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Digital Airborne Camera Performance – The DGPF Test

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ABSTRACT

In 2008 a comprehensive project on the empirical investigation of the performance of digital photogrammetric airborne cameras was performed under the umbrella of the German Society of Photogorammetry, Remote Sensinsing and Geoinformation (DGPF). This project includes empirical test flights in the test field Vaihingen/Enz. Data are currently under investigation, where different working topics have been defined to structure this evaluation phase. More than 25 institutions are already actively participating. In addition to previously done projects, where main focus typically was laid on the geometric sensor performance only, the DGPF project also aims on the analysis of radiometric performance and the investigation of product quality like digital photogrammetric surface models and manual stereo plotting. This paper will introduce the project itself and present some of the findings, mainly focussing on the geometrical topics first. Even though the processing of the very complex data sets is not yet finished, the high potential of digital airborne imaging is already proven.

1. INTRODUCTION

Digital airborne imaging is now established in operational applications. About 10 years after presentation of first digital large format sensor concepts at least 250-300 of the large format systems of Leica Geosystems ADS, Intergraph DMC and Vexcel Imaging Ultracam are sold worldwide. If other large format systems and especially the medium format based camera set-ups are considered the number of operational systems increases significantly. Even though digital sensors are established in production lines, the empirical testing and independent evaluation of these systems is an ongoing issue. Such tests are frequently driven by individual institutions or even national or international organizations. Primarily they help to gain knowledge in digital camera performance which is then for example used for decision-making when changing from analogue to digital sensor flights. Despite the fact, that some national mapping agencies decided to switch to digital image recording and abandon their old analogue cameras and film development equipment, comprehensive testing of the latest generation digital sensor systems including the quality analysis of sensor products (i.e. covering the whole process line) was typically not considered so far (see e.g. [Passini & Jacobsen 2008], [Cramer 2007]). This was one motivation for the German society of Photogrammetry, Remote Sensing and Geoinformation (DGPF) to define a test bed to comprehensively analyse the performance of photogrammetric digital airborne camera systems. Focus is laid on airborne and large format photogrammetric sensor system. The test is not limited to sensor performance but also investigates on the software processing chain which is another important component when photogrammetric products are of interest. In order to allow for a comprehensive analysis, the data had to be captured in similar test flight conditions and controlled environments. For this purpose comprehensive flight campaigns were realized in the Vaihingen/Enz photogrammetric test site, established and maintained by the Institut für Photogrammetrie (ifp), Universität Stuttgart. During the camera test, the ifp served as pilot centre during data collection and preparation and also managed the data distribution to the various participants.

The data is made available for all types of institutions ranging from science, mapping authorities, photogrammetric companies and sensor providers. Meanwhile, more than 25 different institutions have signed the project agreement where their main focus of planned analyses and their corresponding schedule is defined. Almost all participants requested and received their respective data sets. Fig. 1 illustrates the composition of the project group, divided in institutions from research, national mapping or other organizations and companies, the later also including the system providers and manufacturers themselves. As expected the majority of participants is from the scientific sector. 20% is covered by representatives from mapping organizations, which represents one of the later user groups. The remaining one third of participating institutions is from the commercial field. The complete list of project members can be found in the Appendix B of the paper. One of the key ideas of the project is to form a network of expertise from these institutions. In order to structure this cooperation during data evaluation, four working groups were established which are focusing on the topics geometry, radiometry, digital surface models and stereo plotting. The different focus of individual participating members and groups can also be seen from the appendix. Since many of the participants are from photogrammetric background, the traditional topics geometry and surface model generation are more nicely covered than analysis of radiometric aspects, so far.

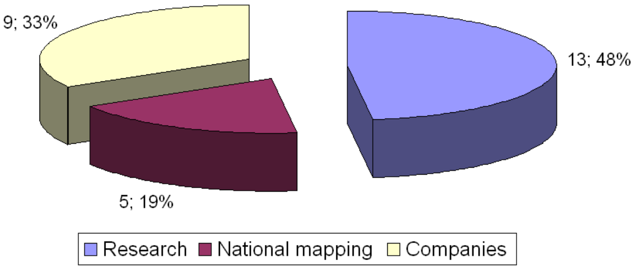

Fig. 1: Participating institutions.

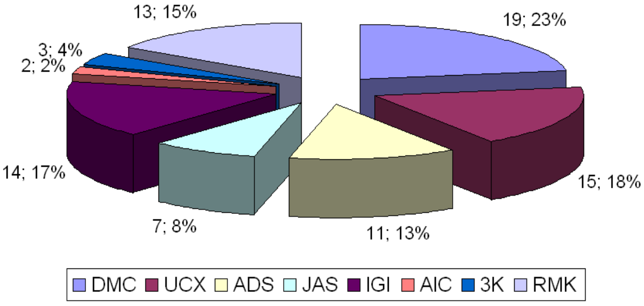

Fig. 2: Distributed data sets.

The main objective of this DGPF test is not to directly compare performance of the different sensors but to evaluate the sensor specific strengths and maybe weaknesses, which are of relevance when later choosing a sensor for specific applications. Still, all findings obtained from this test always are based on the results of the DGPF test flights only and have to be confirmed from other tests.

After a presentation of the data collection phase of the test (airborne sensors and ground reference data) in the following section, this paper tries to give an overview on the ongoing investigations. This report concentrates on issues of geometric sensor accuracy. During the tests frame based camera systems DMC, Ultracam-X and Quattro DigiCAM and line scanning systems ADS40 and JAS-150 were investigated, in order to compare their performance to the performance from classical analogue cameras (RMK-Top15). The findings from digital surface model generation are presented in [Haala 2009]. First comprehensive presentation of results of the participating groups was also done at the annual DGPF meeting in Jena in March, 2009. Additionally a project web site (in German) is available to document project progress and disseminate most recent information [DGPF 2009].

2. DATA ACQUISITION

The data collection was realised in the photogrammetric test site Vaihingen/Enz close to Stuttgart, which is already known from other performance tests [Cramer 2005]. It comprises close to 200 signalized and coordinated reference ground points distributed in a 7.4 x 4.7 km² area. For the DGPF flight campaign the center area of the test field with densified control point distribution (area covers 5.1 x 2.8 km²) was defined for flights with smaller GSD values. This was to minimize data volume and flight effort.

The imaging data was flown at 6 different flight days during a 10 weeks time window starting beginning of July till mid of September 2008. Originally a much shorter 2 weeks time period was planned for data acquisition, which could not be realized due to weather conditions. The different flight campaigns from summer 2008 are listed in Table 1. Most sensors were flown in two different flying heights, resulting in two blocks with previously defined different ground sampling distances (GSD), namely GSD 20cm and GSD 8cm (nominal values). The GSD 20cm blocks covered the whole test area; the GSD 8cm blocks were limited to the center part. Additional flights were done with a Leica ALS 50 LiDAR and the AISA+ and ROSIS hyper-spectral scanners in order to later use this data as reference for the photogrammetrically derived surface models and multi-spectral land cover classification. Again, these reference data flights were done in the center part of the test field only. Valuable findings are also expected from the flights done with a double-hole aircraft installation: DMC images were taken parallel to the AISA+ hyper-spectral data and parallel to the RMK-Top15 camera. Since both sensors are recorded simultaneously, direct comparison of data taken under same environmental conditions is possible.

System	System provider / manufacturer	System flyer	Day(s) of flight	Remark
DMC	Intergraph/ZI	RWE Power	24.07.2008 & 06.08.2008	double-hole flight with RMK-Top15 GSD 8cm with p=60%
ADS40, SH52	Leica Geosystems	Leica Geosystems	06.08.2008	
JAS-150	Jenaoptronik	RWE Power	09.09.2008	
Ultracam-X	Vexcel Imaging Graz	bsf Swissphoto	11.09.2008	
RMK-Top15	Intergraph/ZI	RWE Power	24.07.2008 & 06.08.2008	double-hole flight with DMC GSD 8cm with p=60%
Quattro DigiCAM	IGI	Geoplana	06.08.2008	
AIC-x1	Rolleimetric	Alpha Luftbild	11.09.2008	only GSD 8cm
AIC-x4	Rolleimetric	Vulcan Air	19.09.2008	data not yet made available for project
DLR 3K-camera	DLR Munich	DLR Munich	15.07.2008	only GSD 20cm
AISA+ hyper-spectral	specim FH Anhalt	RWE Power	02.07.2008	double-hole flight with DMC
ROSIS hyper-spectral	DLR München	DLR Munich	15.07.2008	
ALS 50 LiDAR	Leica Geosystems	Leica Geosystems	21.08.2008	

Table 1: Participating sensor systems and flying companies.

The GSD 20cm blocks were flown with p=60% overlap, whereas for the GSD 8cm block a higher forward overlap of 80% was aspired. Due to the fixed test site extensions and different sensor formats slight modifications of the block geometry were necessary (mainly on side lap conditions) which potentially influences the later comparison of sensor performances. Additionally not all cameras finally fulfilled these overlap requirements. Some of the sensors were only flown in one flying height (namely the AIC-x1 and 3K-camera flight), other data sets were influenced by technical problems. The detailed block configurations and flight parameters for RMK-Top15, DMC, Ultracam-X, Quattro DigiCAM and ADS40 can be seen in Appendix A. More information on the data sets and flight conditions could be accessed from the DGPF project web site [DGPF 2009].

Variations in weather conditions also have to be considered especially when looking for the radiometric sensor performance. Almost all flights were affected by clouds. Additionally, due to the test period of more than 2 months, there were significant changes in vegetation and sun angle. Some of the flights were done quite early in the morning, others were flown around noontime.

In all cases the sensor flight data was delivered through the system manufacturer itself to the project pilot centre. All manufacturers had access to 19 ground control points to check that their data sets are consistent and comparable to other flights. This was done before the data was sent to the pilot centre for further dissemination. Obviously some of the sensor providers used the reference points to already go into deeper analysis of the sensor performance. Thus, the finally delivered data sets not in all cases may fully reflect the standard quality (status of pre-processing) of a data set which is obtained in a typical operational survey mission scenario.

In addition to Table 1, which shows the in principle available data sets, Fig. 2 illustrates the number of data set requests and distributions to participants. Close to 60% of the distributed data sets are from frame based systems DMC, Ultracam-X and Quattro DigiCAM, all of them using a multi-head configuration for large area coverage. The data from line scanner systems ADS40 and JAS-150 are covering about 20% of data requests. 15% of delivered data sets are from the RMK flights, which were mainly taken for direct comparison to digital data. The data from smaller format systems AIC-x1 and 3K are of minor interest so far (about 5% of data requests). Such distribution by percentage of requests reflects the current main focus and expertise within the participants group. Obviously the majority of institutions is preferring frame based large format data. Nevertheless, the project also offers the possibility to get access to well controlled data sets from new sensors with different sensor geometries. Some of the project members also took this opportunity to become familiar with other data. This also was one of the intentions of this DGPF test.

Spectrometer measurements were done on the ground, parallel to the sensor flights to get ground references for the later atmospheric corrections and sensor calibrations. This was supported by sun-photometer measurements, which determine the optical depth of the atmosphere, and thus also reflect weather and cloud conditions during the flights. Bidirectional reflectance values were acquired with a special BRDF measurement set-up. Spectrometer measurements were done for artificial and natural targets, but only a few natural objects like asphalt or grass surfaces have been measured but not consistently for all flight campaigns. Fig. 3 shows this radiometric test range which is located east of Vaihingen/Enz and covered by both the GSD 8cm and GSD 20cm flights. The artificial colour targets and different resolution test targets (Siemens star) can be seen. The large Siemens star is of 8m diameter, all other targets are of 2x2m² size. It has to be mentioned that the relatively small colour targets typically were only sufficient for the GSD 8cm flights, especially when the original colour information is considered with less spatial resolution compared to pan-chromatic images. This is the case for the DMC and Ultracam-X frame based sensor systems, where coloured large format images are obtained from pan-sharpening. For radiometric analysis the original colour information before pan-sharpening is of main interest. The remaining frame sensors AIC, Quattro DigiCAM and 3K-Camera use the Bayer pattern for colour generation.

The spectrometer reference measurements are basis for an on-site absolute radiometric sensor calibration (so-called vicarious calibration). Such calibration originally was planned. First investigations using the known ATCOR program [Richter 2009] for atmospheric correction were already done. Unfortunately, this analysis finally showed that the spectral behaviour of the almost exclusively measured artificial colour targets is quite different from natural targets. The terrestrial photo in Fig. 3 already shows a strong directional reflectance behaviour which is not expected for natural targets. Additional neighbouring effects from the surrounding grass due to the limited size of the targets finally prevent the aspired absolute radiometric calibration of the airborne sensors [Schönermark et al., 2009].

To finally complete the reference data for comprehensive radiometric performance analysis, extensive field-walkings were done for documentation of different land use. This especially was quite time consuming, because surveys had to be repeated several times in order to document the changes in land coverage due to the quite long flight interval [Klonus et al., 2009].

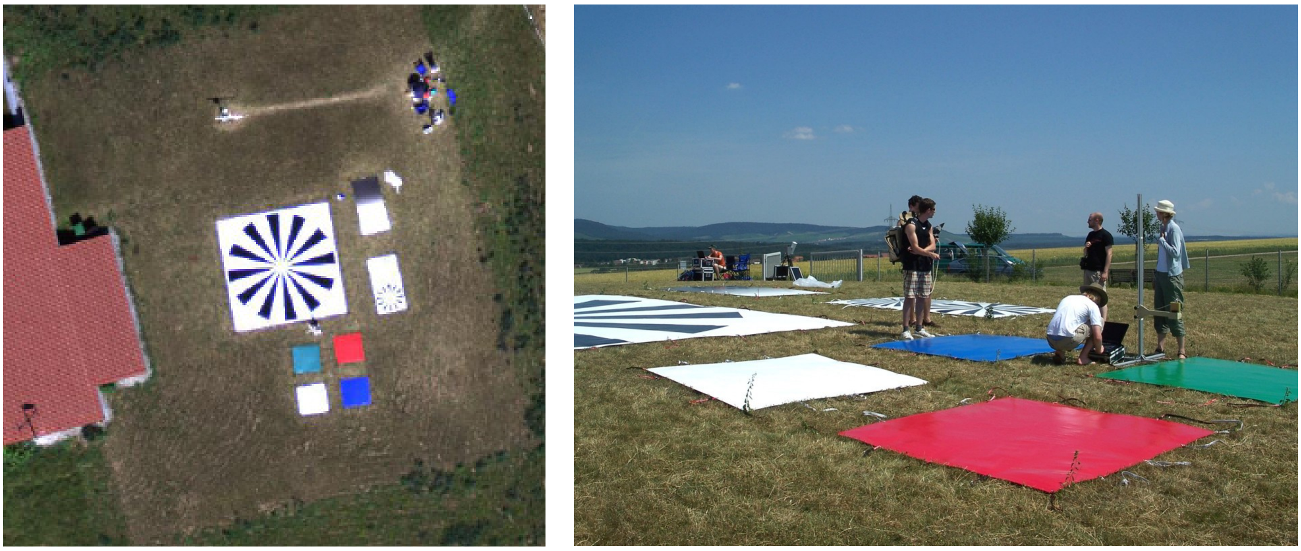

Fig. 3: Vaihingen/Enz radiometric test field from the air (left) and ground team members performing spectrometer measurements parallel to sensor flights (right). Note that airborne and terrestrial image were taken on two different flight days, i.e. the four colour targets were arranged in different order.

3. GEOMETRIC ACCURACY ANALYSES

As already mentioned the DGPF project is structured in four different working topics. Besides analysis of the geometric and radiometric sensor performance, the evaluation of sensor products like image based automatic surface models or manual stereoplotting is of concern. This not only reflects the quality of the individual sensor but also covers the corresponding software processing chain. The process of product generation and to a certain extent the radiometric performance investigations (i.e. BRDF analysis) rely on results from geometric data processing. The exterior orientation is essential information for the product generation process. It is obtained from aerial triangulation, which is deeply analysed from the experts in the geometrical aspects group. In order to avoid delays in the evaluation of automatic surface models and stereo plotting, it was decided that a nominal set of exterior orientation elements was prepared by pilot centre. For later comparison all products are based on these nominal exterior orientation elements. These nominal values not necessarily represent the most optimal result for sensor orientation – this will be one of the results of the geometry group – but still should be accurate enough for use in the working packages automated DSM generation and stereoplotting. Nominal orientation values so far have been delivered for DMC, Ultracam-X, Quattro DigiCAM and RMK-Top15 data. These exterior orientation parameters are based on a self-calibrating bundle adjustment using all available control point information. The results from this adjustment, i.e. image coordinates corrected by self-calibration and all adjusted object coordinates are then used in an absolute image orientation process. All this is described in detail in [Cramer & Haala 2009].

3.1. Dense control point distribution

In order to estimate absolute accuracy, the differences at independent check points are of concern. Within this part results from (self-calibrating) aerial triangulation using a dense distribution of control points are presented. For the results obtained at Institut für Photogrammetrie, Universität Stuttgart control points at least at the border of each block and in 5 additional control point chains, perpendicular to the main flight direction have been used. No additional observations from GPS/inertial sensors were introduced. Image coordinates used for these bundle adjustments already have been corrected by the estimated influence of self-calibration, based on all available control points. The standard 44 parameter model was used. Thus no additional self-calibration was considered here, but results are based on the already pre-corrected image coordinates. The additionally presented evaluations from TU Graz (Institut für Fernerkundung und Photogrammetrie) are based on 82 and 59 control points for the RMK-Top15 flights GSD 8cm and GSD 20cm. For the Quattro DigiCAM GSD 20cm block 109 control points were considered. The later block relied on manual tie point measurement, because the software used for the automatic transfer of tie points (Intergraph ImageStation AT) was not able to handle the large number of smaller images with high overlaps. This is different to experiences at Universität Stuttgart, where the inpho Match-AT was able to handle the convergent image geometry in automatic tie point matching. Remember that the Quattro DigiCAM concept – so far – does not apply any image stitching to form large format virtual images from the individual convergent camera heads. In all cases physical relevant corrections for camera interior orientation and balanced radial distortion are introduced for self-calibration during the TU Graz adjustments resulting in altogether 5 additional parameters. The processing from TU Graz is given in detail in Ladstädter & Kaufmann [2009].
The Table 2 andTable 3 now show the results from check point analysis separated for the GSD 20cm and GSD 8cm blocks, all based on dense control point distributions. The empirical RMS values from check point differences and the theoretical accuracy (standard deviation STD from Qxx matrix) of object point determination from inversion of normal equations are given. Results from digital sensors are compared to the RMK-Top results. Nevertheless, for inter-system comparisons always take into account the different flight and block conditions (see Appendix A).

Institution	Image block	# GCP / ChP	ChP diff. / RMS [m]			STD [m]		
			ΔX	ΔY	ΔZ	σX	σY	σZ
Uni Stuttgart	RMK 47 photos	70 / 116	0.03	0.04	0.05	0.03	0.04	0.07
TU Graz	RMK with GPS	82 / 66	0.04	0.04	0.10	0.03	0.03	0.05
Uni Stuttgart	DMC 60 photos	70 / 114	0.03	0.04	0.08	0.02	0.02	0.06
Uni Stuttgart	Ultracam-X 52 photos	70 / 112	0.03	0.03	0.07	0.02	0.02	0.06
Uni Stuttgart	DigiCAM 188 photos	70 / 116	0.04	0.05	0.09	0.02	0.03	0.09
TU Graz	DigiCAM with GPS/IMU	109 / 73	0.05	0.05	0.08	0.03	0.03	0.07

Table 2: Empirical accuracy RMS and STD – GSD 20cm (dense control point distribution).

Institution	Image block	# GCP / ChP	ChP diff. / RMS [m]			STD [m]		
			ΔX	ΔY	ΔZ	σX	σY	σZ
Uni Stuttgart	RMK 74 photos	60 / 48	0.02	0.02	0.03	0.01	0.02	0.03
TU Graz	RMK with GPS	60 / 48	0.02	0.02	0.03	0.01	0.02	0.03
Uni Stuttgart	DMC 136 photos	60 / 47	0.02	0.02	0.04	0.01	0.01	0.02
Uni Stuttgart	Ultracam-X 215 photos	60 / 50	0.01	0.02	0.04	0.01	0.01	0.02
Uni Stuttgart	DigiCAM 784 photos	60 / 50	0.02	0.02	0.03	0.01	0.01	0.02

Table 3: Empirical accuracy RMS and STD – GSD 8cm (dense control point distribution).

The obtained accuracy from these adjustments is very similar for all sensor systems. Also results from TU Graz and Universität Stuttgart are close. The absolute accuracy RMS (horizontal component) is in the range of ¼ pix or better related to GSD for both flying heights. For the vertical component, an accuracy of ½ pix and better is obtained. When the empirical RMS values are compared to the estimated STD from error propagation, good agreement can be seen for the vertical axis. In case of the horizontal components the theoretical accuracy higher compared to the RMS values (mostly close to factor 2). This may indicate small not completely modeled errors. In this case the accuracy of reference point determination (based on static GPS base line observations) also is of influence. Since the GPS reference coordinates are determined with an accuracy of 1cm for horizontal and 2cm for vertical coordinates, the accuracy of object points from bundle adjustment is already in the accuracy range of the reference points.
Obviously the 44 parameter model used by Uni Stuttgart to pre-correct the image coordinates delivers sufficient accuracy for all sensor systems. Since this self-calibration model is implemented in most of the bundle adjustment software it can be used for a pragmatic processing of digital image blocks. Still it has to be confirmed, whether this pragmatic approach is also valid for larger blocks from operational flights environments. On the other hand the number of additional parameters to compensate for systematic effects should always be as low as possible in order to keep the block geometry stable. From this point of view the TU Graz approach has to be preferred where only a small but meaningful number of physical parameters was introduced. Except for the RMK GSD 20cm block, where the height accuracy is different to the Uni Stuttgart solution, the performances of the Quattro DigiCAM GSD 20cm and RMK GSD 8cm blocks are equivalent. The appropriate choice of self-calibration model is also discussed in the next paper section.

3.2. More realistic control point distribution

As already mentioned the above results for geometric accuracy investigations are based on fairly dense control point distributions which could not be expected for later production environments. Thus, the results above may give a too optimistic estimation of the geometrical accuracy potential of the sensors. Such accuracy not necessarily could be expected for later operational (more realistic) sensor flights when less control points are used and larger blocks are flown. Additionally the use of already pre-corrected image coordinates as done in the previous processing of Uni Stuttgart is not available for operational projects. Thus the so far presented object point accuracy only might be achieved in optimal conditions.

Institution	Image block	# GCP / ChP	ChP diff. / RMS [m]			STD [m]		
			ΔX	ΔY	ΔZ	σX	σY	σZ
Uni Hannover	RMK 47 photos	14 / 82	0.12	0.13	0.08	n.a.	n.a.	n.a.
Uni Hannover	DMC 60 photos	9 / 95	0.04	0.06	0.06	n.a.	n.a.	n.a.
Uni Stuttgart	DMC, 42 photos with GPS/IMU	4 / 180	0.04	0.07	0.11	0.03	0.04	0.10
Uni Hannover	Ultracam-X 52 photos	9 / 99	0.08	0.08	0.08	n.a.	n.a.	n.a.
Uni Stuttgart	Ultracam-X 36 photos with GPS/IMU	4 / 180	0.06	0.06	0.15	0.02	0.03	0.09
Uni Stuttgart	DigiCAM 132 photos with GPS/IMU	4 / 161	0.07	0.10	0.27	0.03	0.04	0.10

Table 4: Empirical accuracy RMS and STD – GSD 20cm (realistic control point distribution).

Institution	Image block	# GCP / ChP	ChP diff. / RMS [m]			STD [m]		
			ΔX	ΔY	ΔZ	σX	σY	σZ
Uni Hannover	RMK 74 photos	14 / 40	0.02	0.04	0.05	n.a.	n.a.	n.a.
Uni Hannover	DMC 135 photos	9 / 45	0.03	0.03	0.04	n.a.	n.a.	n.a.
Uni Stuttgart	DMC 110 photos with GPS/IMU	4 / 113	0.03	0.04	0.05	0.01	0.02	0.03
Uni Hannover	Ultracam-X 215 photos	9 / 99	0.04	0.07	0.04	n.a.	n.a.	n.a.
Uni Stuttgart	Ultracam-X 175 photos with GPS/IMU	4 / 111	0.06	0.03	0.04	0.01	0.01	0.03
Uni Stuttgart	DigiCAM 640 photos with GPS/IMU	4 / 114	0.04	0.07	0.08	0.01	0.01	0.03

Table 5: Empirical accuracy RMS and STD – GSD 8cm (realistic control point distribution).

In order to allow for a more realistic accuracy assessment, the number of control points was now decreased. Results from Institut für Photogrammetrie und Geoinformation at Leibniz Universität Hannover and Universität Stuttgart are given here. In all cases additional parameters have been applied during bundle adjustment. The results of Uni Hannover are obtained from the BLUH program, which allows for different, sensor specific additional parameter models. All details on the BLUH results are published in Jacobsen [2009]. The results from Uni Stuttgart are based on the use of the 44 parameter model, where only the significantly estimated parameters are finally considered. Additionally, the images from the two cross strips have not been used during adjustment, since cross strips might not be flown in later applications, especially when GPS/IMU trajectory information is available. This explains the less number of images per block for Uni Stuttgart –

compared to the Uni Hannover, where all images of all strips have been considered for all flights. For the results from Uni Stuttgart GPS/IMU data are used as weighted observations (integrated sensor orientation). The Uni Hannover has only introduced control points. The number of check points is always different, because not all of the points were visible and measurable in all images. Additionally, a part of the check points were not made public to all other DGPF project members and therefore are only available for the evaluations at Uni Stuttgart. The theoretical accuracy of object point determination (standard deviation STD from Qxx) was not reported by Uni Hannover. Thus these values are not included in the Table 4 and Table 5. These tables now list the results from the bundle adjustments for the three evaluated camera systems DMC, Ultracam-X and Quattro DigiCAM. Even though the configurations applied during the bundle adjustment are fairly heterogeneous (i.e. differences in number of control points, self-calibration model, block geometry, use with/without GPS/IMU observations, different image observations) the finally obtained accuracy from check point analysis is quite consistent. Some noticeable remarks are discussed like follows: The empirical horizontal accuracy (RMS) from RMK images GSD 20cm is worse compared to the other digital sensor systems. This might be influenced by the less accurate image point identification and measurement in scanned analogue images which is due to the less radiometric resolution of analogue scanned images. Since the identification of 60x60cm² targets is more accurate in the higher resolved RMK GSD 8cm images, the obtained accuracy for GSD 8cm is similar to the digital sensors. The results from DMC GSD 8cm blocks are very similar for both institutions but differences can be seen in vertical performance from DMC GSD 20cm. Similar behaviour can also be seen for the Ultracam-X data sets. This on the one hand obviously shows the positive influence of cross strips, which especially for the GSD 20cm blocks cover large parts of the block area and thus allow for a strong overlap, image connection and block geometry. If for example the DMC GSD 20cm block is adjusted still using the 44 parameters but all available images, the accuracy in the vertical component (RMS) is increased to ΔZ=0.09m. The remaining differences in vertical components are most likely due to the use of different self-calibration models. Obviously, the DMC and Ultracam-X camera specific parameters in BLUH are of slightly better performance compared to the 44 parameter model applied by Uni Stuttgart at least for the vertical components. But again, differences are mainly present in the GSD 20cm blocks, not in the GSD 8cm blocks. This underlines the sensitivity of additional parameter models on the individual block geometry which is not new but already known from analogue image blocks. The performance of the Quattro DigiCAM system is almost similar to the large format digital sensors. Since the four images from the Quattro DigiCAM configuration are not merged to obtain a larger format virtual image self-calibration parameters are applied for each sensor head separately. Different to all the other evaluations at Uni Stuttgart only 12 additional Ebner parameters per camera head have been applied for the Quattro DigiCAM. Furthermore, use of the 44 parameters per camera head deteriorated the obtained RMS values, again mainly in vertical component. For the GSD 20cm block for example a vertical accuracy (RMS) of only ΔZ=0.27m was obtained when using the 44 parameter model per camera head. This again illustrates the impact of not appropriately chosen self-calibration models. The demand now is to previously decide on the most optimal self-calibration model for individual sensor and block configurations.

3.3. Line scanning sensor systems

As it was already seen from Table 1, other camera systems have also been flown in the project. Unfortunately the ADS40 and JAS-150 data sets have not been redundantly evaluated so far. Results for ADS40 line scanners are obtained from Jacobsen [2009]. The processing of JAS-150 from RAG Herne colleagues was done in Jena, since the JAS-150 software environment was not available to them. Their results have been documented in an internal report [Spreckels 2009a].

Unfortunately the exact number of check points for the different adjustments was not given there, but the use of least 50 check points, similar to all other evaluations, could be expected.

Institution	Image block	# GCP / ChP	ChP differences / RMS [m]		
			ΔX	ΔY	ΔZ
Uni Hannover	ADS40 GSD 8cm	9 / 52	0.02	0.04	0.05
RAG Herne	JAS-150 GSD 8cm	4 / >50	0.02	0.02	0.05
RAG Herne	JAS-150 GSD 8cm	19 / >50	0.02	0.02	0.04
RAG Herne	JAS-150 GSD 20cm	4 / >50	0.02	0.02	0.05
RAG Herne	JAS-150 GSD 20cm	19 / >50	0.02	0.02	0.07

Table 6: Empirical accuracy RMS for line scanning systems.

Table 6 now depicts the performance (RMS) of line scanning systems ADS40 and JAS-150. For the JAS-150 additional self-calibration parameters have been applied. No information on the use of additional parameters is documented by Uni Hannover. The obtained accuracy of both systems is very similar and at least is fully comparable to the results obtained from frame based sensors. One also might get the impression, that even though the used number of control points is relatively low, the obtained accuracy RMS supersedes the results based on dense control point distributions in Table 2 and Table 3. It is also interesting to see that results from GSD 20cm and GSD 8cm blocks from JAS-150 are almost of same accuracy, which should not be expected. Altogether, since these promising results are based on first evaluations only, they have to be verified from other test participants and through other data sets.

4. FURTHER PROJECT EVALUATIONS

The paper so far has focused on the evaluations of geometric accuracy performance, which is one of the main project topics. As already briefly mentioned in the introductory section of the paper other evaluation topics are focusing on the analysis of radiometric performance, the generation of digital surface models and the performance of manual stereo plotting. The investigations on automatic DSM generation are presented in detail in Haala [2009]. The working group radiometry focuses on the radiometric characterizations of sensors and how their radiometric potential can be used for the later automatic land use classifications. Results are presented in Hanusch & Baltsavias [2009], Schönermark et al. [2009] and Klonus et al. [2009]. Limitations from available data sets due to the sub-optimal weather conditions and reference targets and measurements, will unfortunately not allow for the full analysis of radiometric sensor characteristics and absolute radiometric sensor calibration. The evaluations from manual stereo plotting are currently mainly based on the analyses done by Spreckels [2009b]. Redundant processing is highly aspired to guarantee for a broad analysis und various slightly different aspects and to increase the scientific impact of this study.

5. COMMENTS AND CONCLUSIONS

Although the processing of the DGPF test flight data is still ongoing the benefits of digital image recording for photogrammetric processing were proven impressively. Under optimal conditions the performance of 3D object point determination is close to the quality of the reference data. This on the other hand immediately raises questions and demands on the quality of reference data itself (well within the sub-pixel level), especially when the continuously growing requests in very high resolved image data in the range of 10cm GSD and less are considered.

As it could be demonstrated during the tests, the geometric accuracy of the self-calibrating AT profited from the increasing number of successful matches and the more reliable point measurements if digital cameras are used instead of scanned film. However, matching accuracy and measurement reliability is not only influenced by the respective sensor characteristics, but also by the atmospheric and illumination conditions during image flights.

The presented results on geometric accuracy of different sensors have shown some differences, dependent on data set and evaluation approach. Still it has to be discussed if such, often small, differences are really of concern for later practical applications, or if these accuracy discussions only are of academic interest.

It is not only the imaging sensor, the software chain and influences like environmental conditions during data acquisition increase in importance. Such components and their effects may in some cases be of larger influence on the final result than to the choice of the sensor system itself.

Due to the relatively long test period of more than 2 months, these conditions were subjected to considerable change, which has to be considered if the results for the different camera systems are compared in detail. It always has to be kept in mind that evaluations are only based on the data recorded during this DGPF flight campaigns. Extrapolation to later operational projects still has to be verified.

It is clearly obvious that performance of digital sensors is fully sufficient for classical topographic applications. Still the question on the potential of the cameras in new application scenarios remains open, for example when focusing on the radiometric capabilities of systems which is offensively promoted through some of the manufactures. It is not only comprehensive research and investigations which are missing in this part, system providers also have to deliver more information on their preprocessing of images (i.e. radiometric adjustment and corrections), which is typically not available to users so far. This prevents traceability of grey values. A review of the current status of the art including deficits in the radiometric processes is comprehensively given in Honkavaara et al. [2009b].

6. ACCOMPANYING ACTIVITIES

Although already one year has passed after the DGPF test flights were done and data processing has started late fall 2008, processing still is under current progress and only first but not complete final results could been given in this paper. As already seen from the previous presentation of results substantial work has to be done to harmonize the different processing results. This is under current work. Thus more comprehensive papers will be expected for the near future. The most recent project progress is always documented on the project web site [DGPF 2009]. The next extensive project group meeting will take place as workshop in Stuttgart, October 5-6, 2009. Interesting people are cordially invited to participate in this workshop or any other project activity.

Even though the DGPF project has attracted interest to many people from (especially German speaking) photogrammetric community it is only one of the very important steps to verify the performance of the available and still evolving digital sensor systems. Such investigations have to be done on a broad scientific base to guarantee comprehensive analyses, which should also include

users like national mapping authorities. These are the institutions, that later have to deal with such kind of data in a production environment. From that ongoing activities in the EuroSDR organization, bringing together people from science and national mapping, have to be highlighted. The two projects on “Medium Format Digital Camera Systems” [Grenzdörffer 2008] and “Radiometric Aspects of Digital Photogrammetric Airborne Images” [Honkavaara et al. 2009a] have to be mentioned here. These still mainly scientific and technically oriented investigations on the other hand are pushing the development of new national and international standards for system verification and certification. Within this context the work by the EuroSDR European Digital Airborne Camera Certification (EuroDAC²) group [Cramer 2008], the quality assurance plan by the United States Geological Survey (USGS) [Stensaas & Lee 2008] and the most recent standardization initiatives from the International Organization for Standardization (ISO) [Kresse 2008] have to be considered.
All this empirical testing and development of new standards will finally help to raise understanding and full acceptance of new digital sensor technologies!

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8. REFERENCES

Cramer, M. (2005): 10 Years ifp test site Vaihingen/Enz: An independent performance study, in Fritsch (ed.): Photogrammetric Week 05, Wichmann, Heidelberg, p. 79-92, online available at www.ifp.uni-stuttgart.de/publications/phowo05/120cramer.pdf, last access July 3, 2009.

Cramer, M. (2007): The EuroSDR performance test for digital aerial camera systems, in Fritsch (ed.): Photogrammetric Week 07, Wichmann, Heidelberg, p. 89-106, online available at www.ifp.uni-stuttgart.de/publications/phowo07/120Cramer.pdf, last access July 3, 2009.

Cramer, M. (2008): The EuroSDR approach on digital airborne camera calibration and certification, in IAPRS Volume XXXVII, Part B4, Commission IV, Proceedings ISPRS Congress Beijing, pp. 1753-1758, digitally published on CD, 6 pages.

Cramer, M. & Haala, N. (2009): DGPF-Project: Evaluation of digital photogrammetric aerial based imaging systems – Overview and results from the pilot centre, in Proceedings ISPRS Workshop on High Resolution Earth Imaging for Geospatial Information, Leibniz Universität Hannover, June 2-5, 2009, digitally published on CD, 8 pages.

DGPF (2009): project web site, www.ifp.uni-stuttgart.de/dgpf/ last access July 3, 2009.

Grenzdörffer, G. (2008): Medium format digital cameras – a EuroSDR project, in IAPRS Volume XXXVII, Part B1, Commission I, Proceedings ISPRS Congress Beijing, pp. 1043-1050, digitally published on CD-ROM, 8 pages.

Haala, N. (2009): Comeback of digital image matching, in Fritsch (ed.): Photogrammetric Week 09, Wichmann, Heidelberg, this book.

Hanusch, T. & Baltsavias, M. (2009): Evaluation of digital photogrammetric aerial camera systems – Radiometric evaluation of DMC, ADS40 and Ultracam-X, Annual Meeting of DGPF, Jena 2009, published on CD-Rom, online available at www.ifp.uni-stuttgart.de/dgpf/PDF/JT09-Radiometrie-HANUSCH&BALTSAVIAS.pdf, last access July 3, 2009.

Honkavaara, E., Arbiol, R., Markelin, L., Martinez, L., Cramer, M., Korpela, I., Bovet, S., Thom, C. Chandelier, L., Ilves, R., Klonus, S., Reulke, R., Marshal, P., Schläpfer, D., & Veje, N. (2009a): Status report of the EuroSDR project "Radiometric aspects of digital photogrammetric airborne images", in Proceedings ISPRS Workshop on High Resolution Earth Imaging for Geospatial Information, Leibniz Universität Hannover, June 2-5, 2009, digitally published on CD, 6 pages.

Honkavaara, E., Arbiol, R., Markelin, L., Martinez, L., Cramer, M., Bovet, S., Chandelier, L., Ilves, R., Klonus, S., Marshal, P., Schläpfer, D., Tabor, M., Thom, C. & Veje, N. (2009b): Digital airborne photogrammetry – A new tool for quantitative remote sensing? – A state-of-the-art review on radiometric aspects of digital photogrammetric images, will be published in open access journal Remote Sensing at http://www.mdpi.com/journal/remotesensing, 28 pages.

Jacobsen, K. (2009): DGPF-Projekt: Evaluierung digitaler photogrammetrischer Luftbildkamerasysteme – Auswerteteam Geometrie, Annual Meeting of DGPF, Jena 2009, online available at www.ifp.uni-stuttgart.de/dgpf/PDF/Kameratest_Geometrie_V5.pdf, in German, last access July 3, 2009.

Klonus, S., Hagedorn, S., Jordan, E., Castillo, K., Gonzalo, J., Velez, F. (2009): Digitalisierung der Landnutzungserhebungen und erste Klassifikationsergebnisse, Annual Meeting of DGPF, Jena 2009, online available at www.ifp.uni-stuttgart.de/dgpf/PDF/JT09-Klonus_etal_statusreport.pdf, in German, last access July 3, 2009.

Kresse, W. (2008): Standardization in photogrammetry and remote sensing, in IAPRS Volume XXXVII, Part B4, Commission IV, Proceedings ISPRS Congress Beijing, pp. 1763-1768, digitally published on CD, 6 pages.

Ladstädter, R. & Kaufmann, V. (2009): Geometrische Genauigkeitsstudie im Rahmen des DGPF-Projekts zur Evaluierung digitaler Kamerasysteme, Annual Meeting of DGPF, Jena 2009, CD-ROM publication, online available at www.ifp.uni-stuttgart.de/dgpf/PDF/JT09-Geometrie-LADSTAEDTER&KAUFMANN.pdf, in German, last access July 3, 2009.

Passini, R. & Jacobsen, K. (2008): Accuracy analysis of large size digital aerial cameras, in IAPRS Volume XXXVII, Part B1, Commission I, Proceedings ISPRS Congress Beijing 2008, p. 507-513, digitally published on CD.

Richter, R. (2009): ATCOR-4 User Guide, Version 5.0, available at www.rese.ch/pdf/atcor4_manual.pdf , last access July 3, 2009

Schönermark, M. von, Kirchgäßner, U., Schwarzbach, M., Putze, U. & Dong Z. (2009): Überblick über die Arbeiten der Radiometriegruppe zur DGPF-Jahrestagung, Annual Meeting of DGPF, Jena 2009, online available at www.ifp.uni-stuttgart.de/dgpf/PDF/Jena09-Paper-Schoenermark-Radiometrieueberblick.pdf, in German, last access July 3, 2009.

Spreckels, V. (2009a): Protokoll zur Bündelblockausgleichung der JAS-150 Daten zum Befliegungsgebiet „Vaihingen/Enz“ im Rahmen des DGPF Projektes „Evaluierung digitaler photogrammetrischer Kamerasysteme“ durch die RAG Deutsche Steinkohle, internal report, dated March 5, 2009, in German, 8 pages.

Spreckels, V. (2009b): Auswerteteam Stereoplotting – status quo Bericht, Slides of presentation held at Annual Meeting of DGPF, Jena 2009, online available at www.ifp.uni-stuttgart.de/dgpf/PDF/Jena09-0105-Spreckels-Stereoplotting.pdf, in German, last access July 3, 2009, 27 pages.

Stensaas, G. & Lee, G. (2008): Driving toward a worldwide acceptance procedure for digital airborne sensors, in IAPRS Volume XXXVII, Part B1, Commission I, Proceedings ISPRS Congress Beijing, p. 561-566, digitally published on CD.

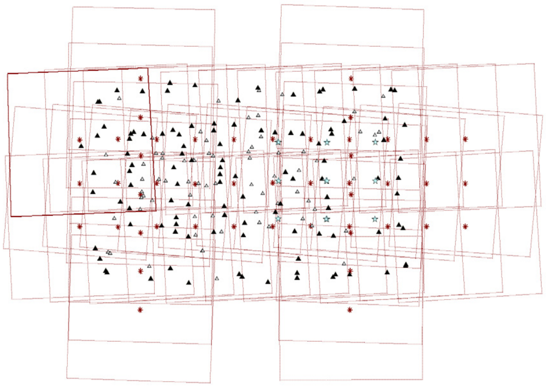
APPENDIX A

Within this appendix the block configurations of different sensor flights are briefly described. More details can be found at DGPF [2009].

A.1 **RMK-Top15** (focal length 154mm)

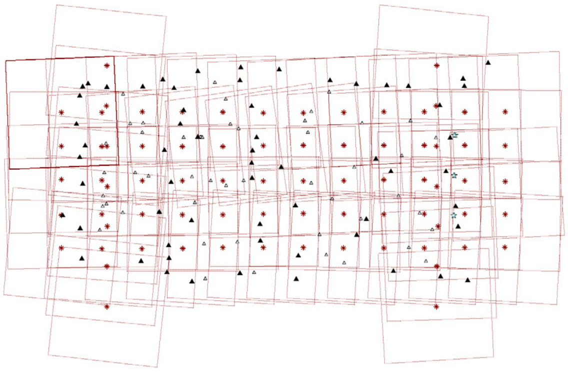
Film: Color infrared (Kodak MS 1443)
Date of flight: August 6, 2008
Flying height a.g.: 2160m (approx.)
GSD nominal: 20cm (14 µm scan)
Overlap: p=60%, q=70% (approx.)

Block layout



Film: Color negative (Agfa X-100)
Date of flight: July 24, 2008
Flying height a.g.: 870m (approx.)
GSD nominal: 8cm (14 µm scan)
Overlap: p=60%, q=70% (approx.)

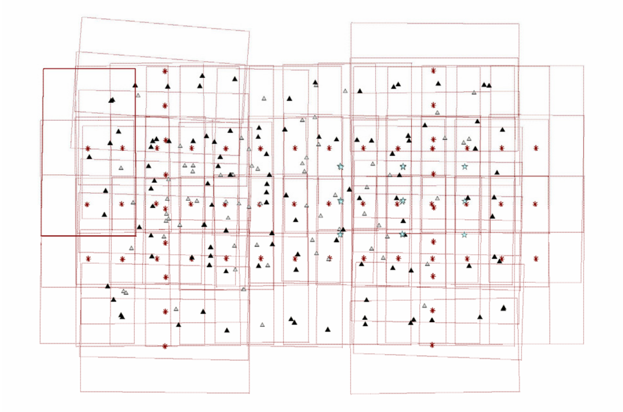
Block layout



A.2 **DMC** (focal length 120mm)

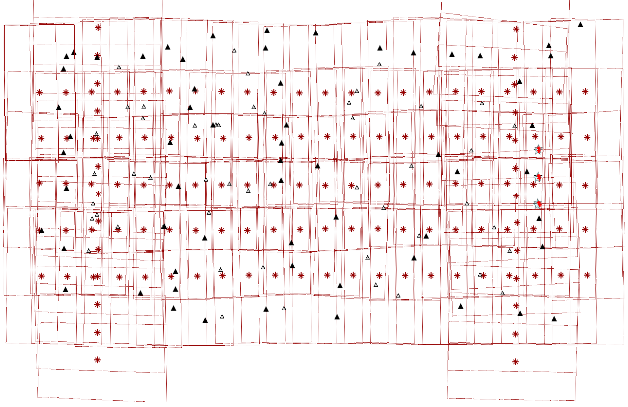
Date of flight: August 6, 2008
Flying height a.g.: 2160m (approx.)
GSD nominal: 20cm (12µm pixel size)
Overlap: p=60%, q=60% (approx.)

Block layout



Date of flight: July 24, 2008
Flying height a.g.: 870m (approx.)
GSD nominal: 8cm (12µm pixel size)
Overlap: p=60%, q=63% (approx.)

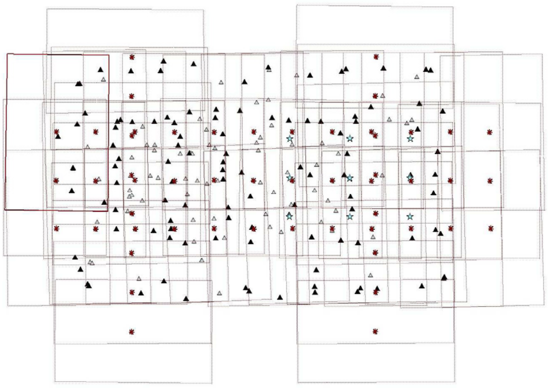
Block layout



A.3 **Ultracam-X** (focal length 100.5mm)

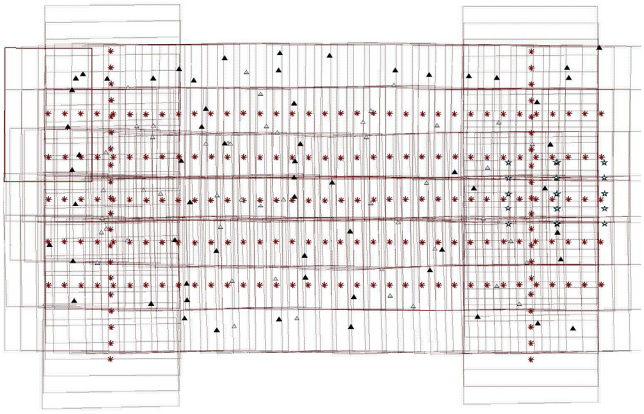
Date of flight: September 11, 2008
Flying height a.g.: 2900m (approx.)
GSD nominal: 20cm (7.2µm pixel size)
Overlap: p=70%, q=70% (approx.)

Block layout



Date of flight: September 11, 2008
Flying height a.g.: 1200m (approx.)
GSD nominal: 8cm (7.2µm pixel size)
Overlap: p=80%, q=70% (approx.)

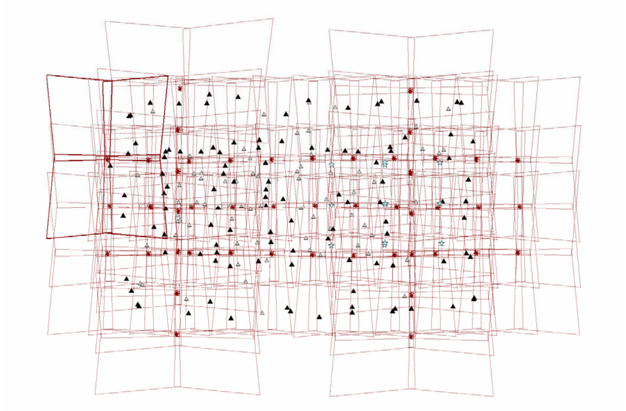
Block layout



A.4 **Quattro DigiCAM** (focal length 82mm)

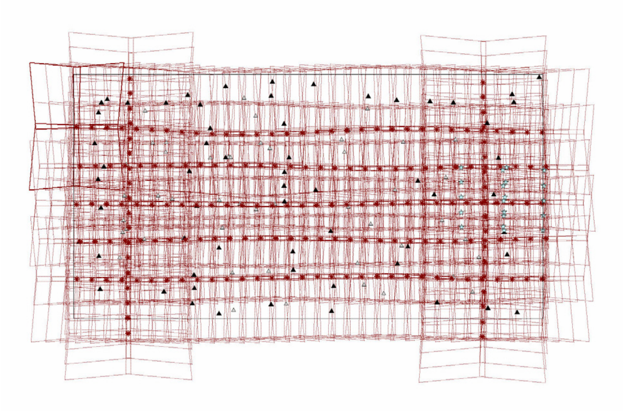
Date of flight: August 6, 2008
Flying height a.g.: 2500m (approx.)
GSD nominal: 20cm (6.8µm pixel size)
Overlap: p=60%, q=70% (approx.), related to area covered by the four camera heads

Block layout



Date of flight: August 6, 2008
Flying height a.g.: 1060m (approx.)
GSD nominal: 8cm (6.8µm pixel size)
Overlap: p=80%, q=70% (approx.), related to area covered by the four camera heads

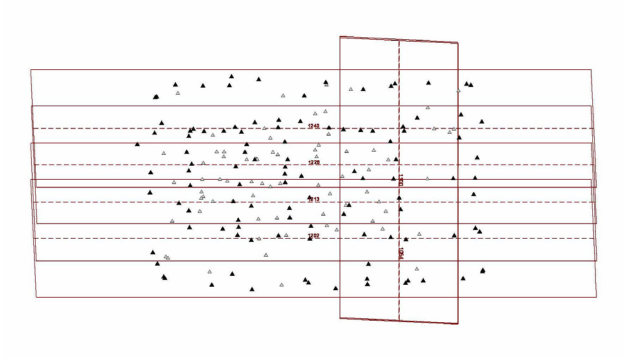
Block layout



A.5 **ADS40, SH52** (focal length 62.7mm)

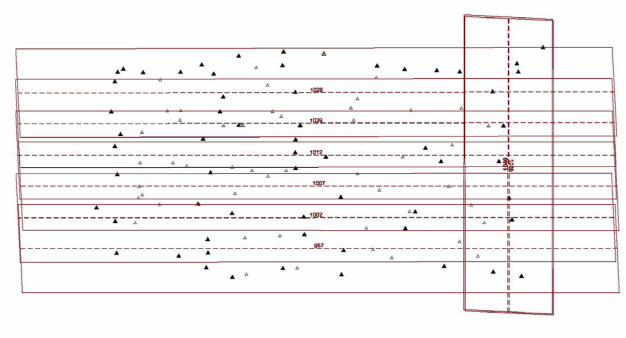
Date of flight: August 6, 2008
Flying height a.g.: 1900m (approx.)
GSD nominal: 20cm (6.5µm pixel size)
Overlap: q=70% (approx.)

Block layout



Date of flight: August 6, 2008
Flying height a.g.: 770m (approx.)
GSD nominal: 8cm (6.5µm pixel size)
Overlap: q=65% (approx.)

Block layout



APPENDIX B

Project participant list (signed project agreement submitted, Status May 2009)

Institution	**Contact person**	**Focus of evaluation**
Heinrich Heine Universität Düsseldorf Geografisches Institut	Prof. Dr. E. Jordan	Radiometry Land use classifications
EFTAS Fernerkundung Technologietransfer GmbH Münster	C. Lücke	Radiometry Land use classifications
Universität Osnabrück Institut für Geoinformatik und Fernerkundung	Prof. Dr. M. Ehlers	Radiometry Land use classifications
Leibniz Universität Hannover Institut für Photogrammetrie und Geoinformation	Dr. K. Jacobsen Dr. F. Rottensteiner	Geometry Digital surface models
Landesamt für Vermessung und Geoinformation München	W. Stößel	Geometry / Radiometry
Deutsches Zentrum für Luft- und Raumfahrt Oberpfaffenhofen	S. Holzwarth, F. Kurz	Radiometry / Geometry
Universität Stuttgart Institut für Raumfahrtsysteme	Dr. M. von Schönermark	Radiometry Spectrometer and BRDF reference measurements
Technische Universität Graz Institut für Fernerkundung und Photogrammetrie	Dr. V. Kaufmann	Geometry
Technische Fachhochschule Berlin, Labor für Photogrammetrie	Prof. Dr. M. Kähler, Prof. M. Breuer	Geometry / Digital surface models / Stereo plotting
aphos Leipzig	Dr. Schulz	Geometry / Stereo plotting
Martin-Luther-Universität Halle-Wittenberg Institut für Geowissenschaften	Prof. Dr. C. Gläßer Dr. A. Jung	Radiometry Spectrometer reference measurements
Amt für Geoinformation, Vermessung- und Katasterwesen Mecklenburg-Vorpommern, Schwerin	S. Baltrusch	Geometry / Digital surface models
C+B Technik Markgröningen	Dr. E. Wild	Stereo plotting
ETH Zürich, Lehrstuhl für Photogrammetrie und Fernerkundung	Prof. Dr. A. Grün, Dr. M. Baltsavias	Geometry / Radiometry / Digital surface models
Bundesamt für Geodäsie und Kartographie, Frankfurt/M.	Dr. A. Busch	Geometry

Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft, Birmensdorf	H. Hastedt	Digital surface models / Stereo plotting Segmentation/Classification for forest applications
Intergraph Z/I Imaging Ltd, Aalen	C. Dörstel, K. Neumann	Manufacturer evaluation
Trimble Holdings GmbH, Metric Imaging Dpt., Braunschweig	T. Tölg	Manufacturer evaluation
Geosystems GmbH, Germering/Berlin	R. Schneider	Digital surface models
RAG Aktiengesellschaft, Herne	V. Spreckels	Geometry / Radiometry / Digital surface models / Stereo plotting
Vexcel Imaging GmbH, Graz	Dr. M. Gruber	Manufacturer evaluation
IGI mbH, Kreuztal	Dr. Jens Kremer	Manufacturer evaluation
FH Oldenburg, Institut für angewandte Photogrammetrie und Geoinformation	Prof. Dr. T. Luhmann	Geometry
Institution INSA Strasbourg	Prof. Dr. P. Grussenmeyer	Geometry / Digital surface models
Landesbetrieb Geoinformation und Vermessung, Hamburg	K. Clausen	Geometry
Jena-Optronik GmbH	G. Albe	Manufacturer evaluation
TU Wien, Institut für Photogrammetrie und Fernerkundung	Prof. Dr. N. Pfeiffer	Geometry
HCU Hamburg, Department Geomatik	Prof. Th. Kersten	Geometry / Digital surface models