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10 Years ifp Test Site Vaihingen/Enz: An Independent Performance Study

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ABSTRACT

The use of test sites in photogrammetry is well known and mainly applied for the following two applications: Test sites are necessary within the sensor calibration process, especially when in-situ calibration methodologies are taken place. This topic especially gains in importance when the new and more complex digital airborne sensor systems are considered. On the other hand, test fields provide external reference data for the independent check of sensor or systems performance within operational conditions. Hence, this is the only way for an empirical analysis of a sensor system and/or a processing chain. Within this paper the topic of sensor calibration is briefly recovered with certain emphasis on the use of test fields. In the main part of the paper the results of an empirical ADS40 performance test within the test field Vaihingen/Enz are presented, as one example of an independent in-flight performance study for one of the new and already commercially used digital airborne camera systems.

1. INTRODUCTION

The use of photogrammetric test sites is well known for the whole range of photogrammetry from space and airborne up to close range applications. Such test areas are typically used to provide external information for the independent estimation of camera or more generally spoken sensor system performance, where both geometric and radiometric parameters are considered. In many cases the use of test sites is closely related to the topic of camera calibration. This is especially relevant for non-metric camera systems mainly used in close-range photogrammetric tasks – in contrary to the laboratory calibration which is applied for metric cameras only. Nonetheless, even in this traditional field of airborne photogrammetry using analogue large format mapping cameras or their digital successors, the topic of test site calibrations becomes more and more relevant. In nowadays use the cameras are quite often equipped with additional sensors, namely GPS/inertial components for direct measurement of exterior orientation parameters. The spatial relation between those sensors and the camera itself can only be determined from on site calibrations. Focusing on the new digital airborne cameras the need for system driven calibrations realized via test site calibrations despite standard component driven approaches from lab calibration becomes obvious. This is due to the more complex system design, i.e. many of the new digital sensors are based on multi-head concepts and almost all are using integrated GPS/inertial systems, which are mandatory for digital line scanners.

Nevertheless, another driving force to perform system tests within specially designed photogrammetric test fields is the need for the empirical analysis of sensor systems performance in operation. Such test flights are particularly necessary in case new sensors and systems become available. Since the advent of digital airborne imagers and their commercial availability main attention in the photogrammetric community was laid on the analysis of the new systems potential and their comparison to the well-known analogue mapping cameras. And this is still the case, since even today new system configurations are showing up. Already available systems are modified and refinements in the processing software are continuously applied. From that, empirical tests are done by the system vendors, in order to guarantee and validate the systems performance from test field results, in some cases the sensors are independently analysed by organizations or universities and finally, tests are done by the potential customers itself before the final purchase decision is made.

This paper tries to briefly recall the need for test sites within the sensor calibration process first. Hence the topic of sensor calibration is covered within the following section, with certain emphasis on the use of test site approaches within the different calibration methods and their design. Some of the current and historical test sites are briefly mentioned. In the second and main part of the paper the results from the comprehensive ADS40 performance test within the ifp test site Vaihingen/Enz are presented as one exemplarily investigation on external quality control of airborne sensors from test site data.

2. SENSOR CALIBRATION

Before starting the brief introduction on sensor calibration concepts, some general definitions should be given, since they are used quite often in the field of sensor calibration. Following the definitions from the joint ISPRS/CEOS working group on calibration and validation the expression *calibration* itself describes the "process of quantitatively defining the system responses to known, controlled signal inputs". From the Manual of Photogrammetry (Slama 1980) some more detailed definitions are cited like follows: *Calibration* is defined as "the act or process of determining certain specific measurements in a camera or other instrument or device by comparison with a standard, for use in correcting or compensating errors or for purposes of record". Photogrammetric *camera calibration* as specialization of the terminus before describes the "determination of calibrated focal length, the location of principal point, the point of symmetry, the resolution of lens, the degree of flatness of the focal plane and the lens distortion referred to the particular calibrated focal length. In a multiple-lens camera the calibration also includes the determination of the angles between the component perspective units. *Laboratory calibration* is performed separately from the photography phase and is undertaken with goniometers or test areas of various sophistication." In case test sites with known coordinates and/or distances are used, a *test site calibration* is performed (Luhmann 2000). In principle, test sites (or test fields) can be used within the lab or in the field. "*On-the-job calibration* of a camera or a photograph utilizes object photography and well-defined object space control points", as provided by test sites for example. Such calibration is directly obtained from the photographs of the desired object itself and therefore combines the test site calibration with the object reconstruction process. Such approach might be advantageous in case the object itself does not provide enough information to perform a self-calibration approach (Luhmann 2000), which is defined as follows: "*Self-calibration* of a camera or a photograph utilizes object photography and well-defined object points." Note that in contrast to the on-the-job calibration the object points non necessarily have to be known in object space for self-calibration. Again the calibration parameters are obtained from the imagery recorded for the desired object reconstruction itself. This results in calibration parameters which are optimal for the operational environments of this image configuration. Since the final last two approaches both deal with the object photographs recorded on-site, they might be classified as *in-situ calibration* approaches.

The term *validation* is closely related to calibration and should finally be mentioned for reasons of completeness. Following the ISPRS/EOS findings *validation* defines the "process of assessing, by independent means, the quantity of data products derived from system outputs".

2.1. Laboratory calibration

From classical photogrammetric point of view the laboratory calibration is the standard methodology used for analogue airborne mapping cameras. The results of such lab calibrations are documented in the well known calibration certificates. In order to verify the validity of calibration parameters, this calibration is repeated within certain time intervals, typically each two years. Special equipment is used, preventing users to perform such calibrations by themselves. In addition, the lab calibration is done under environmental conditions which are different to the conditions the camera will encounter in airborne use. The European calibrations of airborne mapping camera for example are done at the Zeiss (Germany) and Leica (Switzerland) calibration facilities, based on moving collimators, so-called goniometers (see Figure 1 and Figure 2): The camera axis is fixed, pointing horizontal or vertical and the collimator is moving around the entrance node of the lenses. The precisely known grid crosses from the illuminated master grid mounted in the focal plane of the camera are projected through the lens. These grid points are coincided with the collimator telescope and the corresponding angles in object space are measured. Besides the already mentioned calibration facilities other goniometers are available for example at DLR Berlin (Germany), Simmons Aerofilms in the UK or at FGI in Finland.

In contrary to the visual goniometer technique, multi-collimators are closer to the practical conditions in photogrammetry, since the relevant information is presented in object space. Such calibration device for example is available at the US Geological Survey (USGS) Optical Science Lab (Figure 3). A fixed array of collimators (typically arranged in a fan with well defined angles between the different viewing directions) is used, where each collimator projects an image of its individual cross hair on a photographic plate fixed in the camera focal plane. The coordinates of the collimator crosses (radial distances) are measured afterwards and from these observations the calibration parameters are obtained. In addition to the goniometer method, the multi-collimator is more efficient and the calibration includes not only the lens but the photographic emulsion on the plate fixed in the camera. Such approach finally leads to the more general system driven view – considering not only one individual component during calibration (i.e. the lens of the tested camera), but including all other important components forming the overall system.


Figure 1: Goniometer at Zeiss Oberkochen (© Zeiss).


Figure 2: Goniometer at Leica Heerbrugg (© Leica).


Figure 3: Multi-collimator at USGS OSL Reston (© USGS).

2.2. Test field calibration

Although most of the photogrammetric systems users feel comfortable with the traditional system component calibration from laboratory, the need for overall calibration typically based on in-situ calibration methods is already obvious since the 1960ties, at least to supplement the results from lab calibrations (Hallert 1954). Within these early days the test sites were mainly used to estimate the influence of different error sources within the photogrammetric image formation and reconstruction process (Kupfer 1971). Several approaches using different test sites were proposed and different test fields were established. One of the well known test sites at that time was initiated and maintained from the Institut für Photogrammetrie, Universität Bonn, close to the village Rheidt, north-east of Bonn. This test site comprises 41 regularly distributed point groups (with 3 signalized and marked points each) within an 2 x 2 km² area (Figure 4). From such test site investigations different calibrations models were proposed and can be found for example in Hallert (1968), Brown (1966, 1976), Ebner (1976), Grün (1978).

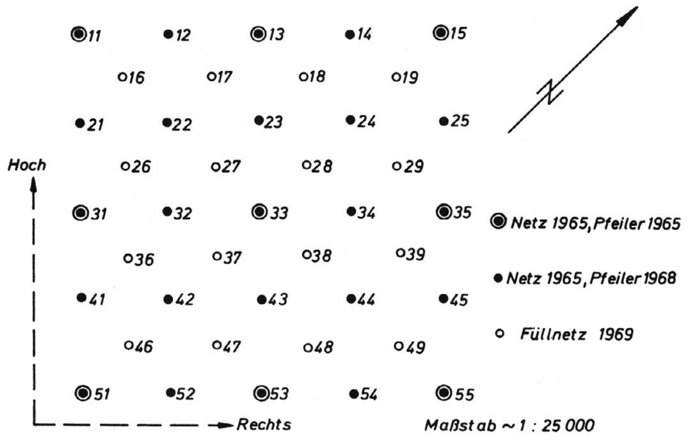

Figure 4: Test field Rheidt (Kupfer 1971).

A challenge in airborne sensors system calibration (including the full set of interior orientation parameters – so-called full calibration unlike partial calibration) so far is the strong correlation between exterior orientations and interior camera parameters, which is due to the less-optimal block configurations with almost parallel and vertical pointing camera views and typically relative small height variations with respect to the flying height above ground. Torlegård (1967) for example proposed the installation of a test site around three rather high broadcasting antennas (190m and 300m), which should be used as control points and flown in 500m above ground flying height, providing significant height changes. This would positively influence the determination of camera parameters. Alternatively the test site installation in very mountainous terrain is recommended. With the availability of high-quality direct exterior orientation measurements this drawback could be solved.

The design of photogrammetric test sites is also very extensively discussed in the field of close-range applications. Comprehensive analyses are given by Wester-Ebbinghaus (1983, 1985), where different test field and camera station layouts are discussed: 2D and 3D with and without use of control points and scales using nadir pointing or convergent camera views. The higher flexibility in design of the image blocks in close-range applications positively influences the determinability of calibration parameters. Nevertheless, in general the use of 3D test fields is preferred to 2D test fields, if installation of such test sites is practicable (Luhmann 2000).

3. THE IFP TEST SITE VAIHINGEN/ENZ

The ifp test site Vaihingen/Enz was originally established summer 1995 (exactly 10 years from now) for the geometrical performance acceptance test of one of the first operational digital airborne line scanning systems, the Digital Photogrammetry Assembly DPA (Hofmann et al 1993). Starting from this, the test site was used several times for different kinds of investigations: For the independent in-flight evaluation of new digital airborne sensors as well as for investigations on the potential of direct georeferencing using integrated GPS/inertial systems in combination with standard analogue frame cameras (Table 1). Besides DPA, the digital airborne line scanners WAAC (Sandau & Eckardt 1996) and HRSC (Wewel et al 1998) from DLR were flown and their accuracy potential was derived from this test field data. Focusing on the new commercial digital sensors the DMC (Hinz et al 2000) engineering model (EM) was flown in 2000. The April 2003 test was done with the fully equipped system with its multi-head PAN and MS components. The latest flight in June 2004 was done with the ADS40 sensor (Sandau et al 2000) and will be covered in more detail in the following section of the paper. Besides these large format sensors the small format IGI dIGIcam-K14 system (based on Kodak small format camera housing and 14M pixel CMOS array), which may complement digital large format airborne sensor systems in terms of higher flexibility for smaller acquisition areas at lower costs, was flown in April 2004. In addition to that, commercially available GPS/inertial systems have been flown to explore the potential of direct sensor orientation and the use of directly measured exterior orientation measurements of high accuracy within an integrated sensor orientation.

# Test campaign	Test date month/year	Airborne sensor	
1	07/1995	DPA	digital line sensor
2	08/1996	DPA	digital line sensor
3	10/1996	DPA	digital line sensor
4	11/1997	WAAC	digital line sensor
5	02/1998	HRSC-A	digital line sensor
6	11/1998	DPA	digital line sensor
7	12/1998	RMK-Top15	POS/AV 510 DG
8	06/2000	RMK-Top15	AEROcontrol-IId
9	06/2000	DMC EM	digital frame sensor
10	11/2000	DMC EM	digital frame sensor
11	09/2002	RMK-Top15	AEROcontrol-IId
12	04/2003	DMC	digital frame sensor
13	04/2004	dIGIcam-K14	digital frame sensor
14	06/2004	ADS40	digital line sensor
15	fall 2005	ADS40	digital line sensor

Table 1: Performed test flights Vaihingen/Enz.

The test site itself is located about 20km north-west of Stuttgart in a hilly area providing several types of vegetation and land use, mostly rural area with smaller forests and villages (Figure 5). The overall spatial extension of the test area is 7.5 km (east-west) x 4.8 km (north-south). The terrain heights differ between 171m and 355m above mean sea level. Although the number of ground control slightly varies throughout the different years their principal locations remain unchanged. These locations are oriented on the ideal point distribution for fully signalized medium-scale (1:13000) wide angle analogue camera flights with 60% forward and side-lap conditions. This point raster is densified in the eastern half of the test site for lower flying heights. Besides these signalised points, manhole covers are additionally measured (Table 2). In the meantime all points are independently coordinated from static GPS surveys, with an estimated accuracy of 2cm for all three coordinate components. From that they may serve as independent check point information to estimate the (absolute) geometric quality of object point determination from airborne sensor data. In some cases additional mobile resolution targets (Siemens star, strip bar pattern) were prepared for the flights, to empirically analyse the spatial resolution potential of airborne sensors.

It has to be mentioned that other test sites similar to the Vaihingen/Enz area are available world-wide and used especially for the independent in-flight performance evaluation of airborne sensors. Without being exhaustive the Finnish test site Sjökulla maintained from the Finnish Geodetic Institute FGI should be mentioned first. Most recently the UltracamD digital airborne sensor was extensively tested within this test site (Honkavaara et al 2005). The Fredrikstad test site, originally established from the University of Åas in Norway, is another currently used test field. This test site is quite well-known to the photogrammetric users community since larger OEEPE (European Organization for Experimental Photogrammetric Research, since 2003 re-named to EuroSDR – European Spatial Data Research) investigations dedicated on integrated sensor orientation using GPS/inertial systems and on the kinematic GPS trajectory performance were done some years ago. Besides that, the new digital sensors DMC, ADS40 and UltracamD were recently flown within this test site also. Those data will partially be used within the EuroSDR network on Digital Camera Calibration (Cramer 2005). Other strong activities using in-flight sensor performance analysis are headed by the US Geological Survey. Using in-situ calibration (validation) methodologies different airborne digital systems are investigated with respect to the system calibration parameters and the final product. From the final results of these tests USGS expects general remarks on the geometric and radiometric accuracy and stability of the individual systems and their use according to mapping standards. These tests are done in cooperation with NASA using the Stennis Space Centre test area (Rufe & Zanoni 2004).

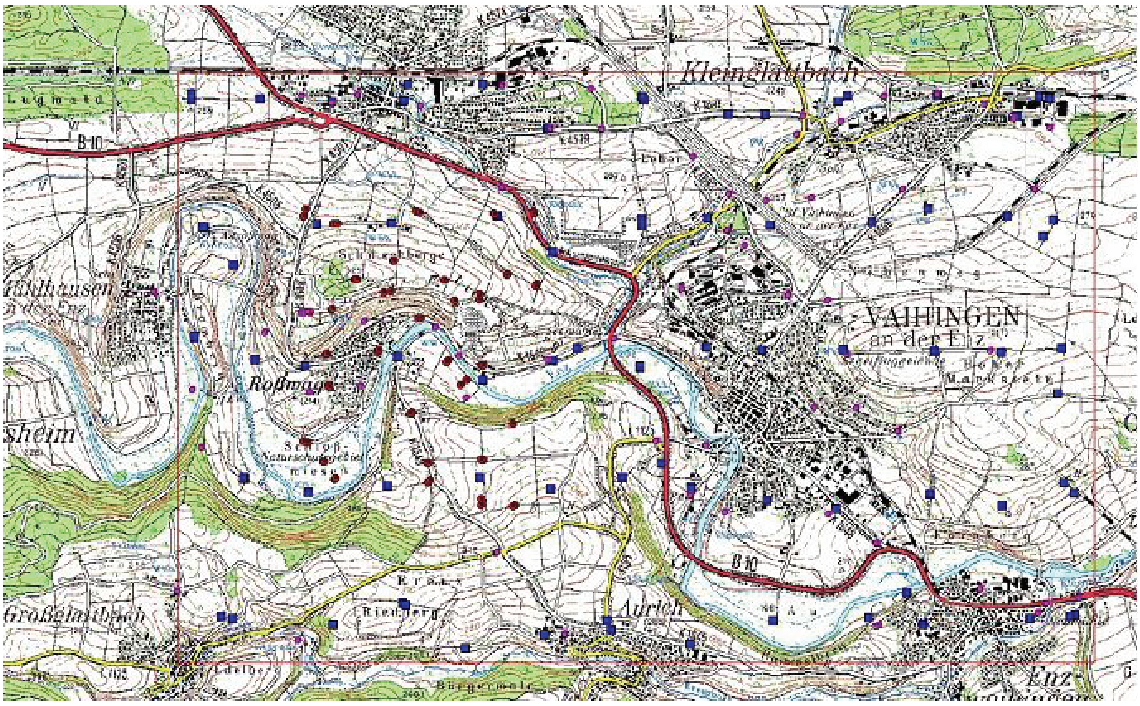

Figure 5: Ground control points distribution in Vaihingen/Enz test site.

#	Point type	# of points	Location of points
1	signalised/painted squares 1m x 1m	83	whole test site
2	signalised/painted squares 0.25m x 0.25m	62	western part of test site
3	well defined natural points (manhole covers)	69	whole test site

Table 2: Vaihingen/Enz ground control points (campaign summer 2004).

4. THE ADS40 PERFORMANCE TEST

4.1. System installation

A quite extensive test focusing on the geometric accuracy as well as the radiometric performance of ADS40 was done in summer 2004, as a joint project of Leica Geosystems and the Institut für Photogrammetrie (ifp), Universität Stuttgart. Within this campaign the Vaihingen/Enz test field with more than 200 signalised and independently coordinated object points (see Figure 5, Table 2) system was flown in different flying heights. In this test not only the empirical object point determination for the standard ADS40 system installation and process flow was analysed, additionally the influence of GPS/inertial system performance on the overall geometric accuracy and the quantification and the improvement of image resolution was of concern. The comprehensive analysis of geometric accuracy was recently finished, an extended report on geometrical test flight analysis is available. Final results on the estimation of resolution refinement can also be found in Becker et al (2005), Reulke et al (2004). Especially the influence of staggered arrays and additional image restauration methodologies is worthwhile to mention. These topics are non considered within this paper.

It has to be mentioned, that in addition to the standard ADS40 system installation, additional GPS/inertial units were installed during the flight. Besides the standard ADS40 configuration including the Applanix LN200 fibre-optic gyro based IMU (Litton) two additional GPS/inertial units were added to the camera housing, namely the Applanix AIMU dry-tuned gyro system based IMU (part of the Applanix POS/AV-510 system and based on the Inertial Science Inc. DMARS IMU) and the IGI IMU-IId fibre-optic gyro unit which is essential part of the IGI AEROcontrol-IId system. The IMU-IId is based on a Litef inertial unit. Since the rigid mount has to be guaranteed (no relative movements between camera and IMUs) for all three systems during the whole flight mission, a special metal hat was constructed by Leica and fixed on top of the ADS40 electronics head as it can be seen in the Figure 6. The two additional IMUs are mounted on top of this hat, the LN200 is on its standard position inside the camera close to the CCD focal plate.

Figure 6: Aircraft installation ADS40 Vaihingen/Enz test flight (June 26, 2004).

#	flying height h_g [m]	scale	theor. GSD [m]	# long strips	# cross strips	Side lap % (east-west)	Side lap % (north-south)
1	4000	64000	0.21	1	2	-	48
2	2500	40000	0.13	3	3	70	29
3	1500	24000	0.09	4	2	44	-
4	500	8000	0.03	8+1	2	55	-

Table 3: ADS40 image block configurations (June 26, 2004).

All three different on-board GPS receivers were connected to the same GPS antenna on top of the aircrafts fuselage. The translation offsets were already considered during GPS/inertial data processing using the appropriate software packages (Applanix POSPac 4.2, IGI AEROoffice 5.0b).
Within the flight mission the Vaihingen/Enz test site was flown in four different flying heights. The different block configurations are given in Table 3. The long strips were flown in east-west direction, the cross strips in north-south. The GSD is related to the theoretical GSD from staggered pixel size (i.e. 3.25µm pixel size in image plane). The true object space resolution is estimated from resolution targets like the Siemens star and black/white strip pattern. The results from these resolution investigations are already given in the before mentioned publications by Becker and Reulke.

4.2. Reconstruction of airborne line scanner imagery

The reconstruction of aircraft trajectory is one essential step for the later high-precision evaluation of push-broom line scanner imagery. Due to the trajectory dependent image geometry of line sensors the imaging component of the sensor system has to be combined with additional GPS/inertial components to directly measure the orientation elements during time of image data recording. Dependent on the quality of the directly measured orientation elements an additional aerial triangulation (AT) process is necessary to finally reconstruct the optimal trajectory and sensor orientation.
Based on the approach originally proposed from Otto Hofmann (1974) GPS/inertial positions and attitude data – typically obtained from data integration based on Kalman filtering – are used to interpolate the aircraft trajectory for the time interval between the so-called explicitly estimated points of orientation fixes. This approach is based on the automatic measurement of numerous tie points in the overlapping images, where the distance between the different orientation fixes is dependent on the quality of used GPS/inertial data. Dependent on the application scenario a certain number of unknowns has to be solved for in the AT process. In the ideal case – for a very smooth aircraft trajectory (i.e. in case of high altitude flying jets) or satellite orbits – the flight trajectory can be reconstructed based on the three line image geometry only, even without any additional information from orientation sensor components. In these cases the sensors movement is described using an appropriate kinematic model like polynomials or Keplerian elements (space borne case). Since this smooth trajectory condition is not guaranteed typically at least the combination of the imaging sensor with an additional IMU is necessary, to measure the relative sensor movement over time. This approach was originally realized within the first flights of the DPA sensor system.
Alternatively, so-called direct sensor orientation is possible if the GPS/inertial data provided are of sufficient accuracy. In such cases the remaining effort for AT is very rudimentary and only necessary to determine a small number of additional unknowns for system calibration (i.e. boresight misalignment angles, lever arms) or remaining datum shift parameters. This can be done with a significantly reduced number of tie point measurements. From an operational point of view this approach should be followed since the knowledge of high-quality exterior orientation parameters simplifies and accelerates the photogrammetric reconstruction process. Mathematically this approach is based on the philosophy of direct georeferencing of airborne sensors originated from Klaus Peter Schwarz beginning of the 1990ties (Schwarz et al 1993).
Both concepts for push-broom line scanner orientation have been applied for this ADS40 data set and will briefly be covered within the following sections.

4.3. Geometrical system performance

Within the extensive analysis of data, several aerial triangulation runs based on different block configurations were calculated with varying number of ground control points (GCP). In all cases the remaining object points were used for independent accuracy check points (ChP). In general two different approaches were used for AT: the standard orientation fix approach as implemented in the standard ORIMA/CAP-A software (Hinsken et al 2002), and the direct georeferencing model which is implemented in the ifp internal AT software dgap authored by Dirk Stallmann. It has to be mentioned that for geometrical analysis all measurements were done in the non staggered PAN and MS imagery. The ORIMA/CAP-A and dgap results presented below are exclusively obtained from the 1500m flight.

4.3.1. Accuracy based on standard LN200 trajectory information

If one focuses on the geometrical accuracy analysis from the 1500m flying height block configuration (see Table 3) the empirical accuracy obtained from independent check point analysis is given for three different control point configurations (Table 4). The processing was done using the standard ADS40 data workflow, including the ORIMA/CAP-A package for triangulation of imagery. The GPS/inertial trajectory information, which is essential for push-broom line scanner processing in general, was obtained from the LN200 IMU, which is used in all standard ADS40 airborne installations. No additional self-calibration was applied, all results are based on the estimation of the inherent boresight-misalignment angles and additional block-wise GPS position and drift correction terms only, where the later six unknowns are only applicable for the 4 and 12 control point cases.

The obtained statistical analysis from check point differences is very consistent and very well fits the theoretical expectations. The theoretical accuracy from normal case equations should be within 7cm and 9cm for horizontal and vertical components, respectively. This estimation is based on 3µm image point measurements accuracy, which corresponds to slightly better than half of a pixel for the original non staggered images. If one compares the obtained accuracy to the theoretical GSD of 9cm (assuming staggered arrays (Table 3)) the accuracy is very well below one pixel for the horizontal and about one pixel for the vertical component even though only non-staggered imagery was used during AT process. Even for the 0 GCP case the horizontal accuracy (RMS) is close to the theoretical value, the vertical component is less than factor 2 worse. This is quite satisfactory, keeping in mind that for this special case the absolute accuracy of object point determination is dependent on the absolute accuracy of the GPS/inertial trajectory. Without using any GCP there is no way to compensate for errors caused by sub-optimal GPS trajectory solutions, systematic effects or datum shifts. Such trajectory offsets – if present – will directly be transferred to global shifts in object point coordinates. The 0 GCP case will be discussed in more detail in the following section.

# GCP / ChP	Accuracy	East [m]	North [m]	Vertical [m]
12 / 190	RMS	0.052	0.054	0.077
	Mean	0.000	-0.022	0.045
	Std.Dev.	0.052	0.050	0.063
	Max.Dev.	0.133	0.188	0.242
4 / 198	RMS	0.055	0.054	0.106
	Mean	-0.008	-0.008	0.083
	Std.Dev.	0.055	0.053	0.065
	Max.Dev.	0.145	0.191	0.295
0 / 202	RMS	0.110	0.086	0.158
	Mean	0.094	-0.064	0.142
	Std.Dev.	0.057	0.056	0.068
	Max.Dev.	0.242	0.256	0.351

Table 4: ORIMA/CAP-A LN200 trajectory based geometric accuracy ADS40 test (h_g=1500m).

4.3.2. Accuracy based on alternative IMU based trajectory information

The results presented so far are exclusively based on the standard system components which are part of the commercially available ADS40 installation. In addition to that the influence of alternative IMU data on the overall object point performance could be investigated when using different IMUs for the GPS/inertial data integration, which is one essential processing step for the evaluation of line imagery in general. In this specific test flight additional IMU data were obtained from the Applanix AIMU and the IGI IMU-IId which are used as part of the Applanix POS/AV-510 and the IGI AEROcontrol-IId integrated GPS/inertial systems, respectively. Using the AIMU based data for the ORIMA/CAP-A triangulation of images the following results could be obtained (Table 5). Within the corresponding Table 6, results are depicted for the AEROcontrol IMU-IId based integrated system. Within all AT runs the same number of unknown parameters is applied, like in the LN200 case before. These tables can be compared to each other and to the LN200 based performance given before (Table 4). If one looks on the GCP based solutions in general the quite similar behaviour in accuracy, which is almost independent on the used IMU, is obvious. This high accuracy level is even more clear, when the given standard deviations (which are non affected from any systematic effects) are considered. They somehow represent the noise level which for both systems is very consistent and similar. Focusing on the RMS values, which reflect the quality of empirical object point determination, the quality is quite close for almost all cases based on 4 and 12 GCPs using LN200, AIMU and IMU-IId trajectory solutions, respectively.

For the no ground control point based solution the obtained performance has to be discussed in more detail. In this case the absolute accuracy of object point determination is essentially dependent on the absolute accuracy of the GPS/inertial trajectory, which itself is based on the absolute performance of prior dGPS processing. Within the context of this ADS40 test campaign two independent dGPS solutions were calculated and involved in GPS/inertial trajectory computations. The two solutions mainly differ by absolute offsets of approx. 5cm and 2cm for vertical and north components, respectively, due to slightly different choice of dGPS processing parameters from two individual users. The one dGPS processing result from the ifp was used for the POSPac data integration with the Applanix units LN200 and AIMU. An independent second dGPS processing was done by IGI itself and integrated within their AEROoffice software to finally obtain the IMU-IId based integrated AEROcontrol trajectory information. Since the quality of dGPS trajectory is essential for the quality of the integrated solutions (mainly for the positioning component) any errors in the dGPS solution are directly shifted in the integrated solution.

# GCP / ChP	Accuracy	East [m]	North [m]	Vertical [m]
12 / 190	RMS	0.054	0.050	0.067
	Mean	0.008	-0.024	0.029
	Std.Dev.	0.054	0.044	0.061
	Max.Dev.	0.159	0.195	0.275
4 / 198	RMS	0.056	0.048	0.081
	Mean	0.009	-0.014	0.051
	Std.Dev.	0.055	0.046	0.062
	Max.Dev.	0.161	0.193	0.307
0 / 202	RMS	0.092	0.097	0.149
	Mean	0.074	-0.085	0.134
	Std.Dev.	0.055	0.048	0.065
	Max.Dev.	0.232	0.269	0.393

Table 5: ORIMA/CAP-A AIMU trajectory based geometric accuracy ADS40 test (h_g=1500m).

# GCP / ChP	Accuracy	East [m]	North [m]	Vertical [m]
12 / 190	RMS	0.056	0.042	0.061
	Mean	0.016	-0.015	0.012
	Std.Dev.	0.054	0.039	0.060
	Max.Dev.	0.132	0.159	0.219
4 / 198	RMS	0.062	0.042	0.084
	Mean	0.027	-0.014	0.059
	Std.Dev.	0.056	0.040	0.060
	Max.Dev.	0.146	0.162	0.264
0 / 202	RMS	0.086	0.061	0.098
	Mean	0.067	-0.044	0.076
	Std.Dev.	0.053	0.043	0.062
	Max.Dev.	0.189	0.203	0.301

Table 6: ORIMA/CAP-A IMU-IId trajectory based geometric accuracy ADS40 test (h_g=1500m).

Although this shift directly deteriorates the RMS values from check point analysis for the 0 GCP case – note that the difference of RMS values from AEROcontrol IMU-IId based trajectory (Table 6) to the RMS from POS/AV AIMU based trajectory (Table 5) exactly matches the already mentioned dGPS trajectory offsets in north and vertical component – the performance of both solutions is similar from a statistics point of view. The remaining shift in object space is very systematic. This indicates that with the use of one single ground control point only, the major part of this systematic error can be corrected, which will increase the accuracy significantly. In the ideal case – if the difference at the one available object point exactly matches the mean offset – the Std.Dev. values given in the tables above should be obtained as RMS accuracy.

4.3.3. Accuracy based on direct georeferencing approach

The results presented so far are based on the standard software processing line, where the AT component from ORIMA/CAP-A is maybe the most essential one. As it was briefly described above, this strategy is based on the orientation fix approach originally proposed by O. Hofmann. Alternatively the concept of direct georeferencing can be applied, which was substantially proposed by K.P. Schwarz and implemented in the ifp bundle dgap. By using this software module similar bundle adjustment configurations as already given in detail before were re-calculated and should be presented in the following. Due to some space limitations only the LN200 based trajectory solution is considered. It should be mentioned, that in contrary to the ORIMA/CAP-A philosophy within dgap the GPS/inertial exterior orientations are handled as fixed observations, i.e. the bundle fully relies on the correctness of these direct exterior orientations elements. This concept assumes, that the exterior orientations from GPS/inertial are of high quality, i.e. the inherent inertial error effects are effectively dampened from the GPS/inertial data integration. Remaining systematic errors in the trajectory (if present) can be modeled by simple polynomial corrections (offset and in some cases linear drift correction components), whereas these corrections are applied on the whole trajectory not only on small segments like this is case for ORIMA/CAP-A time intervals between the defined orientation fix points.

Within the subsequent Table 7 the corresponding accuracies are given for the LN200 based trajectory solution. Again the 1500m block is considered only. Please note, that the dgap AT is based on the use of manually measured points in PAN-A channels only, whereas the ORIMA/CAP-A runs are using the automatic tie point matches in all available channels in addition to the manually measured points. Again, only a minimal number of unknowns is introduced into AT, namely GPS position offset (for the GCP based cases) and the inherent boresight misalignment angles. If one compares these results to the numbers given in Table 4 (from standard ORIMA/CAP-A AT) a high consistency between both approaches is obvious. Even with the use of a relatively small number of image points only, dgap obtains similar results, which indirectly proofs the high and consistent accuracy of GPS/inertial trajectory determination. In this case there is no need to apply piece wise corrections terms to GPS/inertial exterior orientations as it is done within the ORIMA/CAP-A software. This shows that the approach based on the direct georeferencing model is feasible and might offer an attractive alternative to the orientation fix approach even for the ADS40 system. Nevertheless, the direct georeferencing model fully relies on the quality of GPS/inertial trajectory, and therefore might cause problems if very low performance GPS/inertial data are available only. It has to be tested, whether the orientation fix approach is more stable within such conditions.

# GCP / ChP	Accuracy	East [m]	North [m]	Vertical [m]
12 / 190	RMS	0.059	0.047	0.063
	Mean	-0.004	-0.017	0.006
	Std.Dev.	0.059	0.044	0.062
	Max.Dev.	0.183	0.138	0.232
4 / 198	RMS	0.059	0.049	0.065
	Mean	-0.005	-0.022	0.021
	Std.Dev.	0.059	0.044	0.061
	Max.Dev.	0.184	0.144	0.248
0 / 202	RMS	0.095	0.073	0.145
	Mean	0.075	-0.057	0.132
	Std.Dev.	0.059	0.044	0.061
	Max.Dev.	0.264	0.180	0.359

Table 7: dgap LN200 trajectory based geometric accuracy ADS40 test (h_g=1500m).

5. SUMMARY

Within this paper the use of test fields in photogrammetric processing was illustrated in general. After the short introduction on calibration methodologies the main part of the paper is dedicated to the presentation of geometrical ADS40 in-flight performance obtained from an extensive flight campaign in the Vaihingen/Enz test area. The finally obtained absolute accuracies from check point analysis independently proofed the very high geometric accuracy performance of the sensor system and the whole processing chain. Alternatives to the standard orientation fix approach could be pointed out by application of the direct georeferencing model within the AT process.

Due to limited space only a small sub-set of the comprehensive investigations has been presented within this paper. Additional tests have been done for example focusing on the analysis of the influence of variance component weighting in AT, the influence of additional image coordinate measurements in PAN-B and all MS channels, the object point performance related on real-time GPS/inertial trajectory computations and – quite important – the influence of additional self-calibration. All these tests were done for all different flying heights and are documented in the extended final project study report which is available at Leica Geosystems. Although non explicitly shown here, in all cases ADS40 fulfills the expectations and the push-broom concept again was re-confirmed from operational test flight data.

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REFERENCES

Becker, S., Haala, N. & Reulke, R. (2005): Determination and improvement of spatial resolution for digital aerial images, Proceedings ISPRS Workshop on High Resolution Earth Imaging, Hannover, May 17-20, 2005, digitally available on CD, 6 pages.

Brown, D. (1966): Decentring distortions of lenses, Journal of Photogrammetric Engineering and Remote Sensing, 32(3), pp. 444-462.

Brown, D. (1976): The bundle adjustment – progress and prospects, Invited paper of Com. III, XIII. ISP congress Helsinki, 33 pages

Cramer, M. (2005): Digital camera calibration and validation, GeoInformatics 2(8), March 2005, pp. 16-19.

Ebner, H. (1976): Self-calibrating block adjustment, Bildmessung und Luftbildwesen 44, p. 128-139.

Grün, A. (1978): Accuracy, reliability and statistics in close-range photogrammetry, Inter-congress symposium, International Society for Photogrammetry, Com. V, Stockholm, Sweden.

Hallert, B. (1954): A new method for the determination of the distortion and the inner orientation of cameras and projectors, Photogrammetria, 3, pp. 107-115.

Hallert, B. (1968): Notes on calibration of cameras and photographs in photogrammetry, Photogrammetria, 23, pp. 163-178.

Hinsken, L., Miller, S., Tempelmann, U., Uebbing, R. & Walker, S. (2002): Triangulation of LH Systems' ADS40 imagery using ORIMA GPS/IMU, IAPRS, Vol. XXXIV, Part 3A, Graz, Austria, 7 pages, digitally available on CD-Rom.

Hinz, A., Dörstel, C. & Heier, H. & (2000): Digital Modular Camera: System concept and data processing workflow, IAPRS, Vol. XXXIII, Part B1, Amsterdam, pp. 164-171, digitally on CD-Rom.

Hofmann, O., Kaltenecker, A. & Müller, F. (1993): Das flugzeuggestützte digitale Dreizeilenaufnahme- und Auswertesystem DPA - erste Erprobungsberichte. In: Photogrammetric Week '93, D. Fritsch/D. Hobbie (Eds.), Wichmann, Karlsruhe, pp. 97-107.

Hofmann, O. (1974): Studie über voll-elektronische Satellitenbild-Aufnahmesysteme im sichtbaren und nahen Infrarotbereich, Band I und II, durchgeführt von Messerschmidt- Bölkow-Blohm.

Honkavaara, E., Markelin, L., Ilves, R., Savolainen, P., Vilhomaa, J., Ahjokas, E., Jaakola, J. & Kaartinen, H. (2005): In-flight performance evaluation of digital photogrammetric sensors, Proceedings ISPRS Workshop on High Resolution Earth Imaging, Hannover, May 17-20, 2005, digitally available on CD, 5 pages.

Kupfer, G. (1971): Zur Geometrie des Luftbildes, Dissertation, Deutsche Geodätische Kommission DGK, Reihe C, No. 170, 73 pages.

Luhmann, T. (2000): Nahbereichsphotogrammetrie, Wichmann Verlag, Heidelberg, 571 pages.

Reulke, R., Tempelmann, U., Stallmann, D., Cramer, M. & Haala, N. (2004): Improvement of spatial resolution with staggered arrays as used in the airborne optical sensor ADS40, in Proceedings ISPRS congress, Istanbul, July 2004, digitally available on CD, 6 pages.

Rufe P. & Zanoni, V. (2004): Remote sensing characterization project, Digital camera product characterization, In situ test plan for aircraft flyover at Nasa Stennis Space Centre, USGS report digitally available at http://calval.cr.usgs.gov/documents/stennis_in_situ_test_plan_070104.pdf, Version 0.6, Status May 2004, 34 pages, accessed at July 7, 2005.

Sandau, R., Braunecker, B., Driescher, H., Eckart, A., Hilbert, S., Hutton, J., Kirchhofer, W., Lithopoulos, E., Reulke, R. & Wicki, S. (2000): Design principles of the LH Systems ADS40 airborne digital sensor, IAPRS, Vol. XXXIII, Part B1, Amsterdam, pp. 258-265, digitally on CD-Rom.

Sandau, R. & Eckhardt, A. (1996): The stereo camera family WAOSS/WAAC for spaceborne/airborne applications. International Archives of Photogrammetry and Remote Sensing, Vol. 31, Part B1, Vienna, Austria, pp. 170-175.

Schwarz, K. P., Chapman, M., Cannon, M. & Gong, P. (1993): An integrated INS/GPS approach to the georeferencing of remotely sensed data, Photogrammetric Engineering and Remote Sensing PE&RS, Vol. 59, No. 11, pp. 1667-1674.

Slama, C. (1980): Manual of photogrammetry, 4th Edition, American society of Photogrammetry, 1056 pages.

Torlegård, K. (1967): On the determination of interior orientation of close-up cameras under operational conditions using three dimensional test objects, Thesis Roy. Inst. Technol. Stockholm, 100 pages.

Wester-Ebbinghaus, W. (1983): Einzelstandpunkt Selbstkalibrierung – Ein Beitrag zur Feldkalibrierung von Aufnahmekammern, Dissertation, Deutsche Geodätische Kommission DGK, Reihe C, No. 289, 48 pages.

Wester-Ebbinghaus, W. (1985): Verfahren zur Feldkalibrierung von photogrammetrischen Aufnahmekammern im Nahbereich, in Kupfer/Wester-Ebbinghaus (Eds.): Kamerakalibrierung in der photogrammetrischen Praxis, Deutsche Geodätische Kommission DGK, Reihe B, No. 275, pp. 106-114.

Wewel, F., Scholten, F., Neukum, G. & Albertz, J. (1998): Digitale Luftbildaufnahme mit der HRSC – Ein Schritt in die Zukunft der Photogrammetrie, Photogrammetrie, Fernerkundung und Geoinformation PFG, 6, pp. 337-348.