INVESTIGATIONS ON SYSTEM CALIBRATION OF GPS/IMU AND CAMERA FOR DIRECT GEOREFERENCING

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ABSTRACT:

An inevitable task before direct georeferencing can be performed is the calibration of the GPS/IMU system and the imaging sensor. The permanent calibration fields for large- and medium-scale (1:3 300 – 1:16 000) system calibration constructed by Finnish Geodetic Institute are described in this article. Theoretical results concerning the effect of block structure on the accuracy and determinability of various parameters indicate that the block structures with cross-strips give the most stable results both with and without ground control points. The preliminary results of an extensive investigation concerning the calibration of two Applanix POS AV™ 510 GPS/IMU systems recently purchased by National Land Survey of Finland are given. After boresight calibration, the RMS values between rotations obtained by aerial triangulation and GPS/IMU integration varied between 0.003 and 0.007 gon.

1. INTRODUCTION

1.1 Background

Recent results have shown that direct sensor orientation and direct georeferencing (DG) utilising the GPS/IMU-technology is operational. In large- and medium-scale tests for directly determined ground coordinates e.g. accuracies of 5-20 cm in X and Y and 10-30 cm in Z, have been reported (Cramer 2001a, b, Heipke *et al.* 2002). The promising results have been usually obtained under optimal conditions; practical problems, including complexity of system calibration, difficulty of setting up the base station and other technical problems have been reported by Himle (2001).

It has been stated that the DG is extrapolation. Any deviation of the imaging model from the physical reality deteriorates the accuracy of point determination (Skaloud 1999, Cramer 2001a, b, Habib *et al.* 2001, Jacobsen *et al.* 2001, Jacobsen 2001, Heipke *et al.* 2002). Proper system calibration is prerequisite for reliable DG.

The main purpose of the system calibration is the determination of the boresight misalignment, i.e. angular misalignment between the IMU and the camera coordinate frames. Camera calibration parameters and lever arm are other central quantities that could be included to the calibration. (Schwarz *et al.* 1993, Haala *et al.* 1998, Skaloud 1999, Cramer 2001a, b, Jacobsen 2001, Heipke *et al.* 2002).

The airborne system calibration can be performed either by using permanent calibration fields or as in-situ calibration during the mapping flight. Cramer (2001a) has reported the many problems concerning the use of permanent calibration fields. Possible problem of in-situ calibration is the price-quality ratio; the effort of targeting and increase in flying time should not be too high.

Questions concerning the calibration, include

- What are the reasonable calibration field and block structures?
- What is the effect of scale?
- Which parameters should be included to the calibration?
- What is the stability of the parameters, i.e. how often the calibration should be performed?
- How the change of optics affects the parameters?
- How well the calibration parameters can be transferred to the mapping area?
- What are economical procedures for in-situ calibration?

1.2 Aim of the investigation

National Land Survey of Finland (NLS) purchased two Applanix POS AV™ 510 systems (Mostafa et al. 2001) in spring 2002. Since then Finnish Geodetic Institute (FGI) and NLS have been working in co-operation to investigate theoretical and practical questions of DG.

The first phases of the investigation were the construction of a permanent calibration field and the determination of appropriate block structures. Extensive simulations were made to examine the effect of block structure on the determination of various parameters. The practical questions given above will be investigated using the data from the calibration flights in various scales (1:3 300, 1:4 000, 1:8 000, 1:16 000) and the NLS mapping flights of summer 2002. Also GPS base station data with varying base lengths is available.

In this article we will describe the calibration field structure, give the central results of the simulations and give a few preliminary results of the calibration flights.

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2. SJÖKULLA TEST FIELD

FGI has a permanent photogrammetric test field in Kirkkonummi municipality in Sjökulla about 30 km to the west of Helsinki. Construction work started in 1992. The test field contains permanent resolving power bar targets for testing the image quality of airborne sensors. Altogether 43 signalised white circular targets with a diameter of 30 and 40 cm exist for testing the geometric accuracy of aerial photographs in scales 1:3000-1:5000. Private companies and NLS have regularly used the test field for system inspection.

The Sjökulla test field was expanded in summer 2001 by measuring 12 control points over the area of 4 km x 5 km to enable GPS/IMU calibration in scales of 1:8000 - 1:16000. Points were measured with Ashtech double phase GPS receivers. Measurement sessions lasted six hours and all the new points are fixed in the bedrock; 1 x 1 square metre white signals are made of plywood.

The block structures of the large- and medium-scale calibration fields are shown in Table 1 and in Figure 1. More detailed information about the test field and its use in different tests can be found in (Kuittinen *et al.* 1994 and 1996, Ahokas *et al.* 2000, Ahokas 2001).

3. FGIAT BLOCK ADJUSTMENT SOFTWARE

The FGIAT multisensor block adjustment software has been developed at FGI since 1997. Standard photogrammetric bundle block adjustment techniques have been implemented to the airborne part. Additional parameters for GPS, attitude and image observations are:

- GPS-observations. Offset and linear time dependent drift terms can be used for strips or sessions.
- Attitude observations. Offset and linear time dependent drift terms can be used to strips or sessions.
- Image deformations. Any of the following parameters can be selected: interior orientation of the camera, Ebner's 12 parameters and Brown's 21 parameters. The parameters are treated as weighted observations in the adjustement.

The boresight parameters are solved after the block adjustment. First the boresight misalignment is solved for each image from

$$R_p^b = R_m^b R_p^m \qquad (1)$$

where the rotation matrixes are: R_p^b from camera frame to IMU body frame, R_m^b from object frame to IMU body frame and R_p^m from camera frame to object frame. The final boresight values are obtained as average values over the whole block.

4. SIMULATIONS

4.1 Simulation set-up

Simulations were performed with various block structures to demonstrate their potential and limitations. The simulated block structures are the following:

- Block 1: Rectangular block, p=q=80%
- Block 2: Rectangular block, p=q=60%.
- Block 3: Block 2 + 2 cross-strips.
- Block 4: Rectangular block, p=60%, q=30%
- Block 5: Block 4 + 2 cross-strips
- I-block: 4 strips with 10 images each, p=60%, q=100%.

Table 1. Calibration blocks: scale, number of strips and cross-strips, number of images per strip and cross-strip, forward and side overlaps, number of ground control points (GCPs) and the total number of images.

Scale	Strips; Cross-strips*	Images Strips; cross-strips	p [%]	q [%]	GCPs	Ima-ges
1:3300	4; 4	5; 5	60	60	43	50
1:4000	4; 2	6; 4	80	80	43	42
1:8000	4; 2	9; 6	60	60	12	63
1:16000	4; 2	9; 6	80	80	12	63

* Additional strip and cross-strip are flown in opposite direction

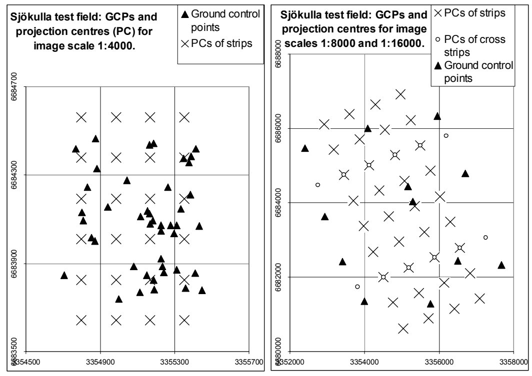

Figure 1. Calibration blocks 1:4 000 and 1: 8000/1:16000.

- L-block: 2 strips + 2 cross-strips with 10 images each, p=60%, q=100%

The rectangular block consists of 4 strips with 10 images per strip. The block structures are shown in Figure 2.

Other details of the simulation:

- Wide-angle camera (f = 150 mm); scale 1:16 000
- Planar object
- Regular 5x5 tie point distribution in each image
- Calculations with and without ground control points (GCPs); distributions of 12 GCPs are shown in Figure 2
- GPS support
- Normally distributed random errors; standard deviations:
    - Tie Points: σ_{tie} = 5 µm
    - GCPs: σ_{xy} = 5 µm, σ_{XY} = 1.5 cm, σ_Z = 3 cm
    - GPS: σ_{XYZ} = 10 cm

Determinability of various additional unknowns was investigated by sequentially increasing their number as follows:

- GPS parameters (only in the cases with GCPs)
    - No GPS parameters
    - Lever arm
    - Lever arm + drift
    - Offset and drift for strips (strip drift)
- Image deformations
    - No additional parameters
    - Interior orientation (only in blocks with 2 scales)
    - Ebner's 12 parameters
    - Brown's 18 parameters: affinity, radial and tangential distortion (in the full 21 parameter set also interior orientation is included)

After adjustment theoretical accuracy of each parameter is calculated from the inverted normal equation matrix; RMS values are then calculated over the whole block. Decreasing

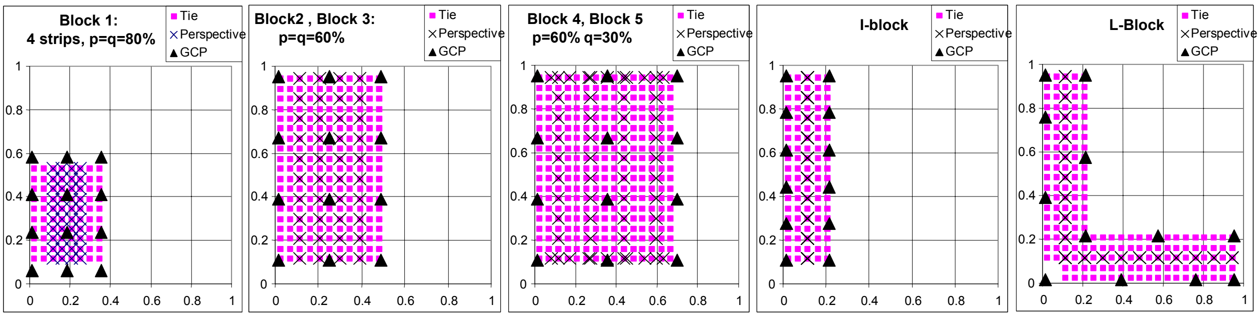

Figure 2. Structures of the simulated blocks (tie points, perspective centres and GCPs).

determinability caused by the increasing number of parameters can be seen as deterioration of accuracy. It should be realized that the calculated accuracies are valid only if the mathematical model is sufficient; too few parameters cause bias, the use of too many parameters is problematic if the block structure does not allow their determination.

4.2 Results of simulation

The RMS values of estimated accuracies of exterior orientations of a few cases are shown in Figures 3, 4 and 5. In all the cases GPS support is used. In Figure 3 no GPS parameters or additional parameters are used. In Figure 4 stripwise GPS drift parameters and 18 Brown's parameters are used. Figure 5 shows the results of the case with no GCPs, GPS support and 18 Brown's parameters.

4.2.1 The use of one scale only: Central conclusions of the performance of various blocks are:

- **Block 1.** In general the block is very stable when GCPs are used. The use of stripwise drift parameters for GPS weakens the accuracy slightly. The use of additional parameters cause some instability when GCPs are not used.
- **Block 2.** Performance of the Block 2 is quite stable, but not as stable as that of the Block 1. The use of GPS parameters, especially the stripwise drift parameters, weakens the accuracy. The use of Brown's parameters weakens accuracy especially when stripwise drift parameters are applied. When GCPs are not used, the additional parameters cause some instability.
- **Block 3.** The cross-strips make the block more stable. Slight deterioration of accuracy can be detected with GPS strip drift parameters. In the cases without GCPs the use of additional parameters does not deteriorate the accuracy significantly.
- **Block 4.** The block is not stable when parameters are added. In general, the use of GPS parameters and additional parameters deteriorate the accuracy.
- **Block 5.** The cross-strips stabilise the performance again. Accuracy is slightly deteriorated when GPS strip drift parameters are used. Performance is stable also when GCPs are not used.
- **I-Block**. I-Block has a strip-structure, thus the geometry is not very stable. The block can be adjusted when there are GCPs, but without GCPs the block is not solvable. When GCPs are used, the accuracy is usually very good. Only the use of Brown's parameters seriously weakens the perspective centre accuracy.
- **L-Block**. When GCPs are used, the performance of L-Block is very stable. The use of Brown's parameters slightly weakens the accuracy. Also the use of stripwise drift parameters deteriorates the accuracy slightly. When GCPs are not used the rotation accuracy is quite weak.

When GCPs and GPS support are used the following conclusions can be drawn:

- The most stable and accurate block configurations are the block with 80% overlaps and the blocks with cross-strips (blocks 1, 3 and 5). Other blocks have problems with some parameters.
- When neither GPS parameters nor additional parameters are used, all the blocks give quite similar accuracy. The accuracy is 0.07-0.08 m in X0 and Y0, 0.03-0.05 m in Z0, 1.5-2.0 mgon in ω and φ and 0.9-1.2 mgon (milli gon) in κ.
- When stripwise drift and 18 Brown's parameters are unknowns, the corresponding values are 0.09-0.13 m in X0 and Y0, 0.06-0.1 m in Z0, 2.0-2.9 in ω and φ and 1.0-1.3 mgon in κ (excluding the I-block, Block 2 and Block 4).

When GCPs are not used the conclusions are the following:

- The blocks with cross-strips (Blocks 3 and 5) give the most stable accuracy. I-Block is not solvable and L-Block has poor rotation accuracy; these two blocks are not included in the following analysis.
- When comparing to the corresponding cases with GCPs, the rotation accuracy is about 0.5-1 mgon poorer, but the perspective centre accuracy is not deteriorated.
- The additional parameters should be used carefully. In the tests their use especially decreased the height accuracy of the point unknowns. The accuracy is deteriorated less if cross-strips are used.
- The approximate accuracy values for blocks 1-5 in the cases with 18 Brown's parameters are 0.07-0.08 m in X0 and Y0, 0.05-0.06 m in Z0, 2-3 mgon in ω and φ and 2 mgon in κ.

4.2.2 Using two scales for the determination of interior orientation: Simulations were made to find out the accuracy and requirements for the determination of interior orientation. Two overlapping blocks with different scales were used: the Block 1 with cross-strips (p=q=80%) in scale 1:16 000 and the Block 3 (p=q=60%) in scale 1:8 000. Some results are shown in Figure 6.

With the block structures and modelling techniques used the interior orientation could be determined accurately in 3 cases:

- GCPs, GPS-support, no GPS parameters. Accuracy was about 1 µm for principal point and 1.5 µm for focal length.
- GCPs, GPS-support, unknown lever arm. Accuracy was about 2 µm for all the components of interior orientation.
- No GCPs, GPS-support, no GPS parameters. Accuracy was about 1 µm for principal point and 3 µm for focal length.

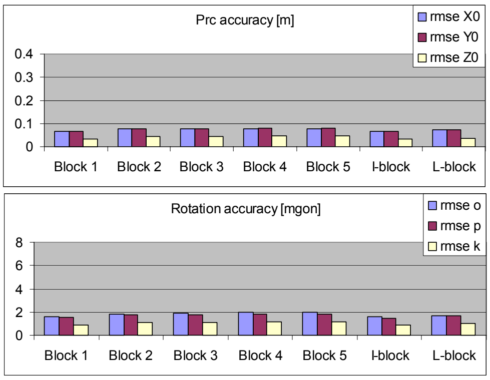

Figure 3. Comparison of simulated blocks. Control: GCPs and GPS. Unknowns: points and exterior orientations.

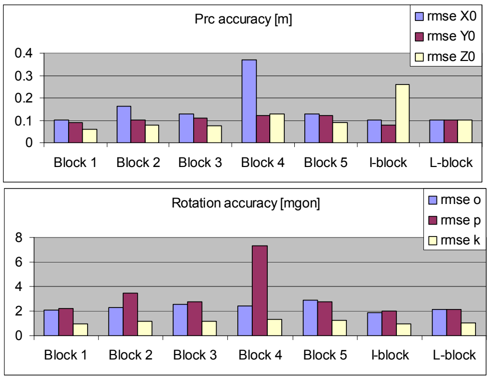

Figure 4. Comparison of simulated blocks. Control: GCPs and GPS. Unknowns: points, exterior orientations, GPS strip drift, Brown's 18 parameters.

5. EMPIRICAL TESTS

5.1 Image blocks

In this article preliminary results of two blocks with 1:8000 scale and wide-angle optics are given. Block structures are described in Chapter 2. The flights were made in April 25th and May 3rd, 2002. NLS performed the GPS/IMU-processing, photogrammetric processing of the image data, scanning and image measurements

GPS/IMU integration was made using the Applanix PosPac Version 3.1. The GPS base station was located about 30 km apart from the calibration field. In the calculation the default parameters of the software were used, expect in PosGps processing the standard deviations of C/A-code and L1-phase observations were changed to 2 m and 0.02 m, respectively. The fixed integer solution was obtained.

The images were scanned with 20 µm resolution. The block was measured using the SocetSet digital photogrammetric workstation of LH-Systems and the HATS automatic tie point measurement software. NLS performed the block adjustment using the ORIMA block adjustment software and delivered the cleaned image observations to FGI for the further processing.

5.2 Results

The block adjustments were performed by the FGIAT block adjustment software (Chapter 3). The a priori standard deviations of the observations were the following:

– $\sigma_0 = 10$ µm

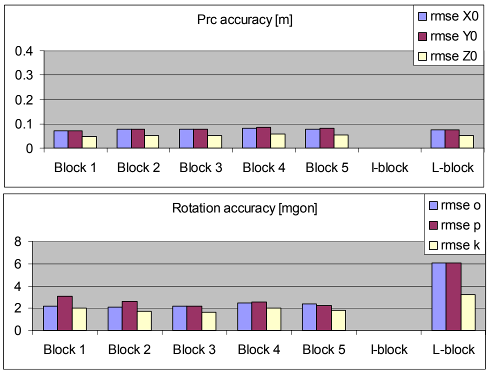

Figure 5. Comparison of simulated blocks. Control: GPS. Unknowns: points, exterior orientations and Brown's 18 parameters.

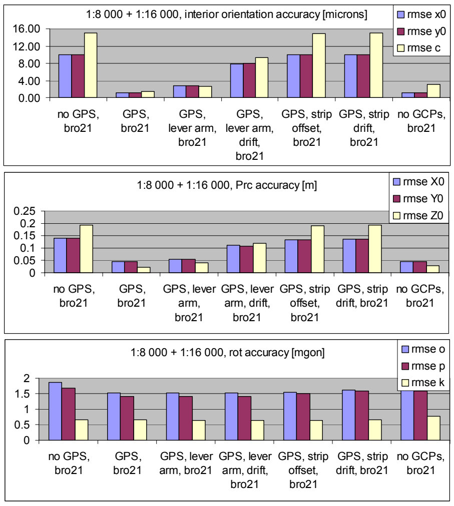

Figure 6. Determination of interior orientation by combining two blocks with different scales. Six first adjustments are with GCPs and the last one is with GPS control only. In all the cases the Brown's 21 parameters are estimated.

– GCPs: $\sigma_{xy} = 10$, $\sigma_{XY} = 1.5$ cm, $\sigma_Z = 3$ cm
– GPS: $\sigma_{XYZ} = 10$ cm
– Attitude: $\sigma_\omega = \sigma_\varphi = 0.00556$ gon, $\sigma_\kappa = 0.00889$ gon

The planimetric coordinates were in the Finnish National Grid; heights were orthometric. Earth curvature and refraction corrections were applied to the image coordinates. Calculations were made with and without GCPs. When GCPs were used, the strip drift parameters were estimated for the GPS observations. Additional parameters were not used. With both blocks two block structures were used: the full block and a block with four strips and no cross-strips.

RMS values of theoretical orientation accuracies are given in Table 2. Based on the simulations it can be expected that theoretical accuracies of exterior orientations excluding κ are better when GCPs are not used (note: this is valid if the model is correct, i.e. no systematic errors in GPS observations). Theoretical accuracy of the four-strip case should be worse than that of the full block. Table 2 is in accordance with these expectations. Obtained accuracy is 0.04-0.08 m in X0 and Y0, 0.025 - 0.045 m in Z0, 2.0-3.3 mgon in ω and φ and 1.0-1.8 mgon in κ.

Accuracy of boresight calibration can be evaluated based on RMS values of the residuals of rotations after applying the boresight alignment (Table 2). Both block structures (full block vs.

Table 2. Quality of exterior orientation, boresight misalignment and its accuracy

Block	Images	GCP	s_0 [μm]	Prc accuracy [mm]			Rotation accuracy [mgon]			Boresight misalignment values [gon]			Boresight misalign-ment accuracy [mgon]		
				X0	Y0	Z0	ω	φ	κ	ω	φ	κ	ω	φ	κ
02121	62	12	7.1	51	48	32	2.1	2.2	1.0	-0.0472	-0.0065	-0.4383	3.8	5.0	3.9
		-	7.2	41	41	25	2.0	2.0	1.2	-0.0454	-0.0077	-0.4384	4.2	5.0	4.0
	35	12	7.1	65	57	41	2.5	2.8	1.3	-0.0473	-0.0054	-0.4382	4.0	6.3	2.9
		-	7.4	49	49	32	2.4	2.5	1.5	-0.0424	-0.0072	-0.4385	3.9	5.0	2.8
02128	63	12	8.5	62	59	38	2.6	2.8	1.2	-0.3786	0.0789	-0.3547	5.7	6.7	4.8
		-	8.6	50	50	30	2.4	2.4	1.5	-0.3758	0.0795	-0.3548	5.7	4.5	4.8
	36	12	8.3	75	65	45	2.9	3.3	1.5	-0.3794	0.0772	-0.3552	6.1	6.8	4.5
		-	8.5	56	56	37	2.7	2.9	1.8	-0.3738	0.0788	-0.3556	6.1	3.9	4.6

four strips) appear to give similar accuracy. In the block 02121 the accuracy can be considered about the same in the cases with and without GCPs. In the block 02128 the accuracy of φ is about 2 mgon better when GCPs are not used. Accuracy of the calibration of the blocks 02121 and 02128 is 3-5 mgon and 4-7 mgon, respectively.

The conclusion that can be drawn at this preliminary stage of the investigation is that the accuracy is promising. Further analysis will be performed later.

6. CONCLUSIONS

The accurate calibration of the GPS/IMU and the camera is the precondition for DG. FGI has constructed permanent calibration fields for large- and medium-scale calibration (scales 1:3 000 to 1:16 000) in Finland. The recommended block structures consists of four strips and crossing strips; the overlaps are p=q=60% and p=q=80%. The preliminary results of boresight determination of two Applanix POS AV™ 510 GPS/IMU systems of NLS indicate promising accuracy. The investigation will continue with the many practical questions given above.

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