Practical results of GPS/IMU/camera system calibration

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Abstract
This article summarizes the results of eleven system calibrations of four GPS/IMU/optics combinations performed in 2002. In addition to the boresight parameters, the interior orientation parameters appeared to be significant calibration quantities. In the direction perpendicular to the flying direction 20-40 µm systematic errors were present with all the optics. With one of the optics significant focal length correction of 25-45 µm was detected. Stability of boresight and interior orientation parameters was evaluated. In boresight parameters, the maximum long-term changes were 20 mgon and the short-term changes were less than 6 mgon; 6 mgon differences appeared even between calibrations made during a single day. Changes of the interior orientation parameters were quite large, but the use of the most significant corrections in y0 and focal length appeared to be advantageous; the variability of the calibration scales affected the analysis. The quality of the attitude observations was on the range given by the system vendors. However, offsets and drifts appeared in the attitude observations; these inaccuracies can be one reason for the detected instability of the boresight parameters. In the best block the precision of the GPS/IMU position observations was better than 10 cm; the accuracy analysis of other blocks was clearly affected by the poor quality of the reference observations. Small stripwise offsets were detected also in the position observations.

1. Introduction

The systems for the direct determination of exterior orientations of airborne images are becoming common. The orientations are determined by integrating GPS (Global Positioning System) and IMU (Inertial Measurement Unit) observations made during the mapping flight; two most significant systems commercially available are the Applanix POS/AV 510 DG [7] and IGI AEROcontrol IId [6]. According to the system vendors the accuracy of the direct position observations is better than 0.1 m and the accuracy of the direct attitude observations is better than 0.005˚ in ω and φ and better than 0.008˚ in κ. Recent empirical investigations have proved the good performance of the systems [1, 3].

There exist many problems hindering the efficient application of the direct georeferencing [2, 4, 5]. The requirements of accurate GPS processing – e.g. close base station and good satellite constellations – are not always easy to fulfil. Several questions – for instance, the stability, the necessary parameters and the efficient calibration procedures – concern the calibration of the systems. Questions also concern the optimal and reliable quality control of the GPS/IMU observations; e.g. the thorough procedure suggested in [8] can be efficiently applied only if implemented properly to the photogrammetric processing environment. In the applications with quite high quality requirements – e.g. better than 2 m geometric accuracy – the accuracy of the datum transformation can be the crucial factor. Results from practical tests are needed to finally prove the performance of the systems. Due to the many questions and uncertainties, the general guideline at the moment is to apply the direct georeferencing only in low accuracy applications, like in orthophoto production [3]. In the applications with higher quality requirements the integrated sensor orientation should be performed.

So far the only extensive results of long-term stability analysis of the systems have been reported in [2]. Long-term stability was evaluated by determining the system calibration 8 times during almost 2 months time period. The standard deviations of the boresight parameters of five calibrations were 3.5, 5.5 and 2.9 mgon for $d\omega$, $d\varphi$ and $d\kappa$, respectively; 3 calibrations were considered as outliers. The authors considered the stability to be sufficient. Other results of system calibration are given in [1, 3, 9]; the results have indicated that besides the boresight parameters also at least the camera interior orientation parameters are necessary calibration quantities.

The objective of this article is to present practical results of GPS/IMU system calibration. The analysis of 11 calibration blocks photographed in 2002 by the National Land Survey of Finland (NLS) over the calibration fields of Finnish Geodetic Institute (FGI) using 2 Applanix POSAV™ 510 systems and 4 GPS/IMU/optics combinations are reported in the following chapters. In Chapter 2 the materials and methods are described. The results are given in Chapter 3 and discussed in Chapter 4.

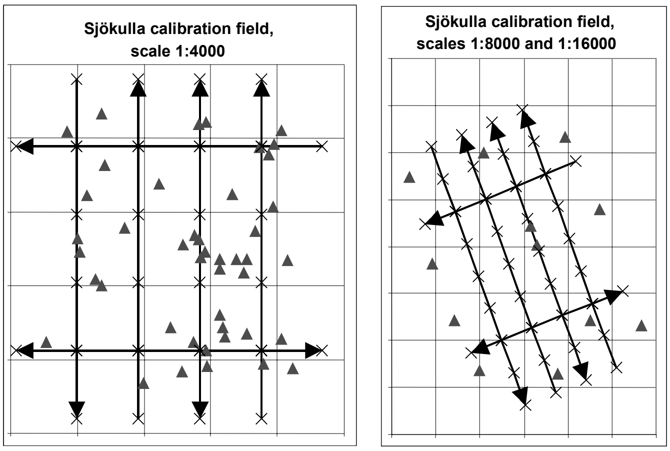

Figure 1. Sjökulla calibration fields: large-scale 1:4000 and medium-scale 1:8000/1:16000. The size of the large-scale calibration field is 1 km x 1 km and it has 43 GCPs (ground control points), with 1 cm planimetric and 2 cm height accuracy, targeted with circular targets with 30 and 40 cm diameter. Size of the medium-scale calibration field is 4 km x 5 km and it has 12 GCPs, with 1.5 cm planimetric and 3 cm height accuracy, targeted with 1 m x 1 m square targets. The calibration blocks consisted of four parallel flight lines and two crossing flight lines, with one parallel and one crossing flight line flown twice in opposite directions.

Table 1. Calibration flights of NLS. The block structures and the GCP distributions are shown in Figure 1.

Date	Block	Optics			
		Plane: OH-CGW		Plane: OH-ACN	
		13026, f=153.300	7163, f=214.066	13153, f=153.030	7183, f=214.108
24.4.2002	2119				1:16 000
	2120				1:8 000
25.4.2002	2121			1:8 000	
	2122			1:4 000	
26.4.2002	2124				1:8 000
3.5.2002	2128	1:8 000			
4.5.2002	2129		1:16 000		
14.7.2002	2134	1:16 000			
15.7.2002	2135		1:16 000		
3.9.2002	2137				1:16 000
4.9.2002	2136			1:16 000	

2. Materials and methods

2.1. Calibration blocks

NLS is operating two aircrafts, both having RC20 cameras with exchangeable wide and normal angle optics. OH-ACN is Rockwell Turbo Commander 690A turbo twin propeller aircraft with a pressurised cabin; OH-CGW is Cessna 401B piston twin propeller aircraft with an unpressurised cabin. The aircrafts were equipped in the spring 2002 with Applanix POSAV^{TM} 510 systems with Litton LN-200 IMU. The calibration task consists of the calibration of all four GPS/IMU/optics-combinations.

In the empirical investigation 11 calibration blocks photographed by NLS in summer 2002 over the Sjökulla calibration fields of FGI were used; the details of the blocks are given in Table 1. The Sjökulla calibration fields can be used for large-scale (1:3000-1:4000) and medium-scale (1:6000 - 1:16000) calibration; the applied block structures are given in Figure 1. One of the calibrations was made in scale 1:4000 in the large-scale calibration field (block 2122), and the rest of the calibrations were made in scales 1:8000 and 1:16000 in the medium-scale calibration field. The optics were exchanged between various calibrations. The GPS base station was located in 30 km distance from the calibration field.

NLS performed all the preprocessing of the data. The GPS/IMU-processing was performed with PosPac software (V. 4.02). The photographs were scanned with 20 µm pixel size by using the LH-Systems DSW500 scanner. Image measurements were made with LH-Systems SocetSet; tie points were measured by APM. Preliminary block adjustments and the elimination of the gross errors were made using the Orima software.

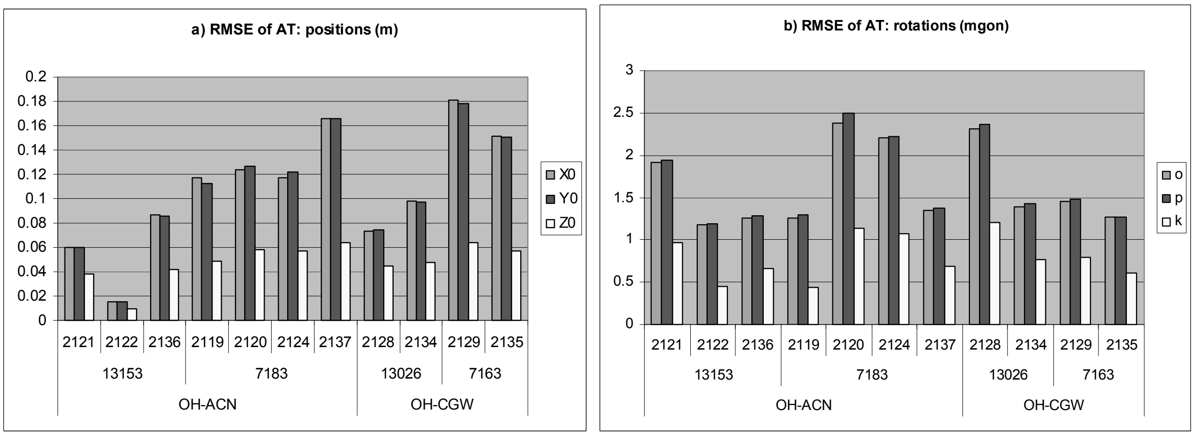

Figure 2. Theoretical RMSE of reference values estimated in AT: a) positions and b) rotations.

2.2. Block adjustment

The calibrations were determined using three different software: FGI used FGIAT software developed at FGI and inBlock software of Inpho Gmbh (V. 1.0.0); NLS used ORIMA software of LH-systems. All the software determine the calibration parameters in a rigorous combined adjustment.

Adjustments were performed in the local tangential coordinate system. At FGI the GPS/IMU observations were transformed directly from ECEF to the local tangential system; at NLS the observations in ECEF were first transformed to the Finnish national grid coordinate system (kkj) and orthometric heights, which were later transformed to the local tangential coordinates internally in ORIMA. The refraction correction was applied to the image observations.

The possible unknowns in the GPS/IMU/camera system calibration were

1. boresight misalignments (dω, dφ, dκ),
2. constant GPS/IMU position shifts (dX, dY, dZ; e.g. caused by wrong initialization of the ambiguities; either stripwise or blockwise),
3. flying direction dependent corrections
   a) GPS/IMU position errors (dX, dY, dZ; e.g. lever arm or timing difference of the sensors),
   b) interior orientations (x0, y0, c),
4. other image deformations (e.g. Ebner's parameters, radial and tangential distortions, affinity) and
5. global datum parameters for GPS/IMU position observations (e.g. a full or a partial 7-parameter similarity transformation).

Because all of the above parameters cannot be determined simultaneously, in the final calibrations the following parameter combinations were used:

– boresight, corrections for interior orientations, 12 Ebner's parameters (FGI),
– boresight, corrections for interior orientations, radial distortion, global shift in X and Y directions (NLS) and
– boresight, datum (7-parameter similarity transformation or global offset), principal point and Ebner's parameters (FGI).

The two flying direction dependent errors (3a from 3b) and height errors (focal length correction from dZ in 2, 3a and 5) could be separated only in one block flown in two scales. In addition the stripwise drift parameters were used to model the GPS/IMU position errors, but they led to the same boresight parameters as the above models.

2.3. Analysis

The analysis concerned the following items:

– Quality of direct attitude observations. The observed attitudes were corrected by using the boresight angles estimated for each block in the GPS/IMU supported aerial triangulation (AT). Reference values were obtained from the block adjustment with GPS/IMU position observations. The theoretical mean errors (the root mean square values (RMSE) of the standard deviations obtained from the inverted normal equation matrix) of the reference attitudes are shown in Figure 2b; the RMSEs were 1.2-2.5 mgon for ω and φ and 0.4-1.2 mgon for κ. The use of the boresight values results in some correlation between the observations and the reference values. Nevertheless, it can be assumed that the quality of the reference attitudes is good enough for the evaluation.

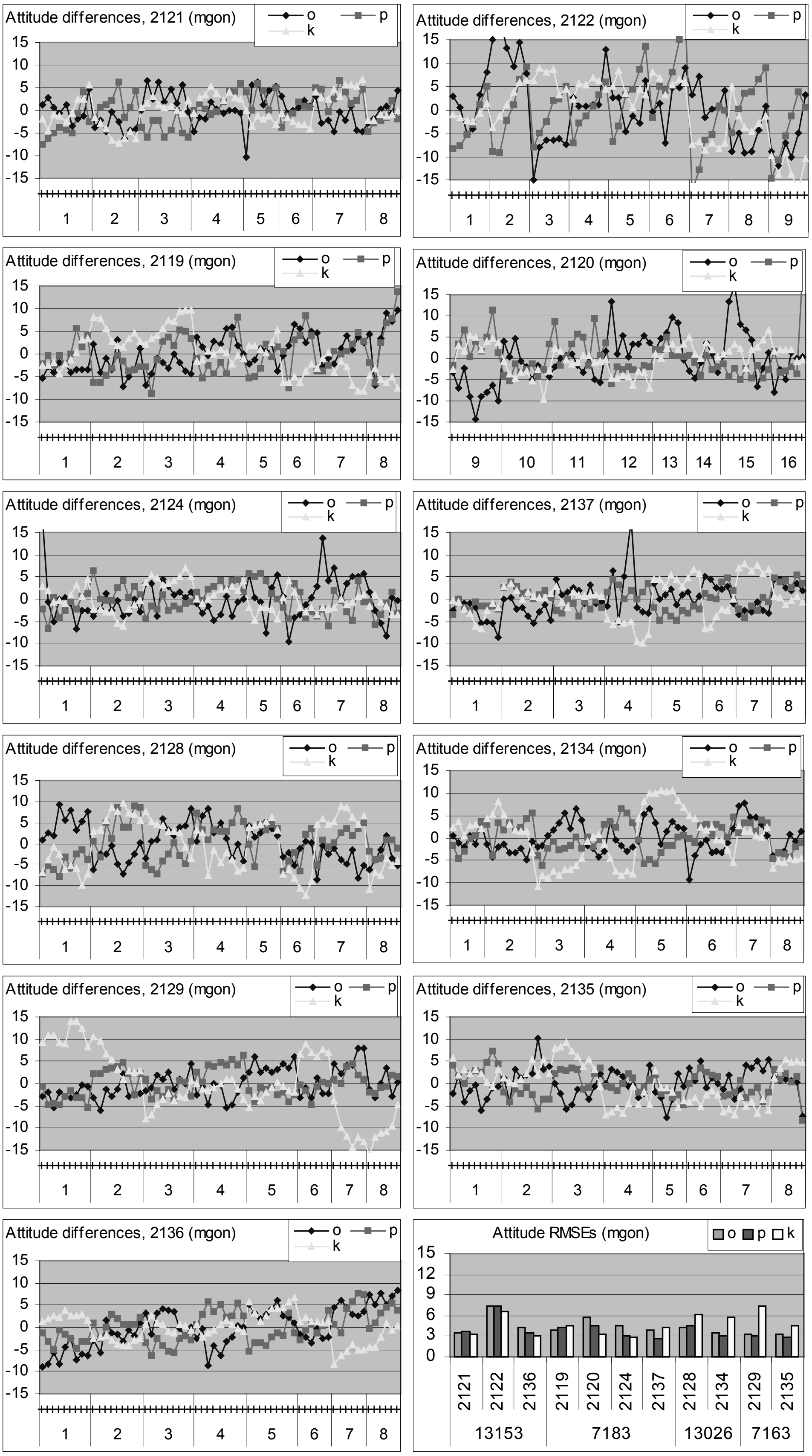

Figure 3. Differences of attitude observations and reference values in mgon (milli gone) for various blocks (o=ω, p=φ, k=κ); the strip numbers and images are shown below the graphs. The RMSEs are given in the last graph.

– Quality of direct position observations. The reference values for the evaluation of the GPS/IMU position observations were obtained from the block adjustment without exterior orientation observations. The theoretical mean errors are shown in Figure 2a. The error decreases when scale decreases and when the wide-angle optics is used instead of normal-angle optics. The error estimates are also affected by the standard error of unit weight and the number of tie point observations. The accuracy is the best in the block 2122 due to the large scale and the large number of GCPs (0.015 m in X0 and Y0, 0.01 m in Z0). The accuracy of Z0 is always better than 0.1 m and the accuracy of X0 and Y0 is also better than 0.1 m in the blocks photographed by wide-angle optics. In the blocks photographed with normal-angle optics the precision of X0 and Y0 was 0.12-0.18 m.
– Boresight and interior orientation parameters: evaluation of the importance and standard deviations of the parameters and comparison of results of various software (FGIAT, InBlock, Orima).
– Evaluation of the stability of the boresight and interior orientation parameters. Differences of the various calibrations were calculated and grouped based on the time differences between the calibrations (within 1 day, 2 days, 4 months, 2 months). Alteration within 0-2 days time period indicates short-term stability and the changes occurred within 2 and 4 months time period represent long-term stability.
– Accuracy of the direct georeferencing. Quality of direct georeferencing was evaluated by back-projecting the GCP ground observations to the images by using the direct exterior orientation observations, and then comparing the calculated values to the measured values. The following corrections were applied: a) the boresight correction estimated for the block, b) the interior orientation, datum and boresight corrections estimated for the block and c) interior orientation and boresight corrections estimated from the first calibration of the optics. In two first cases the same GCPs were used in the determination of the parameters and in the quality control, which should be taken into account in the evaluation of the results.

3. Results

3.1. Quality of GPS/IMU attitude observations

The differences of the observed and the reference attitudes and their RMSEs are shown in Figure 3. The RMSEs were in accordance with the vendors specifications, excluding ω and φ of block 2122 and ω of block 2120. There appeared a data gap in the IMU observations in the beginning of the flight 2122, which could be the reason for the poor results of the block 2122. The average RMSEs were 4, 3 and 4 mgon for ω, φ and κ, respectively.

The differences given in Figure 3 indicate offsets between strips and linear drifts; similar phenomena were also apparent in the residuals after the calibration calculations. Drifts are especially significant in the block 2122, and drifts can be detected in most of the blocks especially in φ and κ observations. Quite large offsets (>10 mgon) between strips are present, for instance, in the blocks 2122 and 2128, and smaller offsets can be detected in most of the blocks. The most feasible explanation for these errors is inaccuracy of the GPS/IMU processing.

3.2. Quality of GPS/IMU position observations

The analysis of the GPS/IMU position observations indicated both global datum errors and systematic flying direction dependent errors. The flying direction dependent errors are analysed in Chapter 3.4. The estimated global shift parameters are shown in Figure 4; the position shifts are typically about 0.1 m and they are at least partially caused by some datum difference between the GCPs and the direct position observations. The large height shifts of optics 7183 are caused by an error in the focal length.

RMSEs of the original GPS/IMU position observations are shown in Figure 5a. RMSEs were quite large; the maximum values were about 0.6 m. The Z0 accuracy was 0.05-0.18 m, excluding the optics 7183 having large height corrections. The main reason for the poor accuracies in X0 and Y0 was the systematic flying direction dependent error.

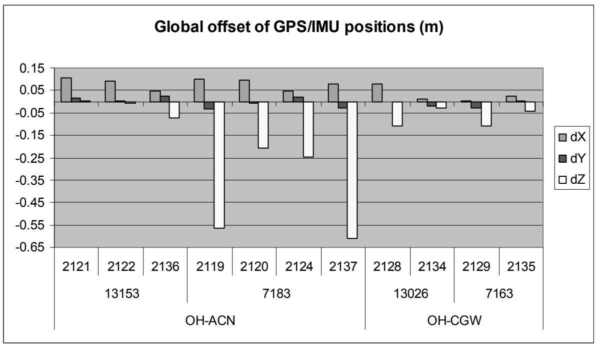

Figure 4. Global offset parameters estimated for the GPS/IMU position observations.

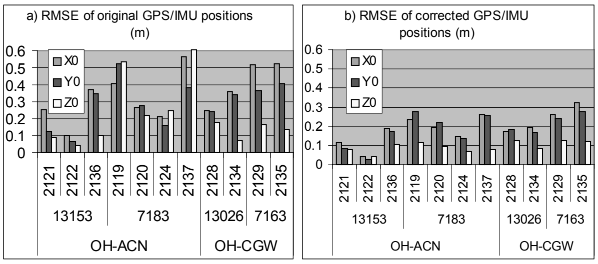

Figure 5. a) Accuracy of original GPS/IMU positions and b) accuracy of the corrected (datum, flying direction dependent error) GPS/IMU positions.

The systematic errors (flying direction dependent error and datum) were determined for each block and eliminated from the GPS/IMU position observations. The results of the comparison of the corrected observations and the reference values are shown in Figure 5b. After the corrections the RMSEs were 0.05 m – 0.3 m in X0 and Y0 and about 0.1 m or less in Z0. The accuracy of X0 and Y0 observations was in most of the cases worse than could be expected, but presumably the poor quality of the reference observations had influence on the results.

The effect of scale can be detected by comparing two cases with blocks flown in the same day (blocks 2121 and 2122 and blocks 2119 and 2120). In both cases the accuracy is better in the larger scale, which indicates the better accuracy of reference values.

The best results were obtained with the block 2122, which is a 1:4000 scale block photographed using the wide-angle optics. The RMSEs were before the corrections 0.10 m, 0.06 m and 0.04 m (X0, Y0 and Z0) and after the corrections less than 0.04 m in all three coordinates.

The blocks with scales 1:4000 and 1:8000 were analysed further. The differences of the corrected position observations (flying direction dependent error and datum) and the reference values are shown in Figure 6; the RMSEs are given in the last graph (the first and the last images of each strip are not included in RMSEs). In the

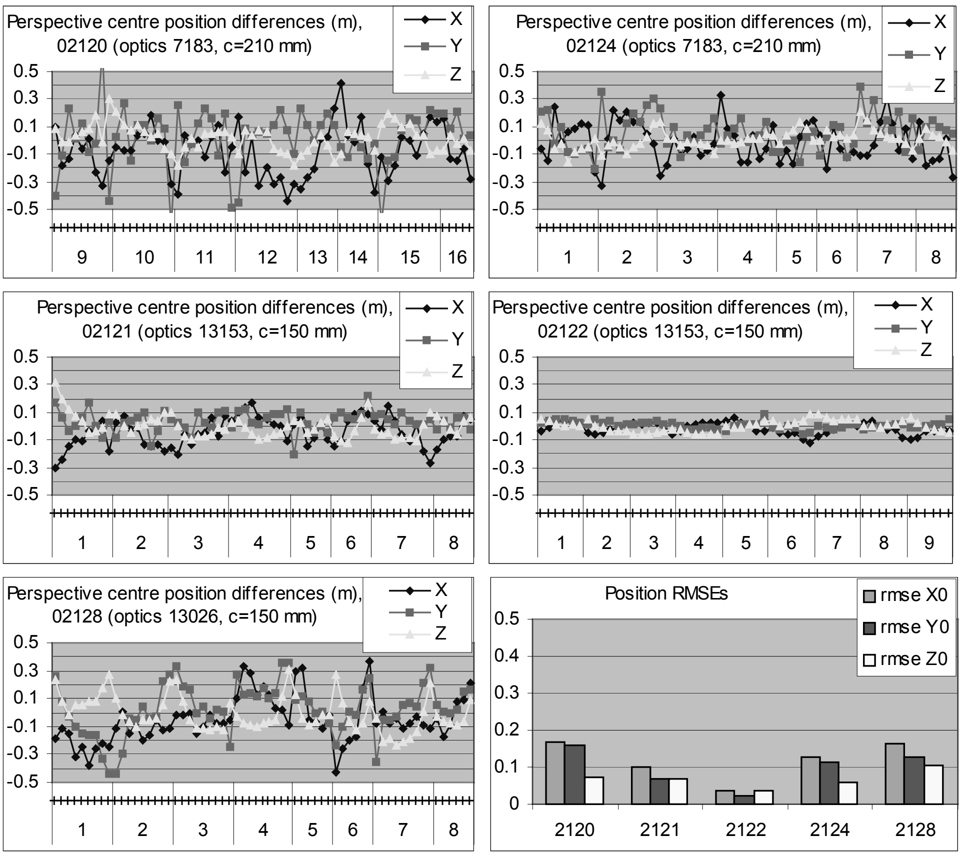

Figure 6. Differences between corrected GPS/IMU position observations (flying direction dependent error, datum) and reference values for 1:4000 and 1:8000 scale calibration blocks; strip numbers and images are shown below the graphs. RMS values of differences are shown in the last graph; the first and the last images of the strips are not included to the RMSE calculation.

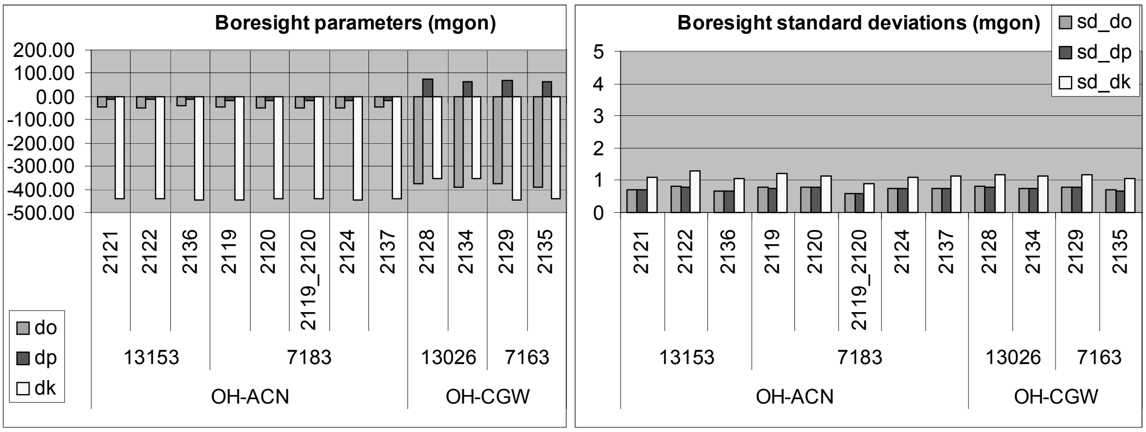

Figure 7. Boresight parameters and estimated standard deviations given by FGIAT software.

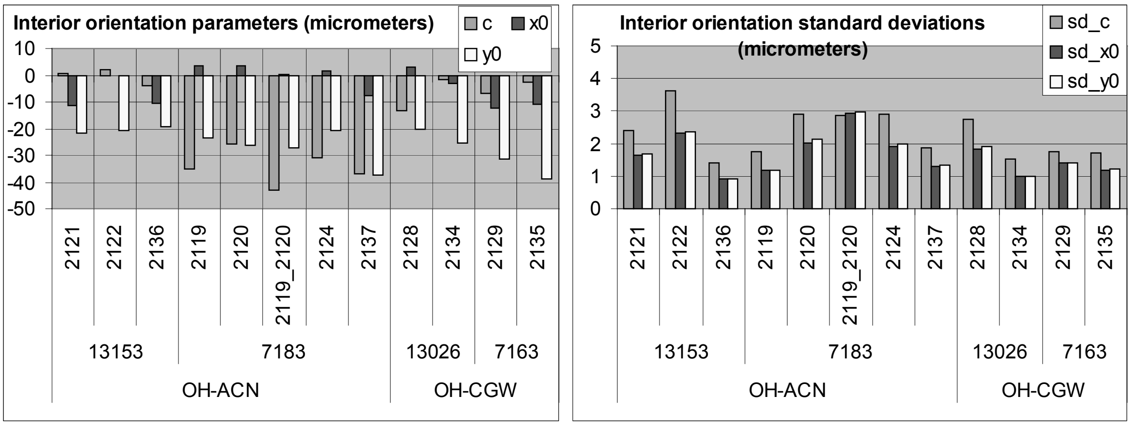

Figure 8. Corrections for interior orientation parameters and estimated standard deviations given by FGIAT software.

block 2122 (scale 1:4000, large-scale calibration) the differences were mostly below 0.1 m; with the other blocks the maximum differences were in general 0.3-0.5 m in X0 and Y0 and less than 0.2 m in Z0. Stripwise shifts and drifts could be detected from the difference plots; these can arise from the systematic errors of the reference values and from the GPS/IMU position observations. Stripwise offsets were evaluated by block adjustment after applying the flying direction error and datum corrections to the position observations. Offsets were in general less than 0.1 m; maximal offsets of 0.1-0.2 m appeared in blocks 2119, 2124, 2129 and 2134, in block 2135 appeared a 0.3 m offset in one strip.

3.3. Borsight parameters

Boresight parameters and their precisions, given by the FGIAT software, are shown in Figure 7. The estimated standard deviations are in average 0.8 mgon in $d\omega$ and $d\varphi$ and 1.2 mgon in $d\kappa$. The analysis of the residuals of attitude observations after the adjustment revealed similar stripwise offsets and drifts as the quality analysis of attitude observation in Chapter 3.1.

3.4. Interior orientation parameters

Corrections for the interior orientation parameters and their standard deviations, given by the FGIAT software, are shown in Figure 8. It should be noticed that these corrections model the systematic errors of both interior orientations and position observations (Chapter 2.2). It can be seen that there was a significant correction of size 20 – 40 µm in direction perpendicular to the flying direction with every optics (y0). With optics 7183 there was a significant correction in height (25-43 µm); with the other optics the height correction was mostly less than 5 µm. Based on the analysis and the NLS experiences, the major reason for these corrections is the change of the interior orientation in the flying conditions.

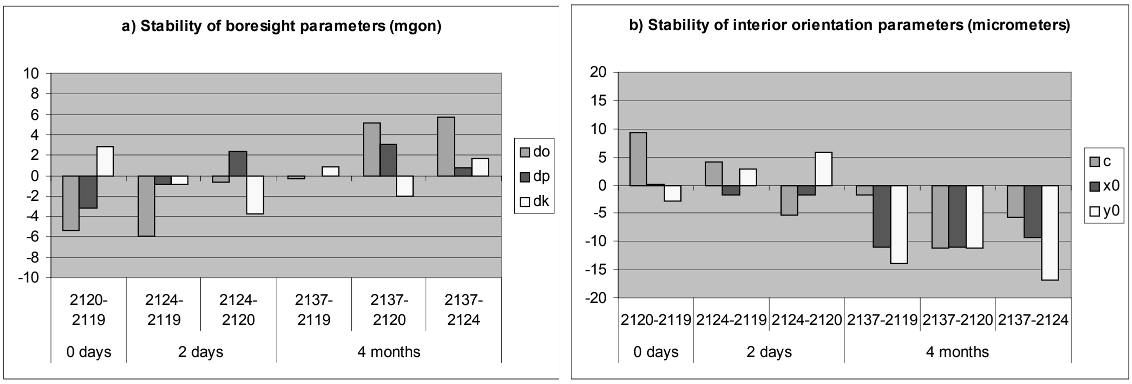

Figure 9. Stability of optics 7183: a) boresight parameters and b) interior orientation parameters.

3.5. Stability

The different scales of the calibration blocks affected especially the analysis of interior orientation, because of the scale dependent phenomena (predominantly different physical conditions in different flying altitudes and the systematic GPS/IMU position errors having different effect in different scales).

Stability of the boresight parameters of optics 7183 is shown in Figure 9a. A general finding was that the changes were the largest in dω and usually the smallest in dφ. Differences of the various calibrations were less than 6 mgon; 6 mgon differences appeared even between the calibrations of blocks 2119 and 2120 photographed consecutively. The short-term results of the other optics were similar. In longer time intervals larger changes occurred with the other optics; e.g. in the two optics of OH-CGW almost 20 mgon change in dω did take place during the summer (Figure 7a). One explanation to the short-term instability is the detected stripwise offsets and drifts of attitude observations. One reason for the long-term instabilities was undoubtedly the exchanges of the optics.

Results of the stability analysis of interior orientation parameters of the block 7183 are shown in Figure 9b. The most representative results are the comparisons between blocks 2124 and 2120 and between blocks 2137 and 2119, having the same scales. The differences of the blocks 2137 and 2119 were the largest, rising up to 15 µm in y0. The differences were about 5 µm or less between blocks 2124 and 2120. From Figure 8 it can be seen that even though the various solutions are quite different, the use of the improved values for c in optics 7183 and for y0 in all the optics would be advantageous in direct georeferencing.

3.6. Combined calibration of two scales

Table 2. Lever arm and interior orientation corrections obtained from the combined adjustment of two scales.

Software	Parameter	Value			Standard deviation		
FGIAT	Lever arm	dX	dY	dZ	dX	dY	dZ
	(m)	0.04	0.06	0.14	0.04	0.04	0.04
	Interior orientation	x0	y0	c	x0	y0	c
	(µm)	0.4	-27.3	-43.3	2.9	3.0	2.9

The blocks 2119 (scale 1:16000) and 2120 (scale 1:8000) were adjusted simultaneously in a single adjustment in order to separate interior orientation corrections from the flying direction dependent and height corrections of GPS/IMU observations. The parameters given by FGIAT software are shown in Table 2. Effect of scale was already apparent in Figure 8 in the focal length correction; the correction for the GPS/IMU heights resulted in different effect in two scales. The results address that the interior orientation is the major source of the flying direction dependent and height errors.

The analysis of the correlations in the combined adjustments made by NLS revealed correlations in the height parameters (perspective centre, focal length, global dZ), thus the parameters are not probably completely reliable. In the lever arm estimation of the PosPac software the estimated lever arms have been a few centimetres, thus the lever arm parameters, estimated by FGIAT, are slightly larger than the PosPac estimates.

3.7. Differences of various software

The parameters obtained from three different software were compared. The calculation of FGIAT and inBlock were made using the same parameters (boresight, interior orientation, Ebner’s parameters), weighting and object

Table 3. Differences of boresight and interior orientation parameters obtained by three different software (RMSE and maximum differences of 11 calibration blocks). Calibration parameters were in FGIAT and inBlock boresight, interior orientation and Ebner's parameters and in Orima boresight, interior orientation, radial distortion and global X and Y shifts.

Comparison	Boresight parameters						Interior orientation parameters					
	RMSE (mgon			(mgon)			RMSE (μm)			(μm)		
	dω	dφ	dκ	dω	dφ	dκ	dc	dx0	dy0	dc	dx0	dy0
FGIAT-Inblock	0.27	0.15	0.2	0.71	0.31	0.48	1.6	1.2	1.5	3.4	3.3	2.9
FGIAT-Orima	1.29	2.46	0.34	2.64	5.14	0.69	11.2	3.2	5.4	25.36	6.3	9.2

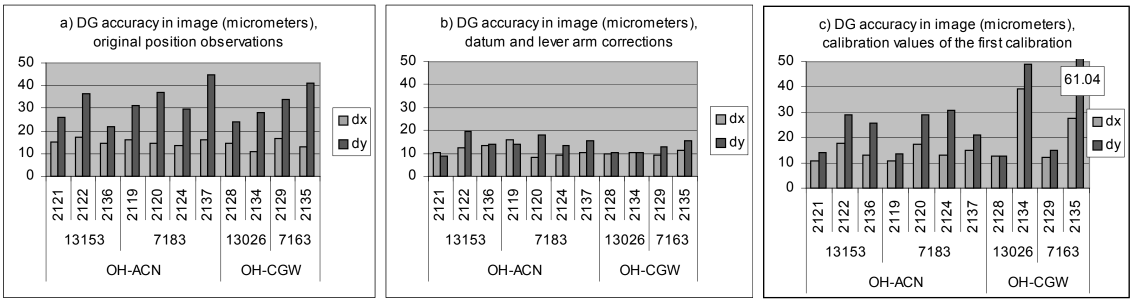

Figure 10. Accuracy of backprojection of the GCPs (RMSE). Corrections applied: a) boresight correction estimated for the block, b) interior orientation, datum and boresight corrections estimated for the block and c) boresight and interior orientation corrections estimated for the first calibration flight of each optics.

coordinates, thus the possible differences should result in from differences in modelling. The processing in Orima was quite different: parameters were boresight, interior orientation, radial distortion and global shift in X and Y directions, the weighting were different and the object coordinate system was different.

Differences of the boresight and interior orientation parameters given by three different software are shown in Table 3. FGIAT and inBlock gave very similar results; in boresight parameters the maximum differences were 0.71 mgon and the RMSEs were less than 0.3 mgon; in interior orientation parameters the maximum differences were less than 3.5 μm and the RMSEs were less than 1.6 μm. The parameters given by Orima software varied more from the results of FGIAT and inBlock; the major reasons for the big differences were the different coordinate systems and the different models. The differences between Orima and the other software were systematic, thus the conclusions of stability and performance were similar in all the systems.

3.8. Accuracy of direct georeferencing

The results of the evaluation of the direct georeferencing accuracy (RMSE) are given in Figure 10.

In the first case, where only the boresight correction was applied (Figure 10a), the error in the direction perpendicular to the flying direction was evident (Chapter 3.4); the accuracy of DG was 10-15 μm in x and 22-45 μm in y.

When the systematic errors (lever arm and datum) were eliminated from the position observations, the accuracy improved to 8-15 μm in x and 10-20 μm in y (Figure 10b). In many cases the accuracy of y was worse than the accuracy of x. One possible explanation for this could be the possible poorer precision of ω-observations. The accuracy of the block 2122 was the poorest, which was probably due to the weakest accuracy of the rotations (Figure 3).

In the last case (Figure 10c) the boresight and interior orientation parameters were estimated from the first calibration block of each optics (2121, 2119, 2128 and 2129). The change of dω in OH-CGW was evident in the results; dx is 30-40 μm and dy is 50-60 μm. In the other blocks dx is 12-18 μm and dy is 20-30 μm. The results are worse than in Figure 10b due to the instability of the parameters.

4. Discussion

In the previous sections results of the GPS/IMU/camera system calibration of four GPS/IMU/optics combinations were given.

A remarkable finding was the large – 20 to 40 μm in image – correction in the direction perpendicular to the flying direction (y0). For one optics the correction for the focal length was 20-40 μm; for the other optics the correction was mostly less than 5 μm. The correction in the flying direction appeared to be about 0-10 μm. On the basis of the above analysis and the previous experiences of NLS, the corrections in y0 and c are caused mainly by the changes of interior orientation of the camera in the flying conditions. Similar findings have been made earlier in [1, 3, 9].

Stability of the calibration parameters was analysed. The boresight parameters varied 6 mgon even in the flights flown successively; the maximum changes of the long-term calibration were about 20 mgon. Possible explanation for the big changes is the exchanges of the wide and normal angle optics between the calibrations. The detected shifts and drifts resulted in instability especially to the short-term stability analysis; the improvement of the GPS/IMU integration methods will hopefully decrease these phenomena. The stability analysis of the interior orientation parameters was difficult because the flights were made in different scales. However, the use of detected significant corrections for y0 and c appeared to be profitable.

The quality of the attitude observations was on the level specified by the system vendors; the average RMSE was about 4 mgon. This indicates, however, only the internal precision, because the boresight parameters were estimated for each flight. Instability of the boresight parameters will deteriorate the direct attitude observations in practise. The analysis revealed shifts and drifts in the GPS/IMU attitude observations; similar findings were reported in [2].

The quality of the reference observations in the evaluation of the position observations was completely sufficient only in one block; the RMS accuracy was better than 0.1 m. The determined height accuracy was better than 0.1 m in many cases. Small stripwise offsets were detected also in the position observations; the maximum corrections varied from less than 0.1 m to about 0.3 m.

This investigation will continue with a complete analysis of the stability. It is essential that the system users systematically gather information of the systems in practical work in order to make conclusions of the performance of the various systems; in this investigation all the four GPS/IMU/optics-system combinations appeared to have differences in their behaviour. The stability appeared to be the weakest point of the analysis; in the future the stability can be improved along the development of the procedures and GPS/IMU-integration methods.

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