Experiences on operational GPS/inertial system calibration in airborne photogrammetry [1]

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Summary

Overall system calibration is one limiting factor in direct georeferencing. Within this context the stability of system calibration over longer time periods and the influence of additional self-calibration is of special interest. The investigations presented are based on test material from a real flight test, where a calibration field was flown several times within a two month period using the same system installation. First statements on operational calibration and long term stability are feasible, which are especially important from practical aspects.

Kurzfassung

Erfahrungen mit der operationellen GPS/inertial-Systemkalibrierung in der Luftbildphotogrammetrie

Die Gesamtsystemkalibrierung ist ein limitierender Faktor der direkten Georeferenzierung. In diesem Zusammenhang ist vor allem die Stabilität der Kalibrierung über längere Zeiträume und der Einfluss von zusätzlicher Selbstkalibration interessant. Die präsentierten Untersuchungen basieren auf Testdaten eines realen Produktionsprojekts, in dem ein Kalibrationsfeld über einen Zeitraum von 2 Monaten mit der selben Systeminstallation beflogen wurde. Damit sind erste Aussagen über operationelle Kalibrierung und Langzeitstabilität möglich, die vor allem für praktischen Anwendungen relevant sind.

1. Introduction

With the advent of high performance integrated GPS/inertial systems the direct georeferencing of airborne sensors becomes feasible even for high-end photogrammetric applications. Meanwhile GPS/inertial modules are central component for orientation of digital sensor systems, like laser scanner systems or imaging multi-line pushbroom scanners. Even for frame based cameras, digital or analogue, direct orientation measurements are useful to strengthen geometry in geometrically less stable applications like corridor surveys and single model orientation. Additionally, the integration of GPS/inertial observations in an automatic aerial triangulation should be aspired to reduce the amount of interactive editing and data preparation and to increase the quality resulting in a more robust, reliable and truly automatic process, finally.

Several independent test flights using commercial high-quality GPS/inertial systems – Applanix POS/AV 510 DG (Reid & Lithopoulos, 1998), IGI AEROcontrol-IId (Kremer, 2001) – in combination with standard RMK cameras have shown the today's accuracy performance of direct georeferencing in airborne environments. From well controlled experimental flight tests performed at the Institute for Photogrammetry (ifp) an accuracy of object point determination about 5-20cm (RMS) for the horizontal and 10-25cm (RMS) for the vertical component was obtained after direct georeferencing based on medium scale images from analogue wide-angle cameras (Cramer, 2001, Cramer, 1999). The accuracy variations are most likely due to the tested different block geometries – large image overlap providing strong block geometry with several multi-ray points positively influences the object point accuracy since multiple image rays compensate for remaining errors in the orientation elements. The

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obtained accuracy potential of direct georeferencing is verified from different independent performance tests, e.g. the results from the OEEPE test on integrated sensor orientation (Heipke et al., 2002). This quality of direct georeferencing is quite remarkable and allows for new and efficient applications like almost “online” orthoimage production for areas with known DTM without any additional effort in aerial triangulation.

Nonetheless, especially the experiences and results from the OEEPE test have shown, that the performance of direct georeferencing is limited by the quality of the overall system calibration, which is due to the extrapolation nature of this approach. Therefore, a correct and highly accurate overall system calibration, sufficiently describing all physical effects like translations and rotations between the different sensor components as well as systematic influences from camera and imagery, is inevitable to obtain optimal performance in object space. Besides the need for a correct calibration the stability and validity of these calibration parameters is still an open task. Within all present test flights the calibration was done only once, directly before flying the test project. Furthermore, due to the lack of physically separated calibration and project sites, the calibration was performed in the final test area itself resulting in high time and spatial correlations. Since no experiences on the variations of system calibration parameters over time are available from former tests this paper is focused on this specific task. Additionally, the results presented here are obtained from real production flight data which is different from all former high accuracy tests where the data were captured in very well controlled environments.

2. Test flight design

The presented data from different calibration flights are only a small part of a big production project in Saudi Arabia flown by Hansa Luftbild German Air Surveys. Within this project more than 9000 images (scale 1:5500) were captured at 12 flight days from January, 29th – March, 25th 2001, covering a time span of approximately 2 months. Parallel to the image data recording, GPS/inertial positions and attitude data were provided by the IGI AEROcontrol-IId system, which was rigidly mounted at the camera body (Figure 1). For each mission day the same fully signalised flight line was normally flown twice with opposite flight directions for system calibration – typically once in the morning before and once in the evening after mission flight. Only for the last three mission days, both flight lines were flown in the morning directly afterwards. The calibration strip consists of altogether 21 signalised ground control points (GCP) located in the standard or Gruber positions of each image resulting in 7 captured images per calibration line. Since almost all images were taken with the same Z/I-Imaging RMK Top30 – GPS/inertial installation (calibration flights 1-19, January, 29th – March, 15th), the results from the multiple calibration flight data allow for first investigations on the long term stability of system calibration. Only the last two missions were flown with a wide-angle RMK Top15, therefore the inertial unit had to be demounted and fixed to the new camera body for this last two mission days (calibration flights 20-23, March, 24th and 25th).

Figure 1, System installation in the aircraft

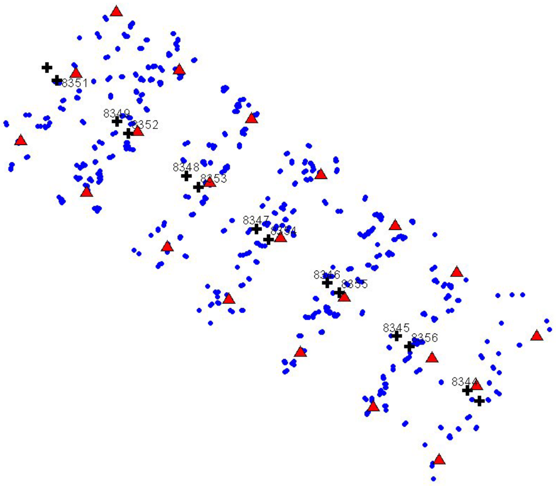

Figure 2, Typical GCP and tie point layout
(normal-angle flights on Mar 12)

The input data for the system calibration were provided by IGI and Hansa Luftbild, respectively. The GPS/inertial data were processed using the AEROoffice software, afterwards the integrated GPS/inertial positions and attitudes are interpolated on the camera exposure times and transformed to the applied local topocentric coordinate frame. Within this transformation the photogrammetric angles omega, phi, kappa are obtained from the navigation angles roll, pitch, yaw. The pre-surveyed translation offsets between GPS-antenna, IMU centre of gravity and camera perspective centre are already considered during GPS/inertial data integration. The image coordinates were obtained from MATCH-AT automatic aerial triangulation, where the GCP image coordinates were measured manually. Figure 2 shows the typical tie point layout from automatic image matching for a normal-angle calibration block formed of the two flight lines flown at one calibration day. Besides the automatically matched tie points the manually measured GCPs are given, where the crosses indicate the location of the camera stations. Due to weather conditions two of the normal angle flight days are excluded from further investigations. Finally, eight calibration flight days are available for the GPS/inertial normal-angle camera configuration, where the two last calibration flight days were done with the wide-angle camera installation. In order to separate between global and strip-dependent shift parameters, the two flight lines per flight day are considered as one calibration block, mostly. Since the automatic AT was done for the different flight lines separately, the two strips are tied together only via the identical GCPs.

3. Test results

3.1 Variation of GPS/inertial exterior orientation elements

As a first result the remaining differences between estimated camera station positions and attitudes and the original GPS/inertial exterior orientation parameters are analysed. The obtained RMS-values indicate a first but rough estimation on the accuracy performance of directly measured positions and attitudes from GPS/inertial. Besides the problem of physical correctness of estimated parameters from AT, it has to be stated that the quality of the estimated “reference” trajectory is within the same accuracy level of GPS/inertial orientation elements, hence the term reference is not appropriate at least for the positioning data of the normal-angle test flights. From these two aspects, the analysis of the residuals did not really reflect the true differences between indirect and directly determined EO parameters which has to be kept in mind in the following. The obtained statistics of difference analysis are given in Table 1.

#	Day	Camera	STD ΔX_0 [m]	STD ΔY_0 [m]	STD ΔZ_0 [m]	STD $\Delta\omega$ [10^{-3} gon]	STD $\Delta\varphi$ [10^{-3} gon]	STD $\Delta\kappa$ [10^{-3} gon]
1	Jan 29	normal	0.183	0.233	0.148	7.937	5.364	8.627
2	Jan 31	normal	0.151	0.357	0.077	6.698	7.990	5.366
3	Feb 05	normal	0.274	0.252	0.103	2.128	6.629	10.983
4	Feb 18	normal	0.197	0.156	0.118	5.825	3.472	22.611
5	Feb 19	normal	0.090	0.130	0.050	5.277	5.141	43.973
6	Feb 21	normal	0.226	0.199	0.135	2.919	6.100	5.225
7	Feb 24	normal	0.223	0.123	0.184	2.906	5.959	6.949
8	Mar 12	normal	0.136	0.183	0.122	5.128	5.199	7.626
9	Mar 24	wide	0.332	0.238	0.185	8.525	23.789	18.509
10	Mar 25	wide	0.333	0.263	0.209	12.343	20.111	18.687

Table 1, Variations of GPS/inertial positions and attitudes

As it can be seen from Table 1 the mean horizontal accuracy (STD) from normal-angle installation is about 20cm horizontally and 10cm vertically which could be expected for such installation. It has to be pointed out that the relation between horizontal and vertical accuracy is similar to the quality of estimated orientation elements from AT indicating that such an installation does not provide values good enough to serve as reference for the GPS/inertial quality assessment. Nevertheless, it has to be mentioned that additional offsets are present. In some cases these offsets remain more or less constant over the flight time per day, where during other mission flight days strip-wise changes are detected in the positioning. The results from the two wide-angle flights show somehow different behaviour. Although the theoretical accuracy from AT is in the range of 5cm resulting in a much better reference than for the normal-angle configuration, the obtained STD is between 20-30cm, only. The horizontal position differences show clear systematic strip dependent shift effects, which might be due to errors in the GPS/inertial positioning data (non optimal ambiguity solution during GPS data processing), or due to uncorrected systematic errors from camera calibration or imagery.

The quality of attitude determination from GPS/inertial is fairly consistent for ω- and φ-angle and in the range of 0.003-0.008gon (10”-26”), where the mean accuracy (STD) is ~0.005gon (16”). The κ-angle performs worse, the mean accuracy (STD) is 0.013gon (43”). At least for three of the normal-angle flights significant jumps can be seen between the two flown image strips. Such strip dependent systematic error might be caused by non optimal estimation of the internal inertial error behaviour within the GPS/inertial data integration process. Former airborne tests using the AEROcontrol-IId system have shown consistently higher quality results indicating that the accuracy potential is not fully reached for these investigated GPS/inertial data from a real flight test flown under true operational environment conditions.

Besides the already discussed STD values, the estimated mean values of attitude differences represent the physical misalignment between internal sensor axes of the IMU and the camera dependent photo coordinates. The variation of these mean values gives a first estimation on the stability of the boresight angles over time. Still, it has to be mentioned that parts of the changes in boresight alignment might be due to remaining effects in image space and non optimal GPS/inertial system integration.

3.2 Integrated sensor orientation for system calibration

Based on the integrated GPS/inertial-AT or integrated sensor orientation (Cramer & Stallmann, 2002) the calibration of system parameters was done for each calibration flight using the given 21 GCPs and the exterior orientation results from the integrated GPS/inertial system. Since no quality measures for the GPS/inertial positions and attitudes were available from GPS/inertial data integration an assumed accuracy of 0.1m and 0.005gon was introduced for the stochastic model of directly observed orientation parameters. Within this system calibration the inevitable angle offsets and position shifts (if significantly present) are introduced as additional unknowns and estimated in combination with the (significant) Ebner self-calibration parameters to compensate for remaining systematic effects from imagery (Ebner, 1976). The Ebner polynomials are preferred to the physical relevant model by Brown (Brown, 1971) since the polynomial coefficients are defined as orthogonal with no or almost little influence and correlation on the exterior orientation elements.

3.2.1 Long-term stability of calibration parameters

The estimated calibration parameters (3 position shifts and 3 boresight alignment angles) for each calibration flight block are given in Table 2 for the normal- and wide-angle installation, respectively.

According to the estimated position offsets, vertical shifts are present for almost all flight days, where the amount of vertical offset correction is not constant but varies between 12–40cm for the different calibration days. For horizontal components smaller offset corrections between 10–20cm are estimated for approximately 50% of the flights. These offsets are non reproducible, and they have already be seen when estimating the external quality of GPS/inertial positioning. Although such offsets should not be expected for high quality GPS positioning, they are well-known from GPS-assisted AT, where in especially in height component conflicts are present mainly due to inconsistencies between physical reality and mathematical model or offset errors in GPS-positioning. In case of direct georeferencing such global shift errors have to be taken into account since they are non detectable without using any ground control.

Nonetheless, during system calibration the main focus is laid on the quality and stability of boresight alignment estimation, since this misorientation between camera and IMU coordinate frame cannot be pre-surveyed manually and therefore has to be estimated from an additional calibration process before the system installation is used for direct georeferencing. Table 2 shows the distinct estimated boresight alignment angles from the 8 normal-angle and the last 2 wide-angle system installations, where in Figure 3 the variations from the mean estimated boresight angle are depicted for the three misalignment angles from the 8 normal-angle flight days. As one can see from the table and the figure the variations are within ±0.007gon (23”) except for the κ-variation for the 3rd – 5th flight day (Feb 05, Feb 18, Feb 19). Here, the difference is significantly larger which is almost due to the non corrected systematic error, already shown in the previous section when comparing the GPS/inertial attitudes to the estimated values from AT. As far as such errors are present, the results from boresight angle stability are less meaningful since the optimal performance from GPS/inertial attitude is not fully exploited during system calibration. Excluding these three data sets, the variation (STD) from estimated mean boresight angles is $\sigma_{\Delta\omega}$=0.0035gon (11”), $\sigma_{\Delta\varphi}$=0.0055gon (18”), $\sigma_{\Delta\kappa}$=0.0029gon (9”). This variation indicates the stability of physical boresight alignment over longer time periods, assuming optimal GPS/inertial data processing and the use of a correct mathematical approach for modelling of physical reality of image formation during AT. Since both assumptions could not be guaranteed totally always, they are influencing the boresight estimation process. This is one general problem during boresight calibration.

#	Day	Camera	ΔX_0 [m]	ΔY_0 [m]	ΔZ_0 [m]	$\Delta\omega$ [gon]	$\Delta\varphi$ [gon]	$\Delta\kappa$ [gon]
1	Jan 29	normal	-0.1613	0	0	0.4851	0.0702	-0.1349
2	Jan 31	normal	-0.1387	-0.0676	-0.4050	0.4805	0.0656	-0.1278
3	Feb 05	normal	0.1382	0	-0.3024	0.4882	0.0607	-0.1124
4	Feb 18	normal	0	-0.2020	-0.1267	0.4880	0.0617	-0.1431
5	Feb 19	normal	0	0	-0.1698	0.4782	0.0689	-0.1207
6	Feb 21	normal	0	0	0	0.4901	0.0563	-0.1289
7	Feb 24	normal	0	0	-0.3826	0.4870	0.0629	-0.1328
8	Mar 12	normal	0	0	-0.2357	0.4900	0.0557	-0.1348
9	Mar 24	wide	0	-0.1046	-0.3071	0.4569	0.0698	-0.2637
10	Mar 25	wide	-0.1103	0	-0.2615	0.4572	0.0667	-0.2897

Table 2, Estimated position shift and boresight alignment from integrated sensor orientation

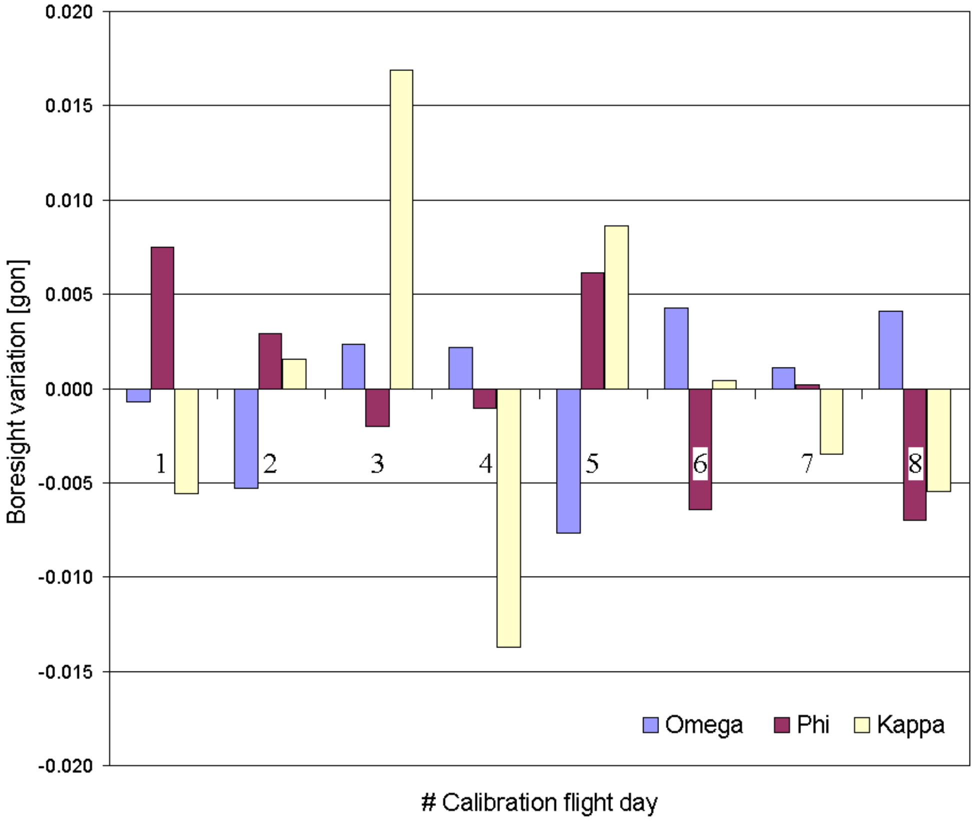

Figure 3, Variation of boresight angles for normal-angle installation

3.2.2 Influence of additional parameters for camera self-calibration

Within traditional aerial triangulation the use of additional parameters for self-calibration is broadly accepted. Using these additional parameters the physical process of image formation is adopted to the assumed mathematical model of central perspective represented with the collinearity equation. Empirical investigations from Nilsen (2001) have shown average systematic image deformations around 5-10μm for typical airborne photogrammetry projects. In especially when using direct georeferencing based on GPS/inertial only these systematic effects are critical since they remain unknown and will deteriorate the obtained object point accuracy significantly. Within the calibration performed here the parameters are derived from integrated sensor orientation where constant position and boresight angle offsets are estimated together with self-calibration terms based on Ebner polynomial coefficients. The graphical representation of self-calibration parameters in image space is given exemplarily for two flight missions in Figures 4-5 for a regular 5x5 image point grid covering the whole image area.

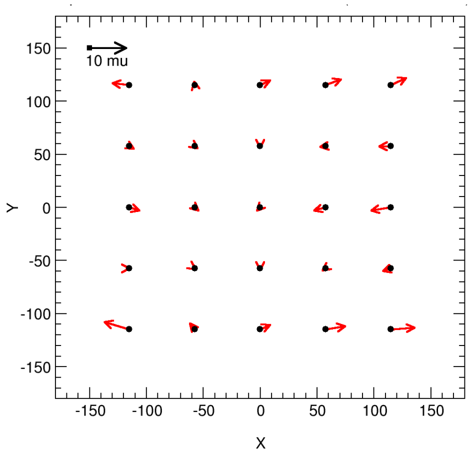

Figure 4, Influence of self-calibration (Jan 31, normal-angle)

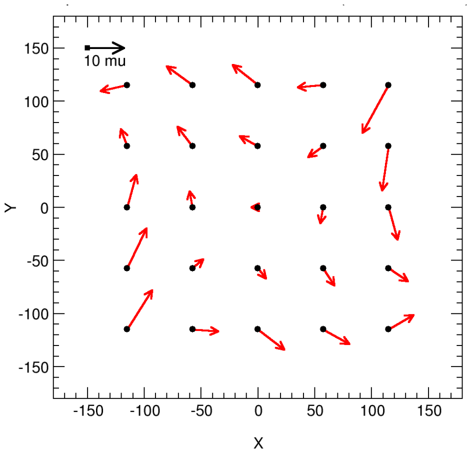

Figure 5, Influence of self-calibration (Mar 24, wide-angle)

As it can be seen from the detailed analysis the influence of self-calibration is non constant but varying. For five normal-angle flight days only relatively small image distortions are present, where for the remaining three normal-angle flights and the two wide-angle flight missions larger distortions are modelled via the self-calibration. In general, for the normal-angle camera flights the estimated influences of additional parameters are showing a slightly cushion effect in flight direction, potentially caused by film transportation or film shrinking. For the flights on Feb 18, Feb 24 (normal-angle) and Mar 24 (wide-angle) an additional shear component is present, which is correlated with boresight κ-angle estimation. In contrary to the normal-angle configurations the final last wide-angle flights show an additional barrel shaped distortion.

It is difficult to say which sensor calibration performs best in terms of absolute accuracy on object point determination for later direct georeferencing. This can only be checked from check point analysis from direct georeferencing based on the pre-determined calibration parameters.

3.3 Quality of direct georeferencing

Within the preceding sections the stability of boresight alignment parameters and self-calibration terms was analysed and certain variations in the parameters have been seen. In order to simulate the later practical use of direct georeferencing, where the calibration parameters from system calibration determined over special calibration sites are used for several mission flights, the long term quality of system alignment is checked using the 21 available control points as independent points for overall quality checking. Since the estimated translation offsets as well as the estimated self-calibration parameters are varying within certain amounts they cannot be corrected in advance. Therefore, within the following investigation only the mean boresight angles are applied and used for direct georeferencing, where the GPS/inertial exterior orientations are introduced as fixed values. It is already shown that for the 3rd – 5th calibration flight day large variations in κ–angle are present since the optimal performance from GPS/inertial attitude is not fully exploited during data integration, which influences the results from boresight angle estimation significantly. These data sets are excluded from determination of mean boresight angle calibration. The resulting quality analysis from 21 check point differences is given in Table 3.

The mean object point accuracy (RMS) is consistently within 2dm for the horizontal and 4dm for the vertical component, which is quite acceptable for the long time range, keeping in mind, that only one set of misalignment angle parameters is applied for all normal- and wide-angle camera test flights respectively. In other words: One calibration procedure and the exclusive correction of boresight misalignment angles is sufficient for all flight missions to obtain the 2-4dm accuracy potential mentioned before.

From analysing the given STD and corresponding distortion vector plots, global and strip dependent systematic errors are seen for many flight days. The strip dependent effects are suppressed when using the different flight lines as one single block. These systematic errors are due to non optimal overall system alignment or data processing. For example, the varying positions offsets detected during system calibration are not considered within direct georeferencing and will result in such global systematic position shifts. The quality of GPS/inertial position – mainly dependent on the pure GPS quality – resulting in global position shifts is a critical component within direct georeferencing, which cannot be corrected without any ground control in the mission area.

#	Day	Camera	RMS ΔX [m]	RMS ΔY [m]	RMS ΔZ [m]	STD ΔX [m]	STD ΔY [m]	STD ΔZ [m]
1	Jan 29	normal	0.174	0.091	0.536	0.120	0.089	0.536
2	Jan 31	normal	0.211	0.066	0.575	0.068	0.062	0.271
3	Feb 05	normal	0.194	0.112	0.385	0.090	0.079	0.330
4	Feb 18	normal	0.076	0.170	0.365	0.075	0.069	0.365
5	Feb 19	normal	0.184	0.167	0.380	0.114	0.148	0.372
6	Feb 21	normal	0.075	0.078	0.271	0.060	0.078	0.203
7	Feb 24	normal	0.073	0.077	0.463	0.050	0.073	0.187
8	Mar 12	normal	0.088	0.094	0.436	0.080	0.088	0.268
9	Mar 24	wide	0.136	0.191	0.336	0.135	0.104	0.250
10	Mar 25	wide	0.117	0.157	0.435	0.086	0.123	0.248

Table 3, Quality of direct georeferencing

There is almost no difference in object point quality from normal- and wide-angle imagery, which is highly unlikely since wide-angle geometry should provide better accuracy in object space. Parts of this error budget are due to lower quality of GPS/inertial exterior orientation elements which can already be seen from the first performance estimation given in Table 1. Additionally, remaining systematic errors from self-calibration have to be considered. As already shown before, the distortions from self-calibration are different for the wide-angle compared to the normal-angle camera, resulting in larger influences from non corrected systematic effects in image space. After re-introducing the additional self-calibration parameters for the wide-angle flights again and performing an integrated sensor orientation (still without ground control), object point determination is possible with an accuracy (STD) about 10cm for all three coordinate components.

4. Conclusions

Results from this real flight test underline the highly operational use of GPS/inertial components for direct georeferencing. The exclusive correction of boresight angles is sufficient for object point accuracy well below 4dm (RMS). No AT process is necessary to reach this quality. The misalignment angles remain valid within the given bounds and can be used for longer time periods. Although the overall quality is less compared to the previous well controlled GPS/inertial accuracy tests, the results are quite remarkable for the true operational test environment.

Nonetheless, the object point quality is dependent on the GPS/inertial accuracy. There is a need for consistently high performance GPS/inertial positioning and attitude determination, which has to be guaranteed throughout the whole mission duration. Special care has to be laid on the κ-angle estimation, its correct sensor scale factor modelling, and the positioning performance, which is mainly due to the quality of pure GPS-processing. Especially when thinking about remote areas and longer baseline distances this topic is important. The vertical component is additionally influenced from camera effects like focal length variations or uncorrected radial-symmetric distortions and therefore very critical. In general, global position shifts cannot be detected and corrected without any ground control in the mission area itself.

Although the long term investigations on system calibration have shown a fairly high stability in boresight angles, certain variations are present for smaller position offsets and remaining influence of self-calibration. Since these effects are hard to model a priori by using a separate calibration site, such variations are limiting the overall quality of direct georeferencing. Especially for the wide-angle camera installation a significant influence of uncorrected systematic errors in imagery on object point determination was shown. Such errors are compensated significantly when using the method of integrated sensor orientation for processing of mission data where additional parameters for self-calibration or boresight alignment refinement are re-introduced and estimated even without ground control. Doing so, the mission area itself serves as calibration site. Still, it has to be mentioned that block geometry and tie points measurements (at least for sub-parts of the block area) are necessary for this approach.

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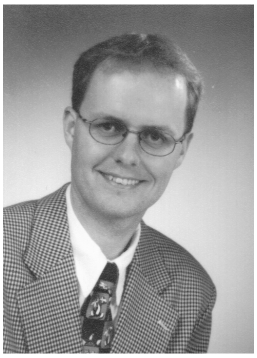

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