RESULTS OF A PERFORMANCE TEST OF A DUAL MID-FORMAT DIGITAL CAMERA SYSTEM

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ABSTRACT:

The low weight and the relatively low cost of medium format digital cameras have pushed the use of those units for aerial survey. These medium format cameras are often used as secondary sensors together with other aerial sensors like LiDAR systems. The rising number of pixels per camera leads to an increasing interest in medium format systems as main sensors, especially for smaller survey aircraft. While the number of pixels across flight direction is not critical for capturing linear objects, like power lines or pipelines, the relatively small number of pixels compared to large format systems increases the necessary flying effort for photogrammetric blocks. In case larger blocks have to be flown efficiently, it is possible to combine two or more of such medium format cameras (dual- or multi-head solutions). This combination of medium format cameras increases the possible image strip widths and therefore reduces the flying time and distance for block projects. A performance test of a dual-head medium format digital camera system flown over the Vaihingen/Enz test field of the Institute for Photogrammetry of Stuttgart University is presented. The operated Dual-DigiCAM-H/39 consisted of two 39Mpixel cameras. To increase the image width across flight direction, the two cameras were mounted to look to the side at an oblique angle of +14.8° and -14.8°, respectively. This configuration results in an effective image width of 13650 pixel. The dual camera system was operated together with a CCNS/AEROcontrol navigation- and GPS/IMU system. The GPS/IMU trajectory was processed with different GPS methods and the different trajectories are compared. The overall system performance was evaluated based on the analysis of independent check point differences.

1. INTRODUCTION

Compared to analogue film based cameras, large format digital aerial systems have many obvious advantages. Nevertheless, the introduction of these systems did not change two of the main challenges for the producers of aerial images. The present-day large format digital aerial cameras are of high weight and volume, which forbids the flexible use in smaller and cheaper aircraft like small single engine aircraft and ultra-light aircraft. Furthermore the relatively high price of those systems is a problem for smaller aerial survey companies and institutions.

These reasons have pushed the development of medium format digital aerial cameras. Those cameras do not offer the same high number of pixels per exposure, but they are able to provide good image quality at lower cost and weight. While the smaller number of pixels across flight direction is not critical for capturing linear objects, like power lines or pipelines, it increases the necessary flying effort for photogrammetric blocks.

In case larger blocks have to be flown efficiently, it is possible to combine two or more of such medium format cameras (dual- or multi-head solutions). This combination of medium format cameras increases the possible image strip widths and therefore reduces the flying time and distance.

In the following a performance test of such a dual-head medium format digital camera system is presented. The operated Dual-DigiCAM-H/39 consisted of two 39Mpixel medium format cameras mounted with an oblique angle of +14.8° and -14.8°, respectively. This configuration results in a width of 13650 pixel and still provides a sufficient overlap in between the two neighbouring images. The two cameras were triggered synchronously within 10µs by a CCNS4 navigation system.

Together with the camera, an AEROcontrol-IId GPS/IMU system was operated to measure position and orientation of the cameras at the instant of the exposures.

The test took place over the Vaihingen/Enz testfield of the Institute for Photogrammetry. This test field has 172 precisely measured and signalised 3-D ground control points. Additionally approximately 70 natural points are available. The test flight configuration consisted of three photogrammetric blocks flown at three different altitudes. This empirical test flight material allows a detailed and independent analysis of the overall system performance.

The first part of this paper describes the used sensor system.
In the second part, the effect of different GPS processing techniques on the accuracy of the trajectory determination is shown.

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In the third part, the results of the test investigation of the system accuracy are presented. Here main focus is laid on the analysis of the Dual-DigiCAM-H/39 geometric accuracy potential, obtained from the analysis of independent check point differences.

The accuracy of the direct georeferencing using the AEROcontrol GPS/IMU results are also analysed.

2. SYSTEM SETUP

The operated Dual-DigiCAM-H/39 consisted of two 39 Mpixel medium format digital cameras (Grimm & Kremer 2005). They were rigidly connected to ensure a fixed relative orientation in-between the two cameras and compared to the attached IMU. The camera on the left side in flight direction was mounted with a roll angle of -14.8° (pointing to the right side) and the camera on the right was mounted with a roll angle of +14.8°. For the used 82.3 mm lenses and the format of 7216*5412 pixels for the single cameras, these mounting angles result in an image overlap of about 782 pixel or 10.8%. With the given image width of 7216 pixel, this configuration gives an effective image width of 13650 pixel. Both cameras were mounted with the short side of the image (5412 pixel) in flight direction.

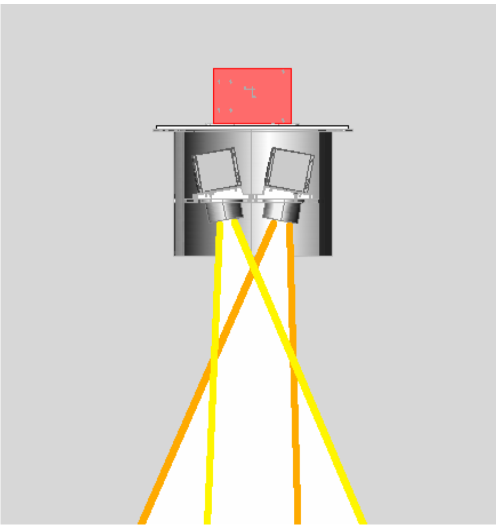

Figure 1: Arrangement of the two cameras and the IMU in the sensor pod.

The camera was operated together with an AEROcontrol-IId (256Hz) GPS/IMU system for the precise determination of position and orientation of the camera at the instant of exposure. The camera system, consisting of the Dual-DigiCAM and the AEROcontrol IMU was mounted in a GSM-3000/IGI stabilised sensor mount from SOMAG AG, Jena, Germany. The real time orientation information of the AEROcontrol was fed into the stabilised mount to improve the levelling accuracy.

For flight guidance and sensor management, a CCNS4 navigation system was operated.

3. FLIGHT PLANNING AND DATA COLLECTION

The flight mission consisted of three sections. The sections were image blocks with three different ground sample distances ("GSD"). The planned average ground sample distance for the different blocks was planned to be 7cm, 14cm and 20cm, respectively.

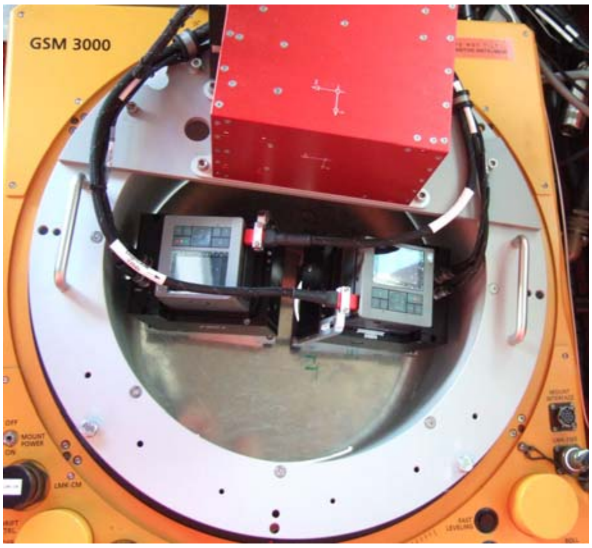

Figure 2: System installation in the aircraft.

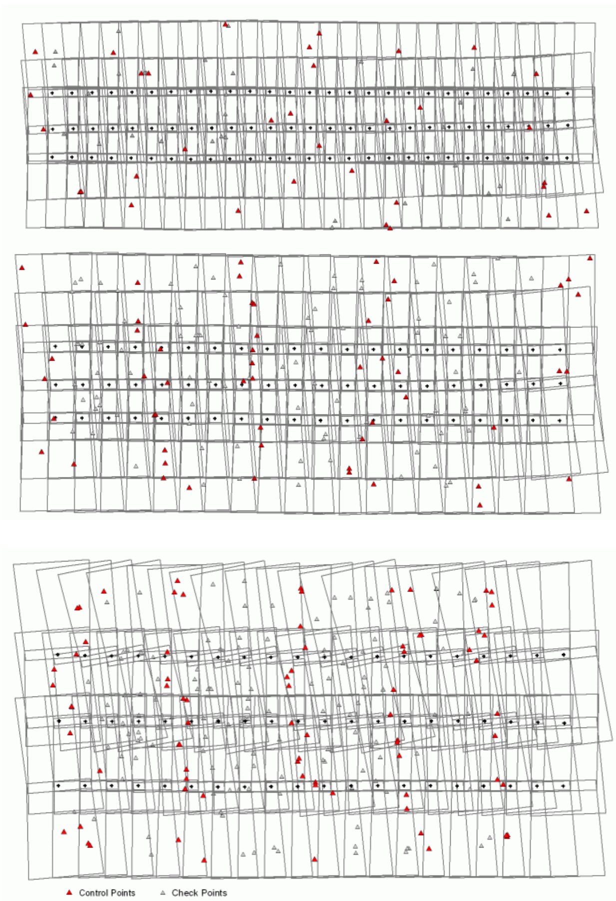

Figure 3: Top: Block layout GSD 7cm. Middle: Block layout GSD 14cm. Bottom: Block layout GSD 20cm.

The 7cm block included three east/west lines with 27 double images each and three cross strips with 13 double images. The overlap was p=60% in forward direction and q=76% in cross flight direction. The 14cm block had three lines east/west with

20 double images and an overlap of p=60% / q=80%. The 20cm block consisted of three lines east/west with 20 double images and an overlap of p=60% / q=64%.
The block layout was chosen to optimally fit to the distribution of ground control points in the Vaihingen/Enz test field. This causes the changes in the overlap conditions. The quite high side laps are not necessary for regularly production flights, they were only realized to obtain very large overlaps between individual camera head imagery for later stable overall system calibration.

The individual block layout is shown in Figure 3. For the 7cm block only the three flight lines without cross strips are given. The figures also illustrate the corresponding distribution of control and check point information, where the later used

control points are given in red (arranged in five control point chains perpendicular to main flight direction) and the remaining signalised points for independent accuracy check are coloured in grey. These check point configurations were utilised for the traditional bundle adjustments, based on control points only. In addition, direct georeferencing was performed, where all available signalised object points served as independent absolute accuracy control.

The mission was conducted on December 19th 2007 by Weser Bildmessflug GmbH, Bremerhaven, Germany. For this flight , a Cessna 206 survey aircraft was operated.

Due to the date and time of this flight mission (19th December 2007, 11:15 to 12:40 LCL) the sun angle was only between 17 and 18 degrees that results in poor colour quality and long shadows. Bright sunlight and light haze gave also a reduced contrast on the outer edges of the frames (Figure 4).

4. COMPARISON OF DIFFERENT GPS TRAJECTORIES

The GPS and IMU processing was done with AEROoffice 5.1c from IGI and GrafNav 8.10 from Novatel Inc. Calgary, Canada. Three different trajectories were created. For trajectory A the GPS base station “0384 Stuttgart” from the German permanent reference station network SAPOS (www.SAPOS.de) was used, trajectory B used a virtual base station provided by SAPOS and trajectory C was processed using precise orbits and clock information with the precise point processing (”PPP”) method provided inside the GrafNav software (Kouba & Héroux, 2000).

Base station “0384 Stuttgart” was located about 25 km to the south-east of the test field centre. The virtual base was calculated to be in the centre of the area.

During the flight over the test field, the number of satellites was between 5 and 9 with an average number of about 7 available satellites.

The GPS processing of trajectories A and B showed a difference between the forward and the reverse solution of max. 3 cm for the horizontal, and of max. 13cm for the vertical component. For trajectory C these differences were 5cm and 25cm, respectively. Based on the different GPS trajectories, GPS/IMU trajectories were processed inside AEROoffice.

Figure 4: Top: Image pointing to the left. Bottom: Image pointing to the right.

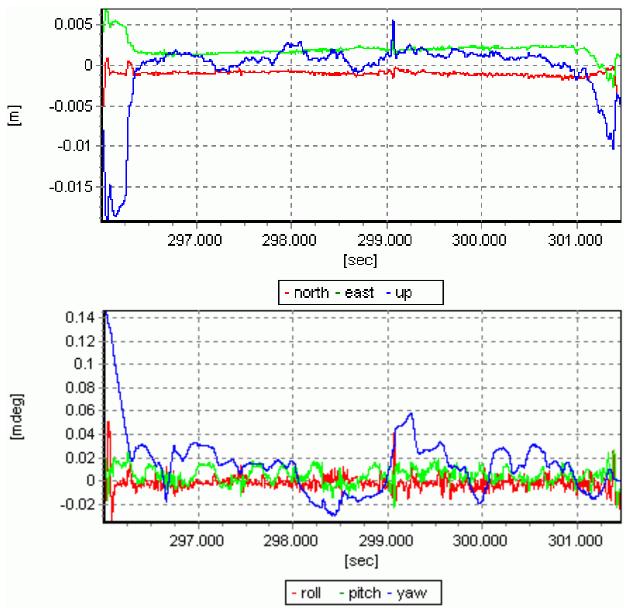

Figure 5: Comparison between solution A and solution B (base station vs. virtual base station).

Figure 5 shows the position and attitude differences between solution A and solution B (base station vs. virtual base station).

The differences between the two solutions are well within the accuracy specifications of the AEROcontrol system.

Figure 6 shows the differences between solution A and solution C (base station vs. PPP). For the application of the trajectory for direct georeferencing, the position differences would have to be considered. The most relevant difference is the height difference of up to 0.2m.

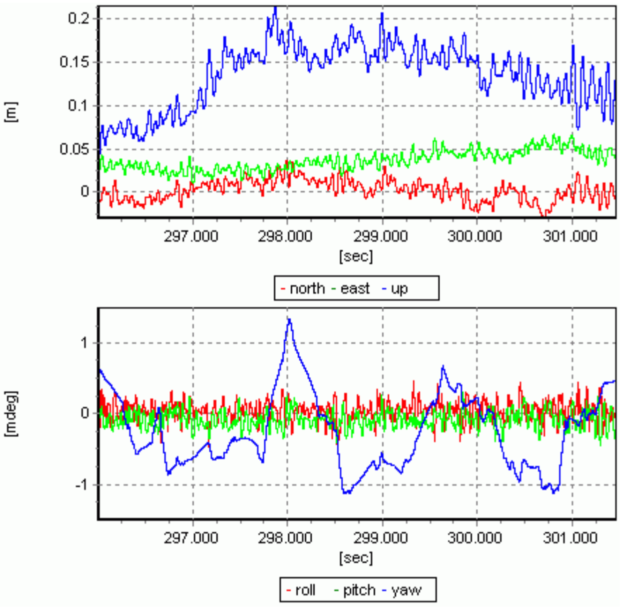

Figure 6: Comparison between solution A and solution C (base station vs. PPP).

The effect of the difference in the GPS solutions to the attitude determination is relatively small. The effect in the resulting orientation angles would be insignificant for the most direct sensor orientation tasks.

For the introduction of the trajectory information as additional measurement into an extended aerial triangulation (Integrated Sensor Orientation "ISO"), the effect of the difference between the different GPS processing methods would not be significant.

	Max. [mm] / RMS [mm]		
	ΔNorth	**ΔEast**	**ΔUp**
Base vs. VBS	6.3 / 1.1	7.0 / 2.2	19.4 / 4.2
Base vs. PPP	37.1 / 12.1	66.4 / 38.1	214.1 / 139.7

Table 1: Position differences between the different solutions.

	Max. [mdeg] / RMS [mdeg]		
	ΔRoll	**ΔPitch**	**ΔYaw**
Base vs. VBS	< 0.1 /< 0.1	< 0.1 /< 0.1	0.1 / <0.1
Base vs. PPP	0.5 / 0.1	0.4 / 0.1	1.3 / 0.6

Table 2: Attitude differences between the different solutions.

5. INVESTIGATION OF THE SYSTEM ACCURACY

The empirical accuracy for the three different flight blocks was obtained from comparison at independent check points in object space. Their coordinates were re-determined through bundle adjustment or direct georeferencing and then compared to their a priori known reference coordinates.

5.1 Quality of reference points test site Vaihingen/Enz

The reference coordinates have been determined through static GPS base line surveys in summer 2007. The whole measurement campaign consisted of 7 measurement days within a three weeks period of time. Two independent survey groups, each using a geodetic GPS receiver, did the base line measurements. The GPS reference station observations were obtained through SAPOS. A virtual reference station was used to keep the base line length as short as possible. To control the overall accuracy of base line observations each GPS group has done repeated measurements of the same distinct point twice each measurement day, in the morning and after finishing their daily measurement. Thus overall 28 repeated measurements of the same point were delivered from the seven measurement days necessary. Their statistical variation is given in Table 3 and reflects the absolute accuracy of the analysed base line. Since the other base lines are of comparable length, the obtained accuracy of about 1cm (std.dev.) for horizontal and 2cm (std.dev.) for vertical coordinates can be transferred to the remaining control points. Note that these accuracy numbers also include the repeatability (i.e. re-identification of object point for each new measurement), besides the pure accuracy from GPS survey. For later processing (during the AT runs) the accuracy (std.dev.) for control points was assumed to be 0.02m for all three coordinates.

	ΔEast [m]	**ΔNorth [m]**	**ΔUp [m]**
Std.Dev.	0.008	0.009	0.018
Max.Diff.	0.019	0.018	0.037
Min.Diff.	-0.018	-0.018	-0.034

Table 3: Accuracy of ground control points in Vaihingen/Enz test site from static GPS survey.

5.2 Determination of boresight misalignment

Direct GPS/IMU exterior orientation (EO) measurements have been done by the AEROcontrol-IId integrated system. The trajectory solution A (based on the station "0384 Stuttgart") has been used for the later bundle adjustments and direct georeferencing. Before those EO parameters can be used for direct georeferencing, they have to be related to the two individual camera heads of the dual head constellation.

The boresight angles for both camera heads have been determined by comparing the measured GPS/IMU angles with the angles of a bundle block adjustment done from the available image blocks. In the bundle block adjustment the images from both cameras together with the uncalibrated GPS/IMU results have been used simultaneously.

5.3 Geometric accuracy performance from independent check point analyses

As already pointed out, the overall absolute geometric accuracy can only be estimated from independent reference points. Thus the three different blocks were independently processed and the reference points differences statistically analysed. At the time of paper writing not all georeferencing variants have been available thus only parts of the processing results are presented and discussed in the following. So far, two different strategies have been investigated. The results from direct georeferencing (DG), based on the above boresight calibration are compared to the classical bundle adjustment (AT) based on control points only. All signalised points have been measured manually in all images, additional automatic tie points were matched using MATCH-AT (Version 5.1) from INPHO GmbH, Stuttgart, Germany.

The theoretical accuracy (precision) of object point determination for each block configuration is reflected in the theoretically estimated values from error propagation, i.e. inversion of normal equation matrix. The precision is only dependent on the individual block geometry and reflects the influence of random errors only, i.e. no influence of systematic errors. The corresponding values for the three block configurations (GSD 7cm, GSD 14cm, GSD 20cm) are listed in Table 4. These values are obtained from all non-control points, including the check points and automatically matched tie points. Quite interesting is the difference in precision for the x- and y- (horizontal) coordinate, which obviously is due to the specific block geometries. The difference in precision in north component is up to three times worse compared to the east component. The block configurations analysed here consist of three parallel flight lines (east-west, west-east) each, with fairly high side-laps. The side looking, oblique dual head camera configuration also causes a special image ray geometry which also influences this effect. Still it is not fully clear why this effect is present and further investigations have to be done to explain it in detail. Considering the precision in the vertical component, the values are close to one pixel (GSD) or slightly below. The precision of object coordinates gives a first estimation on the maximum accuracy that can be expected from the independent analyses at check points. Thus the later presented results from absolute accuracy always have to be compared to the precision values here.

Block	GCP #	ChP #	Std.Dev. [m]		
			ΔEast	ΔNorth	ΔUp
GSD 7cm	32	33	0.011	0.030	0.068
GSD 14cm	51	93	0.017	0.045	0.104
GSD 20cm	77	149	0.028	0.068	0.171

Table 4: Precision (Std.Dev.) of object point coordinates (estimated from error propagation).

The accuracy from check point analysis is given in the following tables for all three different GSD blocks. Table 5 shows the results for the GSD 7cm flight, Table 6 for the flight with 14cm GSD and Table 7 for the 20cm GSD block, finally. Note that for the 7cm block only the three flight lines without cross strips have been used.

As one can see, the ground control point based aerial triangulation was done in three different variants. In the first case no additional parameters have been introduced during processing (AT no). Then the additional parameter set as proposed by Grün (1978) using up to 44 polynomial coefficients is added (AT 44). In the final third case only 3 additional parameters modelling changes in camera principal point and focal length are used (AT io). In all cases two individual sets of additional parameters are estimated, one for each of the two camera heads separately. In order to get the best additional parameter values for each of the blocks their values have been determined in a previous step, where all available control points have been used. For the GSD 7cm block the images from the three cross strips were also involved for the estimation of self-calibration terms. The non significant values have been eliminated. For the final runs, the additional parameters were used as fixed values only, i.e. they have been used with very high weights. Therefore these values basically remained unchanged from their values from the previous run.

Vers.	GCP #	ChP #	σ0 [μm]	RMS [m]		
				ΔEast	ΔNorth	ΔUp
DG	0	65	4.08	0.045	0.075	0.130
AT no	32	33	1.50	0.033	0.070	0.134
AT 44	32	33	1.41	0.022	0.037	0.088
AT io	32	33	1.47	0.022	0.039	0.096

Table 5: Absolute accuracy from check point analysis for GSD 7cm block.

Vers.	GCP #	ChP #	σ0 [μm]	RMS [m]		
				ΔEast	ΔNorth	ΔUp
DG	0	144	5.17	0.075	0.156	0.376
AT no	51	93	1.36	0.039	0.108	0.231
AT 44	51	93	1.27	0.022	0.067	0.161
AT io	51	93	1.33	0.025	0.067	0.173

Table 6: Absolute accuracy from check point analysis for GSD 14cm block.

Vers.	GCP #	ChP #	σ0 [μm]	RMS [m]		
				ΔEast	ΔNorth	ΔUp
DG	0	226	3.28	0.066	0.149	0.333
AT no	77	149	1.98	0.062	0.124	0.250
AT 44	77	149	1.41	0.035	0.070	0.156
AT io	77	149	1.45	0.038	0.071	0.174
GPS-AT no	4	222	1.45	0.098	0.155	0.244

Table 7: Absolute accuracy from check point analysis for GSD 20cm block.

Looking into the results in some more detail one can see that the direct georeferencing already delivers nice results. In all three cases the accuracy (RMS) of the east coordinate is within half of a pixel (GSD), at least. For north component the quality is slightly worse and reaches up to one pixel (GSD). There obviously is a certain difference in performance of both horizontal coordinates, which has to be due to the block geometry, as already shown and discussed from the analyses of object point precision (see Table 4). If one compares the DG cases with the AT without any self-calibration the similar behaviour can be seen in the RMS values of horizontal coordinates.

It is also astonishing to see how well the horizontal performance of DG already agrees with the standard AT case without additional self-calibration. For the GSD 20cm and 7cm the quality is almost identical. The performance of DG for the GSD 14cm block is slightly worse. This can also be seen from the sigma_0 which is the worst of all three blocks. For the vertical accuracy DG delivers less accurate results compared to the ground control point based AT. This might happen due to the extrapolation character of DG compared to interpolating AT, which is less sensitive to any small and non-corrected system calibration parameters. But even though the vertical accuracy is worse for DG it still stays within 1.5 – 2.7 GSD.

If one looks for the AT cases based on control points the sigma_0 comes down to 1/5 of a pixel especially when introducing additional self-calibration. Comparing the two self-calibrating cases (i.e. the fairly complex Grün 44 parameter model versus the 3 interior orientation parameter corrections) the finally obtained absolute accuracy is very close in all cases. This shows that in this case the correction of interior orientation is already sufficient to obtain high performance for object point determination. Additionally it was tried to add additional corrections for radial lens distortion, which in this case does not lead to any improvement in object accuracy. This shows that after lens calibration the data is almost free of non compensated radial distortion effects.

What also should be pointed out is the fact, that the interior orientation corrections have been significantly estimated from bundle adjustment using control points exclusively. No additional exterior orientation (EO) parameters from GPS/IMU have been introduced. Typically such adjustment is not possible mainly due to the large correlations between the estimated EO parameters and the estimations for focal length and principal point correction. In case of this dual head camera installation the tilt between the two camera axes and the additional high overlap of images allowed for the de-correlation of interior orientation (IO) parameters and exterior orientations. From this the IO parameters are determined even without use of directly observed GPS/IMU exterior orientations.

For the GSD 20cm block one final additional adjustment variant is given, which only relies on the use of 4 control points located in the four block corner. This is only 5% of the number of control points used for the previous classical AT. Additionally the camera perspective centre coordinates from GPS/IMU are introduced as weighted observations with std.dev. of 5cm for all three coordinate components (so-called GPS-supported AT). Note, that no additional unknowns are introduced during processing, neither any additional parameters for self-calibration, nor any offset, shift or drift corrections as they are often used in GPS-supported AT. Thus the obtained accuracy has to be compared to the “AT no” case of the same block. If one compares the absolute accuracy the horizontal performance is slightly worse compared to the standard AT with 77 GCPs. The east component is in the range of 1/2 pixel GSD, the north component reaches 3/4 pixel GSD. The height accuracy is identical to the classical AT case, which shows the larger influence of perspective centre coordinate observations on height accuracy mainly.

If one compares the absolute accuracy from check point analyses to the GSD of each of the flights, the accuracy in east component is between 20-30% of a pixel, the accuracy in north is between 35-60% of a pixel. This is clearly within the sub-pixel range. For the vertical axis the accuracy is about 0.8-1.2 pixel GSD.

If finally the empirical accuracy from check point analysis is compared to the theoretical precision values, one also can see high agreements, especially for GSD 20cm block and also for the GSD 7cm block. This in general proves that after use of additional parameters systematic errors are effectively eliminated. As mentioned earlier, the correction of interior orientation (i.e. only three additional parameters for each camera head) in this case seems to be fully sufficient.

The block GSD 14cm performs slightly worse and shows larger differences especially in the vertical component. Here the precision values cannot be reached by absolute accuracy.

Still there are some larger differences between precision and accuracy values in the horizontal (especially east component), but one has to keep in mind, that the accuracy of our reference points is of the same order (1cm) than the precision of this coordinate. Thus the term “reference coordinates” is not fully valid, at least for this high quality, 1-2cm accuracy requirement.

6. CONCLUSION

The results of an accuracy test of a Dual-DigiCAM-H/39 are reported. From the data obtained during a flight over a well controlled test field, two topics were investigated.

1. The GPS/IMU trajectory was processed using a local GPS base station, a virtual base station and using no base station but only precise orbits and precise clock information (“PPP”). The differences in attitude between the trajectories are well below the accuracy of the used GPS/IMU system. The maximum difference in position between the solutions with the different base stations was below 2cm. The max. position difference between the base station solution and the PPP solution was about 7cm for the horizontal and about 21cm for the vertical component. It was shown, that for many sensor orientation tasks, it is not necessary any more to use data of a local base station or of a virtual base station. The “PPP” method delivers results with a sufficient accuracy.
2. The geometric accuracy of the dual camera was evaluated using independent check points. The position of the check points was determined by direct georeferencing and by classical AT using different sets of self-calibration parameters. The use of the focal length and the principal point as free parameters showed very similar results to the use of a full set of 44 self-calibration parameters. The absolute accuracy of the checkpoint coordinates was 0.2 to 0.3 pixel GSD in east direction (flight direction) and 0.35 to 0.6 in north direction (cross flight direction). The vertical accuracy was about 0.8 to 1.2 pixel GSD. For the case of direct georeferencing the horizontal accuracy was in the range of half a pixel for east and about one pixel for north. The vertical accuracy was about 1.5 to 2.7 pixel GSD.

The investigations described in this paper confirmed, that the data from the tested dual camera installation can be processed successfully with standard software packages noted above.

The calculation of the geometric accuracy showed very satisfactory results for data processing with traditional AT as well as with direct georeferencing. Further tests will be done to point out the performance of integrated sensor orientation with low number of control points.

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