Photogrammetric Week '07 Dieter Fritsch (Ed.) Wichmann Verlag, Heidelberg, 2007

The EuroSDR Performance Test for Digital Aerial Camera Systems

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ABSTRACT

This paper gives an overview on the EuroSDR project on Digital Camera Calibration and Validation and summarizes its main results. This project emphasises on the calibration and validation of digital airborne cameras, where mainly the geometric aspects were of concern. The project was officially finished in May 2007, after almost 3,5 years of project duration. Although the whole project was delayed due to several reasons (originally a 2 years period was planned) it finally was a very successful one. This was mainly due to the input of numerous experts forming the EuroSDR Digital Camera Calibration network and their continuous support and active participation in empirical processing of test flight data. This empirical second phase is covered in more detail within this paper. Three empirical test flights from ADS40, DMC and UltracamD sensors were made available to interested network members, then using their own software and expertise to obtain the optimal results for geometric accuracy. Different software and mathematical models were involved during processing, thus this test gives a broad overview on software, methodologies and expertise available for aerial triangulation of large-format digital airborne cameras. The empirical results clearly showed the importance of additional self-calibration during processing, which was necessary in all cases to obtain maximum geometric accuracy.

1. INTRODUCTION

With the advent of first digital airborne photogrammetric imaging sensors in operational environments an immediate focus on the quality and performance of such cameras appeared. There definite is a need for independent tests on sensor performance as well as investigations on the calibration of such digital mapping cameras. Calibration of mapping cameras is well established for the traditional analogue frame cameras but the process has to be modified when dealing with new digital sensors. Since the principle architecture of such digital systems is fairly heterogeneous (i.e. line scanning systems versus frame based solutions, multi-head large format systems versus single-head medium to small format systems, synchronous versus syntopic image data acquisition) individual procedures for system calibration are necessary. With an optional combination and in case of line scanning systems mandatory tight integration of additional GPS/inertial components this situation becomes even more complex. Within this context a need for new and accepted calibration procedures as well as certification processes is evident. Such procedures will not only support digital camera system suppliers but are also of help for potential digital camera users. All these facts defined the background where EuroSDR decided to start an initiative on digital camera calibration and validation.

In October 2003 the EuroSDR project on Digital Camera Calibration and Validation had been accepted and established officially. The goal was to derive the technical background for digital camera calibration and validation procedures based on scientific theory and empirical research. All this research was based on a network of international experts in digital imaging that had to be established first (see appendix). At the time of project initiation legal and certification aspects were put to the background for the time being.

1.1. The EuroSDR organization

The EuroSDR organization (European Spatial Data Research, see www.eurosdr.org) is a European user driven organization already founded in 1953 (formerly known as the OEEPE). Today 18 European countries are officially members of the organization, where each member state is represented by two delegates: One from the national mapping agency and the second representative from research institutions or companies, respectively. The mission of the organization is two-fold:

1. Develop and improve methods, systems and standards for the acquisition, processing, production, maintenance and dissemination of core geospatial information and promote applications of all such data, with special emphasis on the further development of airborne and spaceborne methods for data acquisition.
2. Encourage interaction between research organizations and the public and private sector to exchange ideas about relevant research problems and to transfer research results obtained to geoinformation production organizations.

The EuroSDR research activities are conducted by 5 scientific research commissions. These commissions are responsible for the initiation and coordination of scientific projects and workshops. From the very first beginning the main focus in research was laid on empirical performance tests in Europe. Substantial results for later practical use of new technologies for example were obtained in the field of analytical bundle block adjustment, GPS-supported aerial triangulation and GPS/inertial-based direct georeferencing. From this, the project on Digital Camera Calibration and Validation continues former research projects and fully corresponds to the aims of the organization.

1.2. Objectives of the digital camera calibration project

The project on digital camera calibration and validation itself was divided into two project phases.

1. Collection of publicly available material on digital airborne camera calibration to compile an extensive report describing the current practice and methods (Phase 1).
2. Empirical testing with focus on the development of commonly accepted procedure(s) for airborne camera calibration and validation, based on the experiences and advice of individual experts (Phase 2).

1.2.1. Theoretical phase 1

Phase 1 was already finished after the first project year end of 2004. This first year was mainly dedicated to start-up the project including the acquisition of individual experts to form the network. Besides that a comprehensive report was compiled documenting the different approaches for sensor calibration in general and the calibration methods for digital cameras applied from system manufacturers so far (Cramer 2004). The report is mainly based on extracts from already published scientific papers amended with additional input from the system providers directly, like exemplarily provided calibration protocols for ADS40, DMC and UltracamD systems. Additionally, the report is completed with an extensive bibliography on the topic of camera calibration including many of the fundamental publications. Many of these publications were also made available in digital PDF format. All this is publicly available. This phase 1 status report is also helpful for digital camera system users to gain their experience in digital camera calibration aspects.

The main conclusions from this theoretical phase 1 analysis are summarized like follows:

- A decreased use of standard collimator based laboratory calibration seems to be evident, whereas the importance of in-situ calibration is definitely increasing.
- Such in-situ calibrations, i.e. self-calibration determined from dedicated calibration flights, have to be done by the users regularly, in order to validate and refine the manufacturer's system calibration parameters.
- Due to the fact, that such self-calibrating techniques are not as common in the traditional airborne photogrammetry, clear knowledge deficits, concerning the features and advantages of system calibration in flight, are present right now on the users' side.

It is interesting to note, that in the 2.5 half years period after compiling the phase 1 report substantial changes in the manufacturers calibration procedures have taken place. Intergraph/ZI-Imaging for example has developed a new calibration stand, where now the geometric calibration of each individual DMC camera head is performed fully automatic (Hefele 2006). The maybe most interesting change was recently published by Tempelmann & Hinsken (2007). They introduced a modified parameter set for the geometric calibration of the ADS40 (2nd generation) camera. Now the exclusive calibration of ADS40 from calibration flights becomes feasible. No additional effort has to be spent in goniometer laboratory measurements any more. Such self-calibration is possible without any ground control, but a special calibration flight layout has to be followed (Tempelmann et al 2003).

1.2.2. Empirical phase 2

The second phase then focused on the empirical calibration and testing of a small number of data sets from different digital airborne cameras. In addition to the more theoretically oriented investigations of phase 1, in the second phase now the individual network members themselves were requested to investigate the performance of selected airborne cameras. Based on their individual software methodologies and knowledge the participants tried to obtain the overall best geometric result using most optimal system calibration for the evaluated flight campaign. In general, it was necessary to focus analysis on some of the technical aspects in a sequential order, starting with geometrical aspects and verification of accuracy potential. Analyses and discussions on radiometric and image quality aspects had been postponed to later follow up projects. Main aspect of this empirical phase was the development of recommendations of optimal procedures for the calibration and processing of digital image data. It clearly has to be pointed out that this **phase 2 did not emphasize on the direct comparison of geometric performance of different cameras**, but on the definition and testing of sensor related self-calibration approaches for each camera type individually. The results from this second phase will be discussed in more details below.

It was expected that not all of the network members actively participated in this second empirical phase. Nevertheless, finally altogether 13 different institutions participated in this part and returned their processing results to the pilot centre (Table 1). The pilot centre provided test flight data obtained from the three commercially available large format digital airborne cameras, namely the Leica Geosystems ADS40 (ADS) line scanning system and the Intergraph/ZI-Imaging DMC and Microsoft/Vexcel UltracamD (UCD) frame based systems. As one can see from the table several participants processed more than one data set. The ADS data was analyzed by three participants only, whereas the UCD and DMC flights were processed seven and eight times respectively. This distribution also was expected: A less number of photogrammetric institutions currently have the software and knowledge to handle line images with their specific geometry correctly. Since DMC and UCD provide standard frame based images, the already implemented standard process chains used for analogue imagery can be used in principle. Nevertheless, even when using DMC and UCD frame imagery some modifications in processing might become necessary which will be pointed out later.

In many cases the processing of data has been done using different configurations or parameter sets during bundle adjustment. Thus participants finally supported 157 different versions that had been evaluated by the pilot centre.

#	Institution	Code	Processed data set(s)
1	Institute Cartographic Catalunya, Barcelone, Spain	ICC	DMC
2	Lantmatäriet, Gävle, Sweden	LM	DMC
3	ITACYL, Valladolid, Spain	itacyl	UCD
4	Inpho, Stuttgart, Germany	inpho	DMC, UCD
5	CSIRO Information Sciences, Wembley, Australia	CSIRO	DMC, UCD
6	DLR, Berlin, Germany	DLR-B	ADS
7	University of Applied Science, Stuttgart, Germany	HfT	DMC
8	IPI, University of Hannover, Germany	IPI	DMC, UCD
9	ETH Zürich, Switzerland	ETH	ADS, DMC, UCD
10	University of Pavia, Italy	UoP	ADS
11	University of Nottingham, England	UoN	UCD
12	Intergraph/ZI-Imgaing, Aalen, Germany	IngrZI	DMC
13	Vexcel, Graz, Austria	Vexcel	UCD

Table 1: List of active participants in empirical phase 2

2. EMPIRICAL TEST FLIGHT DATA

The project activities in 2005 were mainly dedicated to find appropriate and publicly accessible empirical data sets for phase 2 analysis. Unfortunately there was no financial budget to perform test flights specially dedicated for this project. The original requirements on the test design were like follows: The sensors should have been flown in photogrammetric test ranges, providing a sufficient number of signalized ground control (GCP) and check points (ChP) – preferable all sensor data should have been acquired in the same test site. Additionally, the flight mission of each sensor should include two different flying heights. GPS/inertial data or at least GPS data should also have been available as additional information for the sensor's exterior orientations. Although several European national mapping agencies besides other companies kindly offered access on different test flight data, the finally chosen data sets were not able to fulfill all of the above requirements.

2.1. Photogrammetric test sites

In the end, two data sets acquired in the Norwegian Fredrikstad test site were exemplarily chosen for the DMC and UltracamD system. The DMC flight data were cordially provided by TerraTec (Norway), the UCD flights were made available through IFMS-Pasewalk (Germany). The Fredrikstad test site is one example of a specially designed photogrammetric test area with a sufficiently high number of signalized ground control points. The test site covers an area of 4.5 x 6 km² and consists of 51 well defined, permanently marked and regularly distributed control points. The accuracy of the GCPs in object space lies in the millimeter range. 20 of those points were made available and used as control points for the DMC and UCD processing. The remaining points were not distributed to the participants but used as independent check points for the absolute quality control performed. The site was already established in 1992 and is maintained by the Department of Mapping Sciences at the Agricultural University of Norway. It is already well-known to the EuroSDR/OEEPE user community from former performance tests like the OEEPE tests on GPS assisted aerial triangulation (Ackermann 1996) or integrated sensor orientation (Heipke et al 2002).

The ADS40 data set was flown in the German test field Vaihingen/Enz. This field is maintained from the Institut für Photogrammetrie (ifp) at Universität Stuttgart and is also well known from former tests of digital airborne sensors or independent performance evaluations of integrated GPS/inertial systems (Cramer 2005). The site covers an area of 7.5 x 4.8km², more than 200 points are available as signalized and coordinated control and check points. Their distribution follows the ideal point distribution for fully signalized medium-scale (1:13000) wide angle analogue camera flights with 60% forward and side-lap conditions. All points are independently determined from static GPS surveys, with an estimated accuracy of 2cm for all three coordinate components. Again, only a sub-set of 12 control points was distributed for the ADS data processing, the remaining points served as independent check points for later absolute performance checks.

Both test sites provide a sufficient number of control and check point information, all of them signalized, and therefore may serve as independent check points for geometric quality assurance. Since no radiometric or dedicated resolution targets were available for the time of flight only the geometric performance was investigated within phase 2.

At the time the selection empirical data sets for phase 2 had to be made, the three flights from the Fredrikstad (DMC and UCD) and Vaihingen/Enz (ADS) test sites was the only data made available to the pilot centre. Today, other data sets appeared, in some cases even more appropriate for such investigations. Especially the test flight activities from the Finnish Geodetic Institute FGI within their Sjökulla test site have to be mentioned within this context (i.e. Honkavaara et al 2006). None of those flights had been discovered within this EuroSDR test.

2.2. Sensor image flights

The basic characteristics of the three different sensor flights in the Fredrikstad and Vaihingen/Enz test sites are summarized in Table 2. All sensors were flown in two different flying heights resulting in different ground sampling distances (GSD) with individual block geometries. This can clearly be seen from the different overlap conditions.

The given ground sampling distance GSD is the theoretical value obtained from sensor pixel size and image scale. In case of ADS40 this value is related to the non-staggered image data. The given number of images relates to the different image strips (pixel carpets) recorded by each of the ADS40 sensor lines. Each flight line consists of data from six simultaneously recording CCD lines, namely the pan-chromatic forward, nadir and backward looking A and B lines. Since the whole strip is acquired by all CCDs from three different viewing angles, ADS40 per se provides 100% overlap in flight direction. Unfortunately, additional GPS/inertial data were only available for the ADS40 flight. In case of the DMC flight no additional GPS or GPS/inertial data was made available. For the UCD project a GPS trajectory was processed and delivered but since the GPS test set-up was sub-optimal (long base line length >100km) the obtained positioning accuracy was limited and influenced by systematic offset and drift errors.

Flight	Altitude a. g. [m]	GSD [m]	# strips long/cross	% overlap long/cross	# Images	Additional data
ADS40 Vaihingen/Enz, June 26, 2004						
low	1500	0.18	4 / 2	100 / 44	36	GPS/INS
high	2500	0.26	3 / 3	100 / 70	36	GPS/INS
DMC Fredrikstad, October 10, 2003						
low	950	0.10	5	60 / 30	115	n.a.
high	1800	0.18	3	60 / 30	34	n.a.
UCD Fredrikstad, September 16, 2004						
low	1900	0.17	4 / 1	80 / 60	131	GPS
high	3800	0.34	2	80 / 60	28	GPS

Table 2: Flight parameters of phase 2 digital sensor flights

Figure 1 illustrates the block geometry for the block *DMC high* and *UCD low*, respectively. Although both flights were done from close to 2000m flying height above ground resulting in approximately 0.2m GSD each, they are of quite different layout. Due to the larger overlap between strips and one additional cross strip the UCD block is of considerably stronger geometric strength than the DMC block. This also positively influences the accuracy of the later object point determination.

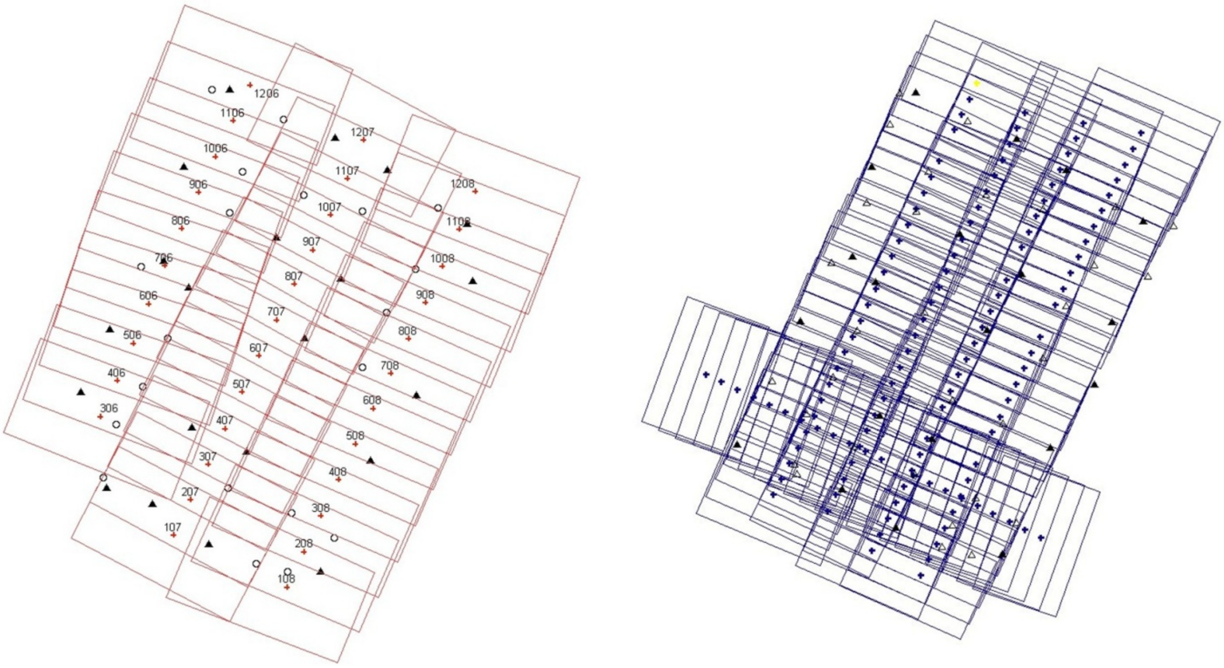


Figure 1: Block geometry of *DMC high* block (GSD 0.18m) (left) and *UCD low* block (GSD 0.17m) (right)

It has to be mentioned that both frame based systems were flown relatively late in the year (September 16 and October 10 for UCD and DMC respectively) at 60deg northern latitude. This results in sun angles between 25-30deg maximum which are quite demanding environmental conditions. This was of negative influence on the radiometric image data quality. Therefore the data is not being used for the analysis of radiometric performance of digital airborne imaging. Furthermore some of the participants rightly complained on the limited visibility of signalized points within the DMC and UCD data, also due to the somewhat limited radiometric image quality. This mainly affects the identification of image points and thus the performance of manual image coordinate measurements. In some cases of phase 2 evaluations not all check and control points had been measured. Therefore the pilot centre slightly modified phase 2 for DMC and UCD data. Within a second step image coordinates of all control and check points were manually measured very carefully by the pilot centre itself and then provided to all participants together with the automatic tie point measurements. Now all processing could rely on the same set of pre-defined image coordinates. This second step of phase 2 was then denoted as phase 2b. For ADS40 no pre-defined image coordinates were provided. In that case all measurements were individually done from the participants by using the obtained ADS40 image strips.

3. TEST FLIGHT ANALYSIS

As already mentioned the main focus was laid on the estimation of the empirical geometric accuracy of the sensor systems and the influence of additional parameter sets during processing. Thus all participants did their own manual and automatic image coordinate measurements first. In case of phase 2b data the pre-measured image coordinates were used. Those measurements then were used as input for the succeeding aerial triangulation which finally leads to the adjusted coordinates of check points. These adjusted check point coordinates then were returned to the pilot centre together with a brief report from each participant mainly describing the used additional parameters during their different adjustments. Since the reference coordinates of check points have not been provided to the participants before, they were used to obtain the absolute accuracy of bundle adjustment. Unfortunately some of the reports provided by participants were only very rudimentary including almost no or only little descriptions on the performed investigations. After the absolute accuracy checks the pilot centre also prepared a report for each participant including the detailed results of the individual calculations. The main results from the other test participants dealing with the same data were also presented, but provided anonymously only. Besides, the results from the processing at the pilot centre were also part of this report. Thus, each participant was able to judge the quality of his evaluations compared to the results from pilot centre and others. In some cases participants refined their processing and returned modified results afterwards.

All following results are exclusively obtained from the three flight campaigns described in the previous section. Note that the flights were done in 2003/04 already and therefore might not fully reflect the current performance of today’s digital sensor versions. Changes regarding hardware and sensor specific software processing might influence the sensor performance. Such changes are especially obvious for the UltracamD and ADS40 camera which recently have been modified and upgraded to UltracamX and ADS40, 2nd generation (Tempelmann & Hinsken 2007).

Table 3 shows the different software packages used for the image point measurement and the bundle adjustment, where image coordinate measurement was not necessary for the phase 2b data. As one can see almost all relevant software products used for measurements, point transfer and bundle adjustment were used during data processing. Besides, the additional parameter sets introduced for the different bundle adjustments are listed. In nearly all cases the participants tried different versions for their adjustments. Self-calibration was applied in general, but almost each participant also provided the solution without using additional parameters during AT. This was mostly done for comparison reasons. Besides standard additional parameter models, like orthogonal polynomials (Ebner or Grün model) or the physical relevant model provided by Brown, some evaluations were done with extended or modified additional parameter sets. These parameter sets were specially adapted to the camera specific sensor layout, i.e. the multi-head configurations of DMC and UCD camera. Typically the two different flight heights were handled as two separate flights. Only a few participants used both flying heights for simultaneous adjustment. All sensor related results will be presented in more detail in the following sub-sections.

Process step	**Software**
Matching and point measurement (only for phase 2)	Manual, Match-AT, LPS, ISAT, GPro, PhotoMod, others
Bundle adjustment	Match-AT, ORIMA, InBlock, BLUH, Bingo, PhotoMod, ACX-Geotex, IS-PhotoT, others

Data set	**Additional parameter sets** (if applied)
DMC	Ebner, Grün, Polynom, BLUH Ebner/Grün per image quadrant, BLUH DMC specific
UCD	Ebner, Grün, BLUH Ebner/Grün per image patch, BLUH UCD specific
ADS40	Brown (with some extensions)

Table 3: Applied software packages and additional parameter sets during phase 2 evaluations

3.1. ADS40 flight Vaihingen/Enz

3.1.1. Evaluations from pilot centre

The ADS40 flight data were part of a joined project of the Institut für Photogrammetrie (ifp) and Leica Geosystems. The whole processing of data was done by ifp, using the standard Leica process chain besides proprietary software products for bundle adjustment. More details on that test can be found in Cramer (2005). Again note, that GSD here relates to the non-staggered images, although the flight was done in so-called staggered mode. Nevertheless, images from A and B pan-chromatic CCD lines were always treated as separate images, no staggering was performed to fuse A and B lines for each of the three viewing directions. Table 4 shows the geometric absolute accuracy (RMS) from investigations at pilot centre obtained from 190 check point differences using standard GPro and ORIMA processing. 12 GCPs are introduced, exactly the same which also were provided to the participants.

ADS flight	Self-calibration	RMS [m]		
		East	North	Vertical
low, GSD 0.18m	not applied	0.052	0.054	0.077
low, GSD 0.18m	applied	0.031	0.040	0.057
high, GSD 0.26m	not applied	0.066	0.060	0.100
high, GSD 0.26m	applied	0.064	0.059	0.087

Table 4: ADS40 results from pilot centre

Both flights were considered individually. Within the first version no additional self-calibration terms had been introduced in the bundle adjustment. In other words, the adjustment was done based on image point measurements from all image channels, the 12 GCPs and GPS/inertial observations weighted with their accuracy estimated in Kalman filtering. Additional unknowns were introduced for the three boresight misalignment angles as well as for six GPS/inertial position and drift parameters, valid for the whole block only. Drift was almost not present. In the second run additional self-calibration was performed. The self-calibration model used by ORIMA can be related to the known Brown parameter model. Comparing the RMS values from both versions it is clearly obvious that in case of this ADS40 data sets additional self-calibration is only of minor influence on the resulting object point accuracy. The obtained refinement is very small for the *ADS high* flight, and of slightly larger influence for the *ADS low* block.

3.1.2. ADS results from participants

As already mentioned in Table 1 only DLR-B, UoP and ETH focused on the ADS data. ETH only considered the 1500m block *ADS low*. The analyses were restricted to the bundle adjustment only, image coordinates were provided by the pilot centre on request of ETH. The used software for point transfer and triangulation of three line sensor (TLS) imagery has been developed at the ETH Zürich. The mathematical model and the methods of self-calibration are published in Kocaman et al (2006). DLR-B also used an own processing chain to evaluate the ADS data. This software chain was originally developed for the orientation, DTM generation and orthophoto production of HRSC data (Scholten et al 2002). The results from UoP were achieved using standard Leica Geosystem processing software, i.e. GPro for tie point transfer and ORIMA for bundle adjustment. All participants investigated the two different flying heights as separated blocks, DLR-B later averaged the results from *ADS high* and *ADS low* to get the final coordinates of control points. Unfortunately DLR-B was not able to provide the separated set of estimated ChP coordinates, thus their results are not included in Figure 2 showing the exemplarily results (RMS accuracy) for the *ADS low* block only. The grayed-out accuracy bars indicate those versions calculated without additional self-calibration. The obtained accuracy (RMS) for the DLR-B processing is about rms_X=0.042m, rms_Y=0.042m and rms_Z=0.082m for the east, north and vertical coordinates respectively. No additional self-calibration was applied during processing, thus those results are consistent to the other results obtained without self-calibration.

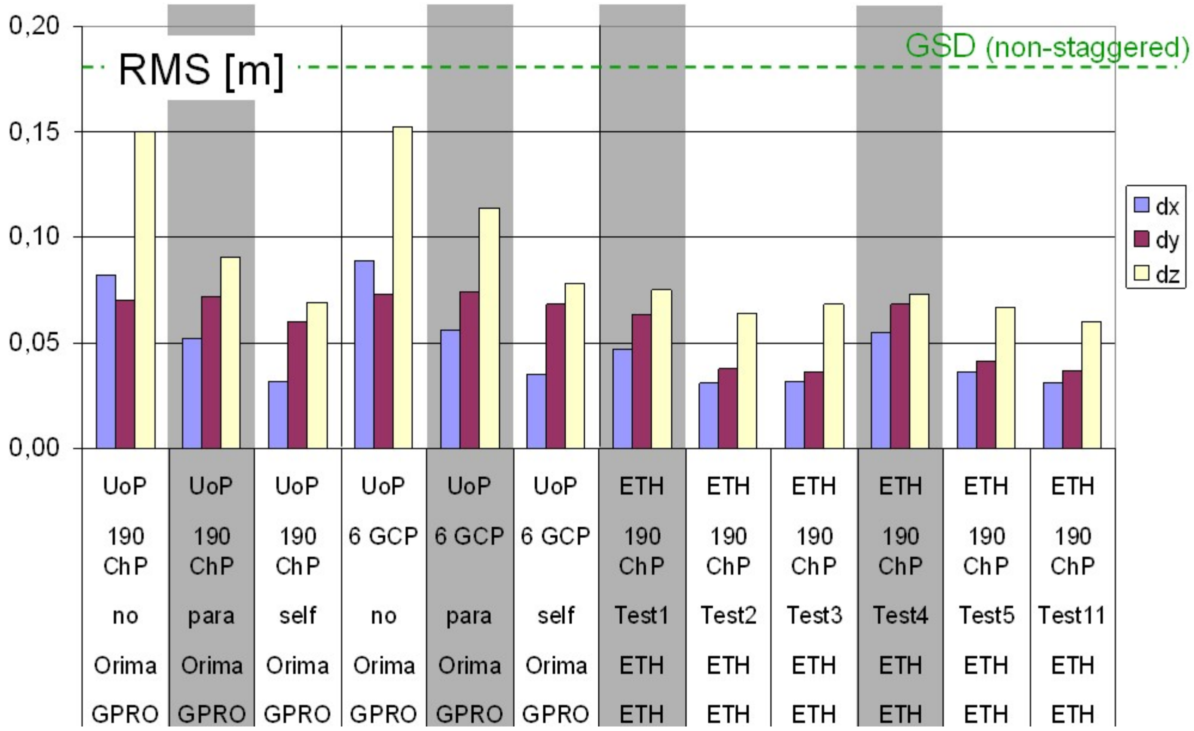


Figure 2: Accuracy (RMS) from *ADS low* data processing of participants (phase 2)

ETH did a very detailed analysis of data. The software supported different trajectory models, to estimate the dynamics of sensor movements. The lagrange interpolation model (LIM) and the direct georeferencing model (DGR) were used here. The LIM approach is similar to the orientation fix points in the ORIMA processing, whereas the DGR model relies more on the performance of a priori GPS/inertial trajectory information. The ETH versions *Test1*, *Test2*, *Test3* and *Test11* are using the DGR model, the remaining two are based on the LIM approach. Additionally, the number of self-calibration parameters was varied. In *Test2*, *Test5* and *Test11* a full set of 18 additional parameters was introduced: namely 6 parameters describing the camera lens behavior (1 focal length correction, 3 radial and 2 tangential distortions) amended by 4 additional parameters for each of the three scan-lines / viewing directions (2 principal point corrections, 1 scan line inclination, 1 affinity across flight direction). In *Test3* six of those parameters were eliminated. Note that all versions except of the last version *Test11* only used a sub-set of four of the 12 provided GCP. In general the DGR based versions obtained high qualities, the more advanced LIM model does not improve the accuracy. This also indicates the high performance GPS/inertial trajectory computations. Using DGR with self-calibration obtains the best results. The RMS values are rms_X=0.031m, rms_Y=0.037m and rms_Z=0.060m, which is fully consistent to the results from pilot centre processing.

In UoP processing two different GCP configurations were used. Besides the use of all 12 GCP again a sub-set including only 6 GCP was established. Three different versions have been calculated for both GCP configurations: The first version *no* does not use additional self-calibration parameters and also does not correct for IMU misalignment errors and GPS/inertial position drift and datum effects. Thus the second version *para* coincides with the no self-calibration case of pilot centre evaluations. Here the additional parameters like IMU misalignment, datum transform and position drift are considered. Finally the version *self* also includes additional self-calibration. Comparing the results to the ETH results and the results from pilot centre, the UoP results are slightly less accurate. Especially in north component a systematic error seems to be present. The difference in north direction showed a mean offset of about 5cm, which deteriorates the RMS value.

3.2. DMC and UCD flights Fredrikstad

3.2.1. Evaluations from pilot centre

During processing of the Fredrikstad flights the pilot centre used different versions for each of the two flying heights of each camera. Within the first step conventional bundle adjustment without additional parameters was performend, based on 20 GCP. The obtained RMS values from check point analysis for DMC data are like follows: rms_X=0.097m, rms_Y=0.054m and rms_Z=0.14m. These numbers relate to the *DMC low* block (GSD 0.1m). Then the additional 44 parameters proposed by Grün were introduced. This mainly refines the accuracy in east component. The accuracy obtained from *DMC low* is: rms_X=0.056m, rms_Y=0.054m and rms_Z=0.124m. Again only 20 GCP are used. Now the horizontal coordinates are of the same accuracy, the systematic error is compensated. The vertical accuracy is only marginally influenced. In the final step all available ground control (GCP and check points) was used to optimally determine the additional 44 parameters. Than the estimated parameters were fixed and a conventional AT was performed, again based on 20 GCP only. The check point analysis results in RMS values of rms_X=0.048m, rms_Y=0.047m and rms_Z=0.116m (*DMC low* block). This solution was used as “reference” solution. It has to be mentioned, that this solution, although all signalized object points had been used for control information, non-necessarily is the best solution. The self-calibration is based on a standard polynomial correction model only, which might be sub-optimal for the modeling of the 4 camera head geometry of the DMC and UCD.

Furthermore the choice of observation weights also influences the final solutions. So far all versions were based on observation standard deviations of 3µm for image coordinates and 0.02m for horizontal and vertical control points. If for example the first, no self-calibration case is done with the following assumptions on standard deviations (image coordinates 1.2µm (automatic tie point transfer) and 3.6µm (manual measured image points), control points 0.01m for horizontal and vertical components) the obtained RMS values from check point analysis are significantly worse, mainly for the vertical component: rms_X=0.118m, rms_Y=0.051m and rms_Z=0.247m. This clearly illustrates, that besides the choice of the mathematical model for self-calibration, the correct assumptions on a priori weights are also of major concern and in some cases might also have larger impact on the final accuracy than the applied parameter set for self-calibration.

Finally, for all UCD and DMC flights the processing was performed using the 44 parameters optimally estimated from all available control information on the ground and than used as fixed values. The chosen observation standard deviations were as follows: 3µm for image coordinates and 0.02m for all control point coordinates. This finally results in the absolute accuracy (RMS) as given in Table 5. It is quite interesting to see that *DMC high* and *DMC low* show almost the same accuracy, although in general lower altitude flights should allow for better geometric accuracy. This might be due to the following reasons: First, the estimated sigma0, which is one factor within error propagation, is higher for the *DMC low* than for the *DMC high* flight. Second, the relative number of control points per image is higher for the *DMC high* block. Furthermore there are no control points within the side lap regions between two strips for the *DMC low* flight. This is especially of concern, since no GPS data was provided. And finally some errors in the control point object coordinates or some systematic errors in object space due to shadowing or meadows will influence the accuracy of signalized points. This also is of higher impact for lower altitude than higher altitude flights. Also remember the demanding radiometric quality of image data, which negatively affects the correct identification of points.

For the UCD flights similar performance is visible for the horizontal coordinates. Although the difference between the two UCD flying heights is about 2km, the horizontal accuracy is almost similar and comparable to the DMC accuracy. For the vertical component the UCD flights are of very high accuracy. This is mainly due to the very large overlaps resulting in much stronger block geometries than for the DMC blocks.

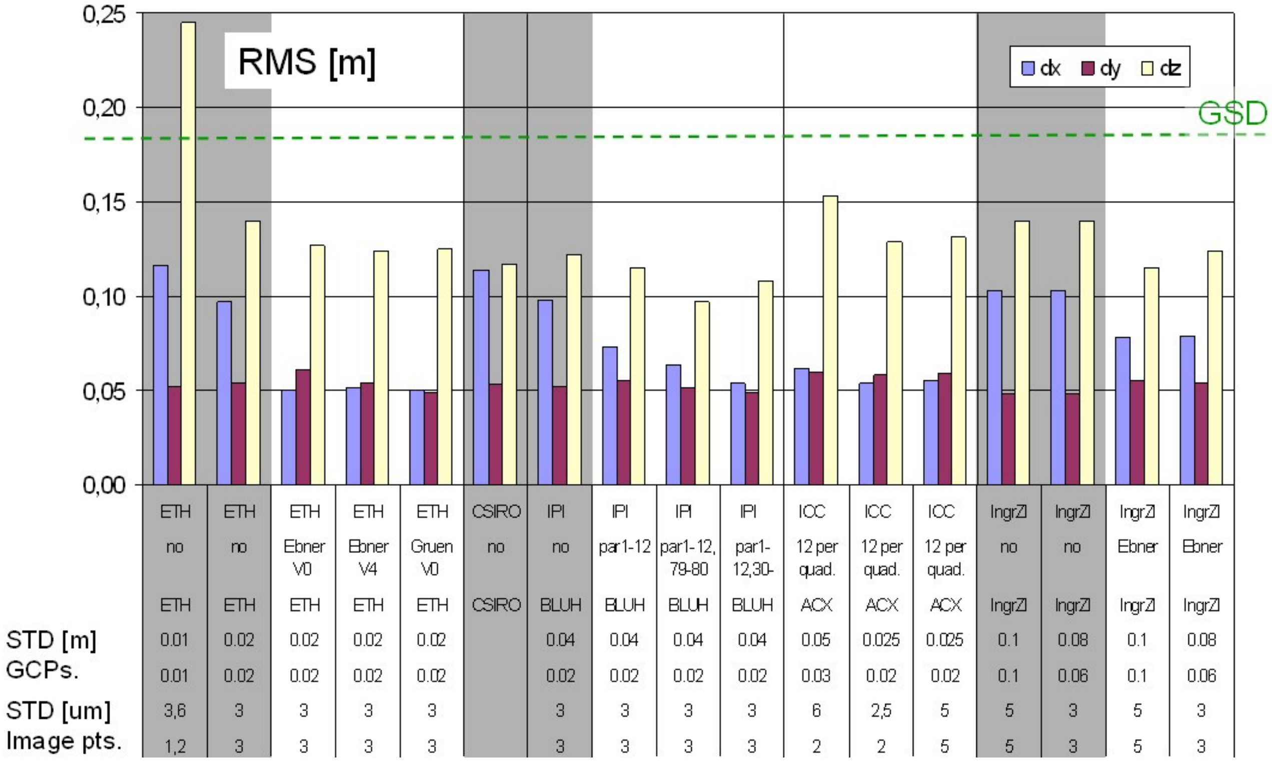
Flight	**Flying height, GSD**	**RMS [m]**		
		East	**North**	**Vertical**
DMC low	950m, 0.10m	0.040	0.048	0.132
DMC high	1800m, 0.18m	0.048	0.047	0.116
UCD low	1900m, 0.17m	0.076	0.060	0.059
UCD high	3800m, 0.34m	0.048	0.068	0.103

Table 5: DMC and UCD results from pilot centre

3.2.2. DMC results from participants

Eight different institutions participated in the evaluation of the DMC flights. Three of them were active in both phase 2 and phase 2b, namely ICC, IPI and IngrZI. Inpho, HfT and LM only provided input for phase 2, where ETH and CSIRO only participated in phase 2b. In all cases the image blocks were handled separately, except from IPI and CSIRO evaluations, where also a simultaneous block adjustment of both flying heights was done. Inpho only provided results from combined adjustment of *DMC low* and *DMC high*. ICC, IPI and ETH used modified or specially designed self-calibration models to take care of the specific DMC sensor geometry. ICC introduces one set of Ebner correction polynomials for each of the four DMC image quadrants. IPI used the BLUH program offering different and flexible sets of additional parameters (Jacobsen 2007). The ETH software approach is similar to ICC, but also the Grün parameters could be introduced per image quadrant in addition to the Ebner model, as it is done at ICC. The others worked with the already known correction models, like Ebner, Grün or Brown physical parameters.

Some more detailed results from the *DMC high* block are shown in Figure 3. Only results from phase 2b processing are given here. Again the grayed-out parts of the figure indicate results from versions calculated without additional self-calibration parameters. Besides participant code, calculated version and software used for AT the used a priori standard deviations for control points (horizontal and vertical) and image coordinates (automatic and manually measure tie points) are mentioned at the bottom of that figure. Since all participants rely on the same pre-measured set of image coordinates (phase 2b results), the obtained RMS values are directly comparable. The deviations are only due to the input standard deviations and the mathematical model of self-calibration, if applied. In case of the no self-calibration cases shown in the grayed-out parts of the diagram, the variations are only due to the variations in input standard deviations. Especially note the large variation in height accuracy (RMS) ranging from 0.247m to 0.117m and the corresponding standard deviations. ETH for example provides two no self-calibration cases with two different sets of input standard deviations, the influence is obvious. In the remaining ETH versions *Ebner V0*, *Ebner V4* and *Gruen V9*, 12 Ebner or 44 Grün parameters are estimated for the four quadrants of DMC pan-chromatic large format virtual images. The data was similarly processed by ICC, but using the 12 Ebner parameters only. Again note the different input standard deviations and their influence in RMS values. A very detailed analysis was done by IPI using the BLUH bundle adjustment. Three different self-calibrating versions were provided. The first version *par1-12* is based on the 12 parameter model implemented in BLUH. These 12 parameters are defined as combination of physical relevant and pure mathematical coefficients and cannot be compared to the 12 Ebner parameters. In the second self-calibrating version *par1-12,79-80* those 12 parameters are amended by additional two parameters, modeling the common viewing angle and the common effect of radial symmetric distortions for all four camera heads together. In the final third version a more complex model is introduced: 4 additional parameters for DMC synchronization, 8 parameters for DMC perspective deformation of individual cameras and 4 parameters for DMC radial symmetric distortion of original images are used to take care of the individual camera head geometry, besides the standard 12 BLUH parameters. As one can see, this last version slightly improves the quality in horizontal coordinates, but in vertical axis the accuracy is slightly worse compared to the second self-calibration case. Within the IngrZI evaluations the traditional 12 Ebner parameters were used for self-calibration. This parameter set seems to be non-sufficient to fully compensate the remaining systematic in the images, the RMS in east component is still higher than for the north component as it already was seen from the non self-calibrating case. Again note the different weightings, which in this case are only of smaller influence on the final accuracy.



	ETH	ETH	ETH	ETH	ETH	CSIRO	IPI	IPI	IPI	IPI	ICC	ICC	ICC	IngrZI	IngrZI	IngrZI	IngrZI
	no	no	Ebner V0	Ebner V4	Gruen V0	no	no	par1-12	par1-12, 79-80	par1-12,30-	12 per quad.	12 per quad.	12 per quad.	no	no	Ebner	Ebner
	ETH	ETH	ETH	ETH	ETH	CSIRO	BLUH	BLUH	BLUH	BLUH	ACX	ACX	ACX	IngrZI	IngrZI	IngrZI	IngrZI
STD [m]	0.01	0.02	0.02	0.02	0.02		0.04	0.04	0.04	0.04	0.05	0.025	0.025	0.1	0.08	0.1	0.08
GCPs.	0.01	0.02	0.02	0.02	0.02		0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.1	0.06	0.1	0.06
STD [um]	3,6	3	3	3	3		3	3	3	3	6	2,5	5	5	3	5	3
Image pts.	1,2	3	3	3	3		3	3	3	3	2	2	5	5	3	5	3

Figure 3: Accuracy (RMS) from *DMC high* data processing of participants (phase 2b)

3.2.3. UCD results from participants

Finally some of the results from UCD evaluations should be presented. As mentioned before, seven different institutions participated in the processing of UCD data. CSIRO and IPI participated in both phase 2 and phase 2b. Those two also were the only ones, who both looked at the flights combined and separately. Inpho provided results from common adjustment of both UCD flying heights only. UoN, itacyl and inpho participated in phase 2, ETH and Vexcel provided results for phase 2b only. Itacyl only focused on the processing of *UCD low* flight.

As for all the other test data most participants provided results from different versions to be evaluated at pilot centre. UoN used the standard Brown parameters and a proprietary (IESSG) approach for self-calibration, but also provided a non self-calibration version. Itacyl only provides a non self-calibration case, but with the use of GPS offset and drift parameters. They "prefer to avoid using of autocorrelation parameters, because the ones included in Match-AT are specific for film cameras". Nevertheless, as results from other evaluations showed, self-calibration is certainly of positive influence on the object point accuracy, even when the parameter sets originally designed for film-based single optic systems are used. The inpho results were based on Grün and Brown parameter models, but estimated from simultaneous adjustment of both flights.

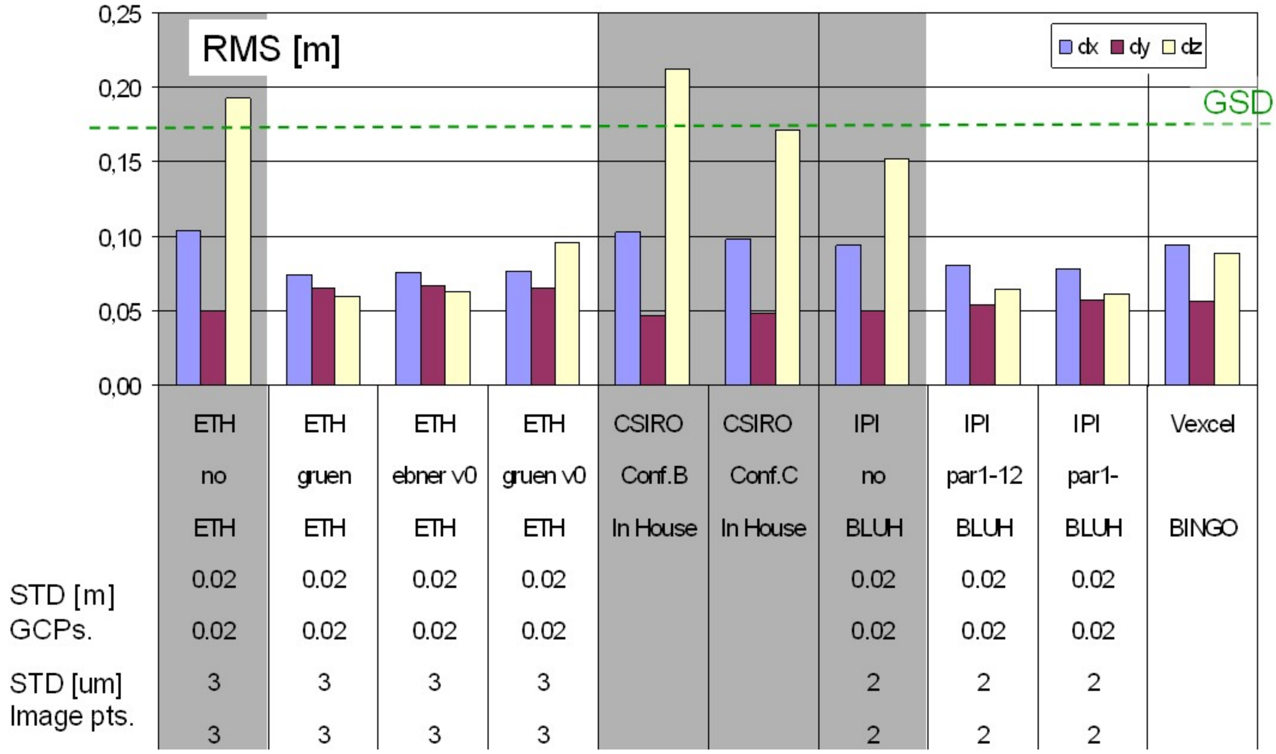


Figure 4: Accuracy (RMS) from *UCD low* data processing of participants (phase 2b)

Figure 4 again shows some more details from phase 2b results. Comparing the non self-calibration cases again a systematic effect influencing the accuracy of east component is obvious. Also compare the variations in RMS values, due to the variations in input standard deviations. In case of the CSIRO processing, the control points were used as fixed observations. Two different versions were considered: *Conf.B* only used the 4 long strips, whereas *Conf.C* used all flight lines (4 long strips and 1 cross strip). Comparing the self-calibrating cases again two different approaches are visible: the first one uses the standard already available models, in the second case modified approaches are defined to describe the UCD geometry more specific. The ETH versions considered both types of parameter sets. Within the *gruen* version the 44 parameters were used for the whole UCD image. This version is similar to the processing at pilot centre. In case of the *ebner v0* and *gruen v0* versions the 12 Ebner or 44 Grün parameters are introduced separately for each of the nine image patches forming the virtual large format UCD image. This second approach does not increase the accuracy significantly. Again very extensive tests of the influence of different self-calibration parameter sets have been done by IPI, only two self-calibrating versions besides the no self-calibration case are mentioned here. For self-calibration again the 12 BLUH parameters (second case, version *par1-12*) were amended by additional UCD specific camera parameters (third case, version *par1-*). These 32 UCD specific parameters comprise 8 scale factors, 18 shift parameters and 8 rotations, all of them related to the individual image patch with respect to one reference CCD patch. Similar to the ETH evaluations this more complex and UCD adapted model is only of marginal influence on the resulting accuracy. Finally the results from the Vexcel evaluations are given. The results were based on Bingo software, unfortunately no detailed information on applied self-calibration model or weightings had been given so far.

4. SUMMARY AND CONCLUSIONS

Although the previous Section 3 already illustrated some of the detailed results from individual evaluations by test participants, only a first insight view on the comprehensive material of this project was possible. The most important findings obtained from that are summarized like follows:

- Self-calibration is obviously necessary to improve the quality of object point determination for all three tested camera systems ADS, DMC and UCD. With self-calibrating aerial triangulation for the ADS flight the horizontal accuracy is in the range of 1/5 pixel and the vertical accuracy in the range of 0.04‰ of flying height. For DMC the accuracy is about 1/4 - 1/3 pixel and 0.05-0.1‰ of flying height. And finally in case of UCD the resulting accuracy is about 1/4 - 1/2 pixel horizontal and 0.03‰ of flying height for vertical component. Again note, these values are obtained from the three empirical test data sets only and are always dependent on the applied mathematical model. Each block has its own geometry. In case of UCD and DMC the radiometric quality might also be of influence on the obtained accuracy. Thus those numbers cannot be transferred to other projects in general but have to be verified from additional investigations.
- The obtained accuracy increase in object point determination using self-calibration is higher for DMC and UCD compared to ADS. Additionally the systematic corrections for UCD are more significant compared to DMC.
- In some cases specially designed self-calibration parameter sets adapted to sensor geometry are necessary. For ADS the standard model based on Brown parameters is sufficient. For the frame based systems DMC and UCD extended or modified self-calibration models had been used. Alternatively high order correction polynomials like the 44 parameter Grün model in some cases also lead to accurate results. The use of only 12 additional parameters like Ebner or the BLUH standard parameters definitely is not sufficient to compensate for the systematic errors.
- Besides self-calibration model the a priori weighting of observations is of larger influence. In some case the choice of weighting factors even exceeds the influence of the applied self-calibration model.

It is quite interesting to see that all three system manufactures participated in this project started to look into more detail to their software processing again to overcome the need for such self-calibration methods. Intergraph/ZI-Imaging for example has already established a special task group to explore and solve for the reasons of the systematic errors in imagery. Similar investigations are done at Microsoft/Vexcel. The modifications within the ADS calibration had already been mentioned before. These manufacturer initiatives were surly pushed by investigations such as this EuroSDR project.

Unfortunately the final report including all participants' results and their individual reports is still pending. It should be compiled in later fall 2007 and then will publicly made available through the project web site www.ifp.uni-stuttgart.de/eurosdr/index.html. Later the final report also including the phase 1 report will become part of the official EuroSDR publication series.

5. OUTLOOK

Just recently decisions on follow-up projects have been made within the EuroSDR group. Two new projects will start end of 2007 that will cover aspects that have not been treated in the Digital Camera Calibration and Validation initiative. The first project is already ready to go and will deal with the *geometric and radiometric performance of digital medium format cameras*. Currently considerable developments in medium format cameras are obvious (several systems providing up to 39Mpix resolution like IGI dIGIcam, Rollei AIC, DiMAC, Applanix DSS and others). Such cameras will play growing future role in photogrammetric market, besides large format systems. The Universität Rostock was addressed as partner to set up this project. Dr. Görres Grenzdörffer, Institute for Geodesy and Geoinformatics will be the project leader. He has already lots of experiences in the development of smaller to medium format digital camera systems mainly used for remote sensing and precision farming applications. In addition, a second project should focus on the *radiometric performance of large format digital cameras* in detail. Project chairs are not yet fixed but first positive responses are already available. This activity should also investigate the influence of pan-sharpening, which is often used in processing of large format sensor image data.

The most important EuroSDR decision was to officially instigate a project to take forward the issue of *European Digital Airborne Camera Certification – EuroDAC²* by EuroSDR. The coordination is between the European National Mapping and Cadastre Agencies (NMCAs) while cooperating closely with all relevant digital airborne mapping camera suppliers and other experts. As NMCAs from eighteen states are currently members of EuroSDR most European NMCAs are involved in this project already. The initiative will lead to a European wide accepted certification procedure substituting the traditional analogue mapping camera certification. Certification of new digital camera systems is a hot issue worldwide today. Many of those activities are driven by the quality assurance plan developed by the US Geological Survey USGS. Close co-operations have already been established between EuroSDR and USGS to align both concepts as much as possible. Details on those initiatives will also be published in Cramer (2007) and Christopherson (2007).

Any expert interested in any of those new activities is cordially invited to contact EuroSDR directly!

6. ACKNOWLEDGEMENTS

The author would like to acknowledge all members of the Digital Camera Network for their continuous support and fruitful discussions. Special thank has to be expressed to all people and institutions actively involved in the empirical phase 2 evaluations. Without their contributions the results of this project would not have been possible. The author also would like to thank the system suppliers Leica Geosystems, Intergraph/ZI-Imaging and Microsoft/Vexcel and for supporting this project and the companies TerraTec (Norway) and IFMS-Pasewalk (Germany) for data provision. Very special thank finally has to be expressed to my dear colleague Werner Schneider who did most of the data handling and preparation and also was responsible for all the tedious and time consuming image measurements and final accuracy checks!

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APPENDIX

Members of the EuroSDR Digital Camera Calibration network (Status as of July 2007)

#	Organization	Network member
System providers		
I.1	ADS 40, Leica Geosystems	U. Tempelmann, P. Fricker, Dr. U. Beisl, Dr. G. Ferrano
I.2	DMC, Intergraph/ZI-Imaging	C. Dörstel, Dr. M. Madani
I.3	Ultracam, Microsoft/Vexcel	Dr. M. Gruber
I.4	DIMAC, Dimac Systems	P. Louis, J. Losseau
I.5	DSS, Applanix Corp.	Dr. M. Mostafa
I.6	Starimager, Starlabo Corp.	Dr. K. Tsuno
I.7	3-DAS-1, Wherli & Ass. Inc.	Dr. H. Wherli
I.8	DigiCAM, IGI mbh	Dr. J. Kremer, M. Müller
Industry & other software developers		
II.1	ISTAR	Dr. P. Nonin
II.2	GEOSYS Technology Solutions	Dr. B. Ameri
II.3	Vito	Mr. J. Everaerts
II.4	Optical Metrology Centre	Dr. T. Clarke
II.5	ORIMA	Dr. L. Hinsken
II.6	inpho	T. Heuchel
II.7	DLR Oberpfaffenhofen	Prof. M. Schroeder, Dr. P. Reinartz, Dr. R. Müller, Dr. M. Lehner
II.8	DLR Berlin	F. Scholten, K. Gwinner
II.9	dgap	D. Stallmann
II.10	CSIRO	X. Wu
II.11	stereocarto	T. F. de Sevilla Riaza
II.12	Geosense Ltd.	A. Clarence
University		
III.1	Ohio State University	Prof. T. Schenk, Prof. D. Merchant
III.2	ETH Zürich	Prof. A. Grün, Dr. M. Baltsavias, S. Kocaman, H. Eisenbeiss, J. A. Parian
III.3	University of Glasgow	Prof. G. Petrie
III.4	University of Rostock	Dr. G. Grenzdörffer
III.5	University of Stuttgart	Dr. N. Haala, Dr. M. Cramer
III.6	University of Hannover	Prof. C. Heipke, Dr. K. Jacobsen
III.7	Humboldt University Berlin	Prof. R. Reulke
III.8	University of Applied Sciences Stuttgart	Prof. E. Gülch
III.9	University of Applied Sciences Anhalt	Prof. H. Ziemann
III.10	Institute de Geomatica Castelldefels	Dr. I. Colomina
III.11	Agricultural University of Norway Aas	Dr. I. Maalen-Johansen
III.12	University of Nottingham	Dr. M. Smith
III.13	University of Pavia	Prof. V. Casella, Dr. M. Franzini
III.14	University of Leon	B. A. Pérez
III.15	University of Hamburg	Prof. H. Spitzer

#	Organization	Network member
National mapping agencies & other authorities		
IV.1	Swedish Land Survey	Dr. D. Klang, D. Akerman
IV.2	Finnish Geodetic Institute	Prof. R. Kuittinen, Prof. J. Hyppä
IV.3	British Ordnance Survey	P. Marshall
IV.4	Swisstopo – Landestopographie, Suisse	Dr. A. Streilein, Dr. S. Bovet
IV.5	US Geological Survey	G. Stensaas, Dr. G. Y. G. Lee, J. Christopherson
IV.6	ICC Barcelona	Dr. J. Talaya, R. Alamus
IV.7	IGN France	Dr. M. Deseilligny
IV.8	Bundesamt für Eich- und Vermessungswesen, Austria	M. Franzen
IV.9	Instituto Cartográfico Valenciano	R. Fernández
IV.10	ITACYL - Junta de Castila y León	D. A. Nafría
IV.11	Bayrisches Landesamt für Vermessung	W. Stößel
IV.12	Institut Géographique National, Belgium	J. Théatre, S. Roovers