SYSTEM CALIBRATION FOR DIRECT GEOREFERENCING

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ABSTRACT

Within the last years extensive tests were done to investigate the accuracy performance of integrated GPS/inertial systems for direct georeferencing in airborne photogrammetric environments. Based on commercially available high performance GPS/inertial systems direct georeferencing was shown to be a serious alternative to standard indirect image orientation using classical or GPS-supported aerial triangulation. Nonetheless, correct overall system calibration including the GPS/inertial component as well as the imaging sensor itself is the limiting factor in this approach. Since direct georeferencing without ground control relies on an extrapolation process only, remaining errors in the system calibration will significantly decrease the quality of object point determination. Therefore, special focus has to be laid on the overall system calibration procedure. Within this context the stability of system calibration over longer time periods and the influence of additional self-calibration on the calibration parameter estimation are of special interest. The investigations presented in this paper are based on test material from a real flight test, where as one part of a big project a calibration field was flown several times within a two month period using the same GPS/inertial-camera system installation. From this test data first statements on the long term stability of system calibration are feasible, which are important especially from a practical point of view when applying direct georeferencing in photogrammetric production processes.

KURZFASSUNG

In den letzten Jahren wurden ausgiebige Tests zur Ermittlung des Genauigkeitspotenzials der direkten Georeferenzierung mit integrierten GPS/inertial-Modulen in luftgestützten photogrammetrischen Anwendungen vorgenommen. Unter Verwendung kommerzieller, hochgenauer integrierter GPS/inertial-Systeme wurde mit der direkten Georeferenzierung eine ernstzunehmende Alternative zur üblichen indirekten Sensororientierung durch klassische oder GPS-gestützte Aerotriangulation vorgestellt. Die korrekte Gesamtsystemkalibrierung bestehend aus GPS/inertial-Komponenten und der Kamera ist jedoch der limitierende Genauigkeitsfaktor. Da die direkte Georeferenzierung ohne Passpunkte auf einem Extrapolationsprozess basiert, werden nicht korrigierte Fehler in der Systemkalibration die Qualität der Objektpunktbestimmung signifikant verschlechtern. Daher muss das Hauptaugenmerk auf dem Kalibrationsprozess liegen. In diesem Zusammenhang ist die Stabilität der Systemkalibration und der Einfluss von zusätzlichen Selbstkalibrationstermen von besonderem Interesse. Die in diesem Papier präsentierten Ergebnisse beruhen auf Testdaten, die im Rahmen eines großen kommerziellen Projekts aufgezeichnet wurden. Innerhalb dieses Gesamtprojekts wurde über einen Zeitraum von zwei Monaten ein Kalibrationsfeld mehrfach mit der selben GPS/inertial-Kamera Systeminstallation überflogen, sodass erste Aussagen über die Langzeitstabilität der Systemkalibration möglich sind. Diese Ergebnisse sind besonders hinsichtlich der praktischen Anwendung der direkten Georeferenzierung im photogrammetrischen Auswerteprozess relevant.

1. INTRODUCTION

With the advent of high performance integrated GPS/inertial systems the direct georeferencing (DG) 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 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*a*, 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 obtained accuracy potential of direct georeferencing is verified from different independent 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 (Heipke et al., 2002) 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.

Within the next sections the functional mathematical model used for system calibration and the test data material is presented, where Section 4 is focused on the analysis of results from the different real calibration flights. Since the flight data was captured over a 8 week time interval using the same GPS/inertial-camera system installation, recommendations on long term stability of system calibration parameters are possible.

2. SYSTEM CALIBRATION

System calibration is one major task in direct georeferencing. One possible approach for system calibration is performed in a two-step procedure, where the directly measured GPS/inertial positions and attitudes are compared to the estimated exterior orientations from conventional aerial triangulation. From analysing positioning and attitude differences at each distinct camera station the most common six calibration parameters (translation offsets and misalignments between camera and GPS/inertial component) are obtained. Although this procedure has advantages since the output, i.e. camera positions and attitudes, of any bundle adjustment software provides comparison values for system calibration, this approach almost neglects the existing correlations between estimated orientation elements and interior orientation of the imaging sensor. A quite obvious example for these correlations is obtained from the experiences of former test flights, where systematic vertical offsets were proven which might be due to several reasons, e.g. shifts in GPS/inertial positions, inconsistency in assumed focal length or uncorrected systematic effects from image space. To model these dependencies correctly an integrated or combined bundle adjustment is favoured to determine the calibration terms within one step. Besides consideration of the correlations the integrated approach allows for handling the associated accuracy of directly measured exterior orientation elements properly. The basic mathematical model is presented in the following.

2.1 Functional model

The functional model of integrated sensor orientation is based on the well-known collinearity equations in Equation (1). The tilde symbol indicates that the corresponding values are introduced as directly observed unknowns from GPS/inertial systems.

$$\bar{x} = \bar{z} \cdot \frac{\tilde{r}_{11}(X-\tilde{X}_0)+\tilde{r}_{12}(Y-\tilde{Y}_0)+\tilde{r}_{13}(Z-\tilde{Z}_0)}{\tilde{r}_{13}(X-\tilde{X}_0)+\tilde{r}_{23}(Y-\tilde{Y}_0)+\tilde{r}_{33}(Z-\tilde{Z}_0)}+\Delta x$$

$$\bar{y} = \bar{z} \cdot \frac{\tilde{r}_{21}(X-\tilde{X}_0)+\tilde{r}_{22}(Y-\tilde{Y}_0)+\tilde{r}_{23}(Z-\tilde{Z}_0)}{\tilde{r}_{13}(X-\tilde{X}_0)+\tilde{r}_{23}(Y-\tilde{Y}_0)+\tilde{r}_{33}(Z-\tilde{Z}_0)}+\Delta y \qquad (1)$$

where $\bar{x},\bar{y},\bar{z}$ = reduced image coordinates related to perspective centre
X_0,Y_0,Z_0 = coordinates of perspective centre
r_{ij} = elements of rotation matrix $\underline{R}$
$\Delta x,\Delta y$ = influence of additional parameters.

The elements of rotation Matrix $\underline{R}$ are obtained from the matrix product

$$\underline{R} = \underline{R}_P^L = \underline{R}_B^L(\tilde{\omega},\tilde{\varphi},\tilde{\kappa}) \cdot \Delta\underline{R}_P^B(\Delta\omega,\Delta\varphi,\Delta\kappa) \qquad (2)$$

where the indices indicate the *P* (photo or camera), *B* (body, defined by inertial sensor axes) and *L* (local level) coordinate frame. More details on the different coordinate frames and appropriate rotations are given in Cramer, 2001*b*. The attitudes $\tilde{\omega},\tilde{\varphi},\tilde{\kappa}$ are directly obtained from the GPS/inertial navigation angles after transformation to the photogrammetric, e.g. local-level reference coordinate system. $\Delta\omega,\Delta\varphi,\Delta\kappa$ represent the physical misalignment – so-called boresight alignment – between body and camera or photo frame. This unknown attitude offset has to be determined during calibration. The translation offsets are not modelled so far, since they are measured with standard survey methods before the flight missions and already considered during GPS/inertial data integration, normally.

Besides the already mentioned calibration parameters for boresight calibration the functional model is extended by additional parameters to model systematic offsets or linear drifts of directly measured positions and attitudes. Therefore, Equation (1) is modified with following Equation (3):

$$\begin{aligned} \tilde{X}_0 &= X_0 + a_0 + a_1 \cdot t & \tilde{\omega} &= \omega + u_0 + u_1 \cdot t \\ \tilde{Y}_0 &= Y_0 + b_0 + b_1 \cdot t & \tilde{\varphi} &= \varphi + v_0 + v_1 \cdot t \\ \tilde{Z}_0 &= Z_0 + c_0 + c_1 \cdot t & \tilde{\kappa} &= \kappa + w_0 + w_1 \cdot t \end{aligned} \qquad (3)$$

This approach is quite similar to standard GPS-supported aerial triangulation, where additional offset and drift correction terms take care of remaining systematic errors in the GPS determined perspective centre coordinates. Since the attitude offsets in Equation (3) are highly correlated with the boresight alignment as given in Equation (2) the *u₀, v₀, w₀* parameters are also modelling the physical misalignment, which replaces the three attitude offsets in the $\Delta\underline{R}_P^B$ matrix. Since all unknown parameters are re-introduced as pseudo-observations to model the appropriate stochastic properties, the final linearised observation equations are given in Equation (4).

$$\begin{bmatrix} \underline{v} \\ \underline{v}_p \\ \underline{v}_t \\ \underline{v}_a \end{bmatrix} = \begin{bmatrix} \underline{A}_p & \underline{A}_t & \underline{A}_a \\ \underline{I} & \underline{0} & \underline{0} \\ \underline{0} & \underline{I} & \underline{0} \\ \underline{0} & \underline{0} & \underline{I} \end{bmatrix} \cdot \begin{bmatrix} \hat{\underline{x}}_p \\ \hat{\underline{x}}_t \\ \hat{\underline{x}}_a \end{bmatrix} - \begin{bmatrix} \underline{l} \\ \underline{l}_p \\ \underline{l}_t \\ \underline{l}_a \end{bmatrix} \qquad (4)$$

where $\underline{v}, \underline{v}_p, \underline{v}_t, \underline{v}_a$ = residuals at image coordinates and additional unknowns (object point coordinates (index *p*), exterior orientations (index *t*), additional self-calibration parameters (index *a*))

$\underline{A}_p, \underline{A}_t, \underline{A}_a$ = design matrices

$\underline{I}$ = identity matrix

$\underline{\hat{x}}_p, \underline{\hat{x}}_t, \underline{\hat{x}}_a$ = change in estimated unknowns

$\underline{l}, \underline{l}_p, \underline{l}_t, \underline{l}_a$ = reduced observation vectors.

Using an appropriate stochastic model e.g. weights P_t for the different unknown parameters (e.g. EO parameters), this model covers the whole range of photogrammetric applications from direct georeferencing, where GPS/inertial data are used as fixed parameters (high weight $P_t \to \infty$) and object points are obtained from over determined forward intersection, to standard aerial triangulation, where the EO parameters are estimated as unknown parameters ($P_t \to 0$) based on ground control points only.

2.2 Influence of self-calibration parameters

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. In other words, the additional parameters compensate for any remaining systematic inconsistencies between mathematical model and physical reality. 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.

Using additional parameters there are two different approaches for modelling: In the first approach physical relevant parameters like focal length and principle point corrections plus different types of image deformations, like radial, decentering and in-plane distortions are estimated. Such parameter sets as proposed by Brown (1971) are typically used for close-range camera calibration and implemented in commercial close-range photogrammetry packages (e.g. Fraser, 1997). On the other hand, self-calibration in standard aerial triangulation often relies on mathematical polynomial approaches as proposed e.g. by Ebner (1976) and Grün (1978). In contrary to the physical relevant parameters such polynomials are modelling in-plane distortions only, based on the assumption that other effects are negligible due to the strong interior geometry of standard airborne cameras. Furthermore, in standard airborne flight configurations variations in the camera interior orientation parameters cannot be estimated as far as no additional observations for the camera stations provided by GPS or imagery from different flying heights resulting in different image scales are available. The Ebner or Grün polynomial corrections are formulated as orthogonal to each other and with respect to the exterior orientation elements of imagery. This is of particular interest in case of GPS/inertial system calibration due to the strong correlations of GPS/inertial position and boresight alignment offsets to be calibrated with the exterior orientation of imaging sensor. Normally, the two modelling approaches are seen in competition, nonetheless the estimation of physical significant parameters and polynomial coefficients is supplementary and both models can also be used simultaneously, as already pointed out in Brown (1976).

The influence of different additional parameter sets during GPS/inertial-camera calibration is illustrated with the following example from a real flight test. Within this test an integrated GPS/inertial-AT for system calibration based on ground control points and GPS/inertial measurements was performed, where the position offsets and boresight angles were estimated as unknown parameters in addition to additional self-calibration terms using the Ebner and Brown parameter model, respectively. The test data were taken from the calibration block presented in more detail in Section 3. The total influence of the estimated significant self-calibration parameters on image deformations is depicted in Figures 1 and 2. The unit vector is about 10µm and given in the upper left corner of the plots.

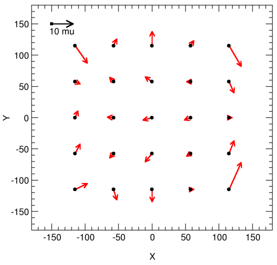

Figure 1. Total deformations (Ebner parameters).

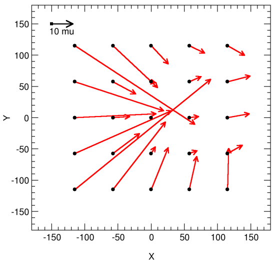

Figure 2. Total deformations (Brown parameters).

As it can be seen from the distortion vector plots in Figures 1 and 2 the estimated total image deformation is significantly different, where the obtained $\hat{\sigma}_0$ from AT is identical. Using Ebner polynomial coefficients the parameters model a sort of barrel-shaped distortions. The image deformation is about 10µm maximum and therefore within the expected average range. In contrary to this, the deformations from the Brown parameter sets seem to be very irregular and significantly larger. They reach maximum distortions about 60µm. Since such large image deformations are highly unlikely for airborne frame cameras the Brown parameters over-compensate for other remaining systematic errors from object space. Due to certain correlations with the exterior orientation and boresight calibration parameters the physical interpretability of estimated Brown parameters is questionable. Self-calibration here partly compensates effects from the boresight parameters. In Table 1 the estimated calibration terms are explicitly given dependent on the chosen additional parameter set. The estimated calibration parameters ΔZ_0 and $\Delta\varphi$ differ significantly, resulting in different object point coordinates when applying this system calibration for direct georeferencing. The choice of appropriate self-calibration models to estimate true physical parameters is of major importance during overall system calibration.

Calibration term		Ebner	Brown
ΔX_0	[m]	-0.110	-0.100
ΔY_0	[m]	eliminated	eliminated
ΔZ_0	[m]	-0.262	-0.343
$\Delta\omega$	[gon]	0.4573	0.4598
$\Delta\varphi$	[gon]	0.0668	0.0538
$\Delta\kappa$	[gon]	-0.2897	-0.2907

Table 1. Estimated system calibration parameters.

3. TEST FLIGHT CONFIGURATION

The presented data from different calibration flights are 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, whose IMU was rigidly mounted at the camera body. 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. This 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). These wide-angle flights are non considered in more detail in the following.

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. The pre-surveyed translation offsets 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.

4. TEST RESULTS

Based on the integrated GPS/inertial-AT described in Section 2 the calibration of system parameters was done for each calibration flight based on 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. This empirical accuracy should be expected from such high quality integrated GPS/inertial system if its accuracy potential is fully exploited.

Within system calibration the inevitable angle offset and position shifts (if significantly present) are estimated in combination with the Ebner self-calibration parameters. In order to separate between global and strip-dependent shift parameters, the two flight lines per flight day were considered as one calibration block. Since the automatic AT was done for the different flight lines separately, the two strips are tied together only via the identical GCPs. For two of the normal-angle flight days only one complete calibration strip was flown due to weather conditions. These non-complete calibration flights are not considered in the further processing. Overall, eight complete calibration flight days are available for the GPS/inertial normal-angle camera configuration.

4.1 Quality of GPS/inertial exterior orientations

As one first result the directly measured exterior orientations from GPS/inertial are compared to the estimated values from AT. The remaining differences serve as first indication of the quality of GPS/inertial position and attitude determination. In Figures 3-6 the particular position and attitude differences are shown for the distinct camera stations from four representative calibration flight lines handled as two calibration blocks flown on January 29th and February 18th. The statistical analysis from all considered normal-angle calibration flight blocks is given in Tables 2 and 3, respectively.

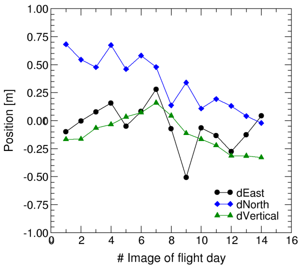

Figure 3. Position variations (Flights 1+2, Jan 29).

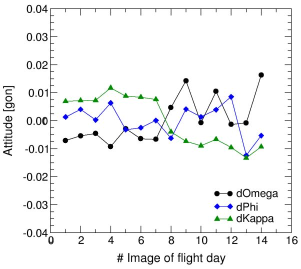

Figure 4. Attitude variations (Flights 1+2, Jan 29).

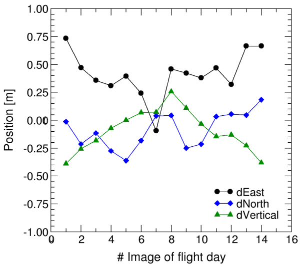

Figure 5. Position variations (Flights 10+11, Feb 18).

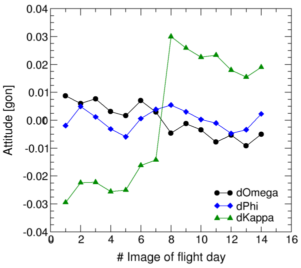

Figure 6. Attitude variations (Flights 10+11, Feb 18).

As it can be seen from Table 2 the variations (STD) in the GPS/inertial positions are quite consistent and mostly in the range of 2dm which coincides with the typical GPS positioning performance after differential phase processing. Nevertheless, significant offsets or even drift effects are present, which can be clearly seen from Figures 3 and 4. Additional systematic errors are seen in attitude determination (Table 3). Although the mean variation in ω– and φ–angle is within the 15" level for the presented normal angle flights, the differences in κ show larger systematic effects for some calibration blocks resulting in large STD values >0.01gon (>30"). As illustrated in Figure 6 for the calibration block flown on February 18th the κ–angle shows a clear strip dependent systematic offset, which might be due to non optimal system alignment or insufficiently damping of inherent inertial error behaviour during GPS/inertial data processing. Errors in the estimated gyro scale factor will result in such a jump between two flight lines with opposite flight directions. Any uncompensated error will deteriorate the quality of object point determination after direct georeferencing.

Former airborne tests using the AEROcontrol IId system have shown consistently higher quality results indicating that for some of the mission days the accuracy potential is not fully reached with the GPS/inertial data investigated so far. This fact reconfirms the high demands for careful processing of GPS/inertial data and well defined test flight conditions especially when data are used in system calibration and for later production projects.

Day	#Flight	STD ΔX_0 [m]	STD ΔY_0 [m]	STD ΔZ_0 [m]
Jan 29	1+2	0.183	0.233	0.148
Jan 31	5+6	0.151	0.357	0.077
Feb 05	8+9	0.274	0.252	0.103
Feb 18	10+11	0.197	0.156	0.118
Feb 19	12+13	0.090	0.130	0.050
Feb 21	14+15	0.226	0.199	0.135
Feb 24	16+17	0.223	0.123	0.184
Mar 12	18+19	0.136	0.183	0.122
	Mean	*0.185*	*0.204*	*0.117*

Table 2. Variation of GPS/inertial positions.

Day	#Flight	STD $\Delta\omega$ [gon]	STD $\Delta\varphi$ [gon]	STD $\Delta\kappa$ [gon]
Jan 29	1+2	0.0079	0.0053	0.0086
Jan 31	5+6	0.0066	0.0079	0.0053
Feb 05	8+9	0.0021	0.0066	0.0109
Feb 18	10+11	0.0058	0.0034	0.0226
Feb 19	12+13	0.0052	0.0051	0.0439
Feb 21	14+15	0.0029	0.0061	0.0052
Feb 24	16+17	0.0029	0.0059	0.0069
Mar 12	18+19	0.0051	0.0051	0.0076
	Mean	*0.0048*	*0.0057*	*0.0139*

Table 3. Variation of GPS/inertial attitudes.

4.2 Stability of boresight alignment

Within the following subsection the results from long term stability analysis of estimated system calibration parameters are presented. As already mentioned the parameters are derived from an GPS/inertial-AT where constant position and boresight angle offsets are estimated together with self-calibration terms based on Ebner polynomial coefficients.

For all investigated flights the influence of self-calibration shows similar behaviour with a slight cushion effect in flight direction, potentially caused by film transportation or film shrinking. For some mission days an additional shear component is present indicating the variation of influences of additional self-calibration. As it is known from the beginning of self-calibrating bundle adjustment the a priori estimation of image distortion parameters is difficult. Hence, uncorrected effects have to be taken into account in direct georeferencing.

According to the estimated positioning offsets, vertical shifts are present for almost all flight days, where the amount of vertical offset correction (if significantly present) is not constant but shows day-to-day variations between 12–40cm for the different calibration flight days. For horizontal components smaller offset corrections between 10–20cm are estimated for approximately 50% of the flights. 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. In general, it seems to be reasonable to correct for mean vertical offset. Anyway, day-to-day variations have to be taken into account and will deteriorate the quality of direct georeferencing in case position offset calibration is not refined for each mission flight.

Nonetheless, during system calibration the main focus is laid on the quality and stability of boresight alignment estimation, since this effect 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. The question is, whether the estimated boresight misalignment remains constant for a longer time period? This open task should be answered from flight data material presented here.

Table 4 shows the distinct estimated boresight alignment angles from the 8 normal-angle system installations, where in Figure 7 the variations from the mean estimated boresight angle are depicted for normal-angle flight days.

#	Day	#Flight	$\Delta\omega$ [gon]	$\Delta\varphi$ [gon]	$\Delta\kappa$ [gon]
1	Jan 29	1+2	0.4851	0.0702	-0.1349
2	Jan 31	5+6	0.4805	0.0656	-0.1278
3	Feb 05	8+9	0.4882	0.0607	-0.1124
4	Feb 18	10+11	0.4880	0.0617	-0.1431
5	Feb 19	12+13	0.4782	0.0689	-0.1207
6	Feb 21	14+15	0.4901	0.0563	-0.1289
7	Feb 24	16+17	0.4870	0.0629	-0.1328
8	Mar 12	18+19	0.4900	0.0557	-0.1348
		Mean	*0.4859*	*0.0628*	*-0.1294*
		STD	*0.0041*	*0.0049*	*0.0088*

Table 4. Estimated boresight alignment angles.

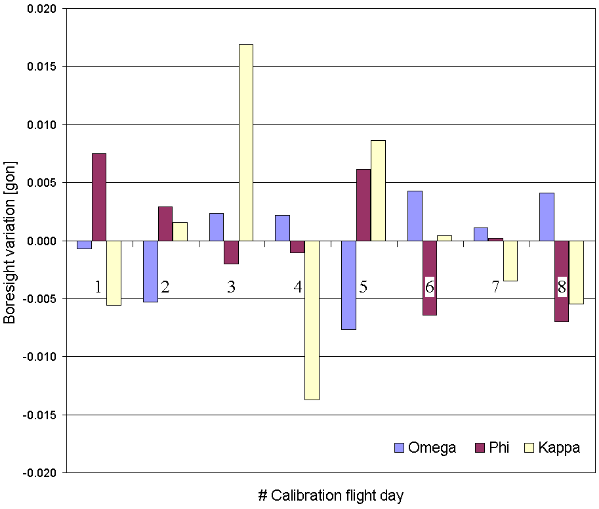

Figure 7. Variation of estimated boresight angles.

At a glance the results from analysis of the stability of boresight alignment seems to be worse especially in κ. The variation of the mean κ–boresight angle about 0.009gon (30”) cannot be accepted for high performance requirements. The question is, whether these estimated variations truly represent the physical misorientation changes between the inertial measurement unit and the camera coordinate frame over the 2 months time period? Fortunately the answer is no, since the results given in Table 4 and Figure 7 are strongly influenced from remaining errors in the GPS/inertial attitude determination. This can be seen clearly from the 3rd–5th calibration flight day, where the large variations in κ–angle coincide with the high RMS values from Table 3. 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 from boresight calibration, the variations (STD) of mean estimated boresight angles are well within the noise level of GPS/inertial attitude determination: $\sigma_{\Delta\omega}$=0.0035gon (11”), $\sigma_{\Delta\varphi}$=0.0055gon (18”), $\sigma_{\Delta\kappa}$=0.0029gon (9”). This variation values indicate a quite high 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.

4.3 DG based on long term boresight angle calibration

Within the preceding sub-section the stability of boresight alignment parameters and self-calibration terms was analysed and certain variations in some parameters have been seen. In order to simulate the later practical use of direct georeferencing, where the calibration parameters from system calibration should be used for several mission flights ideally, the long term quality of system alignment is checked using the 21 available control points as independent check points for overall quality checking. Only the mean boresight calibration is applied since position offsets as well as influence from self-calibration are varying and cannot be corrected in advance. The performance analysis from check point differences from over-determined forward intersection is given in Table 5.

Day	#Flight	RMS ΔX [m]	RMS ΔY [m]	RMS ΔZ [m]
Jan 29	1+2	0.174	0.091	0.536
Jan 31	5+6	0.211	0.066	0.575
Feb 05	8+9	0.194	0.112	0.385
Feb 18	10+11	0.076	0.170	0.365
Feb 19	12+13	0.184	0.167	0.380
Feb 21	14+15	0.072	0.078	0.270
Feb 24	16+17	0.073	0.077	0.463
Mar 12	18+19	0.088	0.094	0.436
	Mean	*0.134*	*0.106*	*0.426*

Table 5. Quality of DG based on long term calibration.

As to be expected, the maximum deviations are present in vertical component and raise to values up to 50cm, the mean RMS is about 4dm. In horizontal component the differences are within 2dm maximum, the mean RMS is about 12cm. Comparing these numbers to the values obtained from direct georeferencing with optimal system alignment, the accuracy is significantly worse, which shows the influence of non-optimal overall system alignment mainly due to remaining global position offsets. Nevertheless, such global errors can be easily overcome if integrated sensor orientation with minimal number of GCPs is applied.

5. CONCLUSIONS

The results presented above have reconfirmed that GPS/inertial data integration and overall system calibration is the most critical factor during direct georeferencing. Besides the need for consistently high GPS/inertial positioning and attitude quality, which has to be guaranteed throughout the whole mission duration, the estimation of physical relevant and correct calibration parameters is the crucial task during system calibration. Especially the correlations appearing between different parameters used in calibration are eminent since they compensate the impact from other physical effects, which might cause trouble when the calibration is transferred to the mission site. System calibration is "the" challenging task, where the silver bullet for the most efficient calibration procedure is – unfortunately – not found yet.

Nonetheless, results from this real flight test underline the highly operational use of GPS/inertial components for direct georeferencing. The exclusive correction of mean boresight angles is sufficient for object point accuracy within 4-5dm (RMS) if strong image overlap, i.e. block geometry is given. No AT process (except for calibration) is necessary to reach this quality. The boresight angles remain constant within a certain interval and can be used for longer time periods. Although the overall quality is less compared to the well controlled GPS/inertial accuracy tests, the results are quite remarkable for the first long term test in true production environment.

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