy and reliability requirements. In this context system calibration means determination of the spatial shifts and misorientations between the sensor components (misalignment between IMU and camera), the interior orientation of the camera and any remaining systematic effects from image space.

To investigate the influence of system calibration a final test is performed where the results of direct georeferencing are directly compared to the reference accuracy from traditional indirect image orientation using standard AT. For this purpose the sub block consisting of two east-west strips (scale 1:13000) with standard overlap was chosen again (Table 5). The GPS/inertial orientation parameters are obtained from the 25km baseline result originally. To simulate production environments where the system calibration (e.g. misalignment correction) is performed using a calibration site which is different to the aspired block area, the calibration angles from all 72 images are applied. In the first step the standard AT is calculated using 9 well distributed ground control points (CoP). Applying additional self-calibration parameters (radial lens distortion and decentering distortion) the σ_0 a posteriori is about 4.2µm and the empirical maximum deviations from 122 check points (ChP) did not exceed 22cm and 35cm for the horizontal and vertical coordinates, respectively (Table 6). Comparing this accuracy level to the object point accuracy from direct georeferencing without any ground control (DG, Version 2) the results are worse. Since the GPS/inertial exterior orientations are used as fixed values and assumed to be error-free, the σ_0 of about 10µm indicates remaining tensions between the image observations and the orientation parameters. The non-optimal determined system calibration for the misalignment and the image distortions provoke the errors in object space. The only way to overcome these systematic errors and to determine the calibration terms optimally is to re-introduce AT with additional self-calibration functionality 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 their 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 self-calibration terms are estimated. In Version 3 the calibration parameters proposed by Brown (1971) (see Section 2.1) are introduced, which increases the accuracy in height and north, but slightly decreases the accuracy in the east component. For the second run of combined GPS/inertial AT (Version 4) the Brown self-calibration terms are supplemented with three additional offset angles to correct for the non-optimal misalignment between inertial and camera coordinate frame. This step improves the east component. Now the RMS values are about 5cm and 9cm for the horizontal and 13cm for the height component. There are still some differences to the AT accuracy (Version 1), especially in the north coordinate. This is mainly due to the fact, that for this 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	4.24	4.5	6.3	12.1
2	DG	0	131	10.80	8.8	11.9	17.8
3	DG + AT (with SC)	1	130	4.61	13.4	9.5	13.3
4		1	130	4.46	5.2	9.2	13.3

Table 6, Combined GPS/inertial AT (14 images, 2 parallel strips, standard photogrammetric overlap conditions)

4 CONCLUSIONS

The presented results proved the high quality of direct exterior orientation measurements using highly sophisticated integrated GPS/inertial systems in a standard photogrammetric environment. For some parts of the photogrammetric production line (e.g. ortho image generation, flexible block design, initial data acquisition in remote areas) this technique offers high benefits for time and cost reduction. Nevertheless, an overall system calibration problem still remains. Although special calibration sites are imaginable where the integrated system (camera and orientation module) is calibrated optimally within certain time intervals, the precise transfer and correctness of the calibrated parameters for the actual operation area cannot be guaranteed. If very high accuracy applications within a few cm in object space are aspired, the error budget of uncorrected systematic errors is at least of the same size as the influence of GPS/inertial position and attitude variations assuming a proper system installation. Since these systematic effects are mainly due to environmental aspects like changes in temperature, pressure, atmospheric refraction and therefore dependent on local and time variations their sufficient a priori modeling is not possible. Only the re-introduction of AT offers this self-calibration capability to determine the specific systematic error behaviour for a distinct area. Since the orientation parameters are almost known from GPS/inertial integration, the computational burden (i.e. block preparation, approximation values, tie point matching) is significantly less compared to a standard AT. Therefore, this combined GPS/inertial AT is the most reliable, flexible and accurate approach and thus should be recommended for highest photogrammetric accuracy demands.

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