THE GERMAN CAMERA EVALUATION PROJECT - RESULTS FROM THE GEOMETRY GROUP

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ABSTRACT:

The so-called German camera evaluation project was initiated by the German society of Photogrammetry, Remote Sensing and Geoinformation (DGPF) in order to allow for comprehensive empirical test on photogrammetric digital airborne camera systems. During this test, the digital camera systems DMC, Ultracam-X, ADS40 (2nd generation), JAS-150, Quattro DigiCAM and AIC-x1 were flown in the test site Vaihingen/Enz in summer 2008. In addition, RMK analogue images and ALS50 LiDAR data were recorded for comparison, while reference measurements on the ground were made available as well. Parts of the test field were also covered from hyper-spectral sensor flights, namely the AISA+ and ROSIS system. After data collection all this material was prepared, documented and distributed to more than 30 institutions which participated in the evaluation and formed the project network of expertise. This evaluation phase included topics like the analysis of geometric accuracy and sensor calibration, the radiometric performance including on-site radiometric calibration and multi-spectral land classifications. Additionally, the performance of photogrammetric surface model generation and the potential of manual stereo plotting from digital images were investigated. Within this paper, the major findings from the geometric evaluations, namely sensor orientation and height model generation are presented.

1. INTRODUCTION

Digital airborne photogrammetric imaging has become common practice within operational projects, resulting in sales figures of digital airborne cameras, which outnumbered the original expectations. Despite their successful spread, comprehensive empirical tests on system performance and the respective quality of the derived photogrammetric products are only partially available. This motivated the German Society of Photogrammetry, Remote Sensing and Geoinformation (DGPF) to organize an independent evaluation of digital photogrammetric camera systems. The aim was not only to broaden existing investigations as for example given by Passini & Jacobsen (2008), but to include the latest generation of digital camera systems. Thus, within the so-called DGPF test, the digital camera systems DMC, Ultracam-X, ADS40 (2nd generation), JAS-150, Quattro DigiCAM, AIC-x1, AIC-x4, and DLR 3K were flown in the test site Vaihingen/Enz in summer 2008. For comparsion, RMK analogue images and ALS 50 LiDAR data were recorded. The following comprehensive evaluation was not limited to pure camera data but covered the complete processing chain and product generation including various geometric and radiometric aspects of the sensor systems. This was motivated by the close link between sensor design and data processing for digital systems which is for example required during tasks like virtual image formation or line-scanner image rectification.

The outlines of the DGPF project on camera evaluation were officially presented during the DGPF annual meeting in spring 2008. Since then, interested people mainly from the German speaking countries were invited to actively participate in this project. More than 100 different people showed interest and became part of the project mailing list. About 35 institutions signed the official project agreement, fixing the common topics of analysis and a rough working schedule. A list of the test participants is available in Cramer (2009). About 50% of the participants are members of the scientific sector, one third of the participating institutions represent the commercial field and the remaining 15% are affiliated with mapping organizations. About 60% of all data requests were related to the multi-head, frame-based camera systems DMC, Ultracam-X and Quattro DigiCAM. Less than 20% of delivered data sets were from JAS-150 and ADS40, another 20% of requests covered the smaller format systems AIC-x1 and 3K-camera and the RMK data. The scanned analogue RMK image data mainly served as direct comparison between analogue and digital image data quality. In order to structure the data evaluation process and to stimulate discussions and exchange between the different participating institutions, four competence teams were established. They individually focused on the topics geometry, radiometry, digital surface models and manual stereo plotting. The main results from these four competence teams are highlighted in Jacobsen et al. (2010), Haala et al. (2010), Spreckels et al. (2010) (Schönermark (2010), Waser et al. (2010).

Within this paper, the major findings from the two teams *geometry* and *digital surface models* are presented. This covers accuracy investigations with respect to sensor orientation and surface reconstruction from image matching. In the following section the test field Vaihingen/Enz, the available reference data and the test data flown by the different camera systems are presented. The geometric performance of the digital photogrammetric camera systems in terms of accuracy results from

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bundle block adjustment is presented in section 3, while section 4 discusses the quality of photogrammetric DSM generation using the respective systems.

2. DATA COLLECTION

During the DGPF camera test, several flight campaigns were carried out using the Vaihingen/Enz photogrammetric test site. This is the most used airborne test site for photogrammetric applications in Germany and one of the three to four well established and manufacturer independent photogrammetric airborne sites available in Europe (Cramer 2005). The test site is maintained by the Institute for Photogrammetry (ifp), Universität Stuttgart, which also served as Pilot Centre during the test and was responsible for the project coordination under the umbrella of the DGPF. The Pilot Centre also prepared reference orientations which were commonly used by the test participants to derive the respective sensor products (Cramer & Haala 2009).

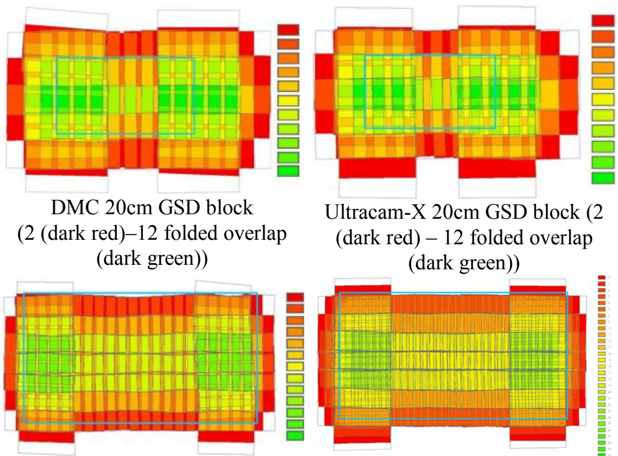
2.1 Digital camera test flights

As it is visible in Table 1, the digital camera flights were put through at six different flight days during a period of 10 weeks between July and mid of September 2008. Originally, a shorter time slot of two weeks was planned for the airborne data acquisition but could not be realized due to weather conditions. As agreed in the project definition phase, most sensors were flown in two different flying heights, resulting in two blocks with the previously defined ground sampling distances 20cm GSD and 8cm GSD as nominal values. The 20cm GSD blocks, which were planned with a forward overlap of p=60% covered the whole test area; the GSD 8cm blocks with a forward overlap of p=80% were limited to the centre part. The side overlap between image strips was consistently defined with q=60%.

System	System provider / manufacturer	Day(s) of flight / Remarks
DMC	Intergraph/ZI	24.07.2008 & 06.08.2008 / double-hole flight with RMK-Top15, 8cm GSD with p=60%
ADS40, SH52	Leica Geosystems	06.08.2008
JAS-150	Jenaoptronik	09.09.2008
Ultracam-X	Vexcel Imaging Graz	11.09.2008
RMK-Top15	Intergraph/ZI	24.07.2008 & 06.08.2008 / double-hole flight with DMC 8cm GSD with p=60%
Quattro DigiCAM	IGI	06.08.2008
AIC-x1	Rolleimetric, now Trimble	11.09.2008 / only 8cm GSD, no cross strips
AIC-x4	Rolleimetric, now Trimble	19.09.2008 / data not made available for project
DLR 3K-camera	DLR Oberpfaffenhofen	15.07.2008 / only 20cm GSD, no cross strips
AISA+ hyperspectral	specim FH Anhalt	02.07.2008 / double-hole flight with DMC
ROSIS hyperspectral	DLR Oberpfaffenhofen	15.07.2008
ALS 50 LiDAR	Leica Geosystems	21.08.2008

Table 1: Sensor systems flown during DGPF test.

Due to the fixed test site extensions and different sensor formats, slight adaptations of the block geometry were necessary which potentially influenced the later comparison of sensor performance. Additionally, not all test data finally fulfilled the defined overlap requirements. Some of the sensors, namely the AIC-x1 and 3K-camera, were only flown in one flying height other data sets were influenced by technical problems. This is why AIC-x4 images finally were not made available. It is also worth to note that the DMC and RMK-Top15 flights were done as true double-hole flights, where the flight trajectory was fixed to the DMC sensor geometry. Since analogue RMK images were scanned with 14µm resolution the requested 20cm GSD and 8cm GSD images are obtained.



DMC 20cm GSD block (2 (dark red)–12 folded overlap (dark green))

Ultracam-X 20cm GSD block (2 (dark red) – 12 folded overlap (dark green))

DMC 8cm GSD block (2 (dark red) – 14 folded overlap (dark green))

Ultracam-X 8cm GSD block (2 (dark red) – 30 folded overlap (dark green))

Figure 1: Block configurations / image overlap conditions (colour-coded) for DMC and Ultracam-X blocks.

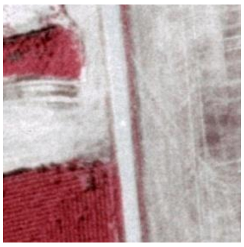
The overlap conditions for DMC and Ultracam-X blocks 20cm GSD and 8cm GSD are depicted in Figure 1. Notice the different scaling of the legend colours. The red colour always depicts areas with 2 folded image overlap while the maximum overlap for DMC and Ultracam-X blocks varies from 12 folded for 20cm GSD blocks to 30 folded images for the 8cm GSD Ultracam-X block, with a 14 folded overlap maximum for the DMC 8cm GSD block. The larger deviation for the 8cm GSD blocks results from the higher forward overlap (p=80%) of the Ultracam-X flight compared to 60% for the DMC block. These differences definitely influence the geometric block layout and the quality of object points. More detailed block configurations and flight parameters for the difference systems are available in (Cramer, 2010) and are documented in the project web site (DGPF 2009, in German).

2.2 Target measurements

Overall, the Vaihingen/Enz test area covers about 7.4 x 4.7km² and is located 25km north-west of Stuttgart, Germany. Some 200 regularly distributed, signalized points are available, which are marked permanently with white painted squares of size 60 x 60cm². The targets in the central part of the test area additionally contain 30 x 30cm² black squares, which were additionally painted in the middle of the larger white targets. This enables the precise detection of point centres in high resolution imagery.

Correct identification and measuring of the signalized targets is essential for highly accurate results. Because of the strong variety of the shape of object points and varying background, image coordinates of control and check points are usually measured manually. These manual measurements partially dominate the determination of the object point coordinates. In (Jacobsen et al., 2010) manually obtained image coordinates provided by different operators from different institutions are compared and analysed to estimate the corresponding variance of image point observations. Assuming flights with a GSD of 20cm the target size in the Vaihingen/Enz test area will be in the range of at least 3 x 3pixel in image space, which is sufficient for manual measurements. Effectively, due to blooming effects the imaged points appear much larger in the test data (about 6 x 6pixel for 20cm GSD). Still, measurements of image points have shown that especially for scanned analogue images, the clear identification of signals caused problems for some points in lower contrast areas and for operators not familiar with the test field and point locations.

Point on a paved country side road in the inner part of the site.



RMK 20cm GSD CIR

DMC 20cm GSD CIR

Figure 2: Signalized point within RMK and DMC images.

Figure 2 exemplarily shows a signalized point located in the inner part of the test site and how this point is imaged in a analogue RMK (top) and digital DMC (bottom) image. These two systems were flown simultaneously with an airplane equipped for two cameras resulting in almost parallel image recording from the same flying heights and in same environmental conditions. Thus the images of the two systems can be compared directly. The differences in the quality of point identification due to the superior radiometric image quality of the DMC as a representative for a digital camera are obvious for this 20cm GSD image samples. For further investigations, the geometric resolution of different sensors and their image products were quantified from the analysis of a Siemens star resolution target.

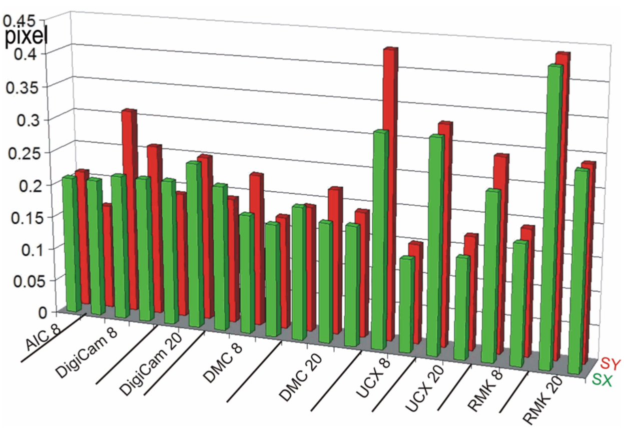


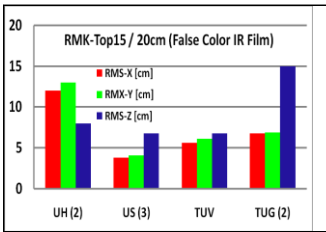
Figure 3: Standard deviation of manual control and check point measurements [pixels].

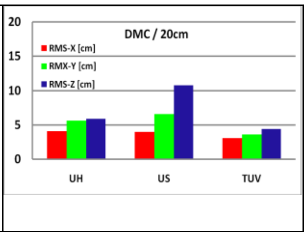
Figure 3 shows with any pair of columns (SX and SY) typical root mean square differences (RMS) of the manual measurements for the different cameras. The number following the camera names indicates the GSD. The RMS values were computed from measurement differences provided by always two independent test participants. These differences were divided by 1.414 to reduce it to the standard deviation of single manual pointing – what is correct if both of the compared measurements have the same accuracy. This may give a realistic view on the variations in manual image coordinate measurements and to some of the limitations of such a test with accurate reference. The precision of the manual control and check point image coordinate measurements of course depends on the qualification and precision of the human operators, but also on the image quality. The point identification in the digitized analogue images of the RMK, especially with 20cm GSD, is quite more difficult as with other images, which already reflects the lower radiometric quality of scanned analogue images compared to digital imaging. The slightly higher values for the Quattro-DigiCAM are concentrated to the same operator, while for the UltraCamX no clear explanation can be seen – the same operators got better pointing values with other cameras, so this may be caused by a learning process of the operators, measuring the same points in images taken with different cameras. Such a variation of the manual pointing is influencing the finally reached results of the block adjustments. The differences between the cameras may also reflect the impact of different environmental conditions during sensor flights, which also influence the radiometric quality of the image data

3. GEOMETRIC ACCURACY ANALYSIS FROM BUNDLE BLOCK ADJUSTMENT

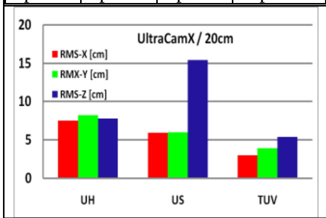
In the frame of the DGPF-project, different strategies were used by the participants to evaluate the geometric performance of the respective camera systems. This results from the large number of factors which influence the achievable geometric accuracy. It depends on the correct mathematical modelling, the coverage and block configuration of the project area, the automatic aerial triangulation (AAT) including number and distribution of tie points, the quality of manual control and check point measurement as well as the application of direct sensor orientation. Furthermore, different sets of additional parameters are in use for camera calibration. Finally, the quality of the images itself is of importance, which also might be influenced by the environmental conditions during image data acquisition.

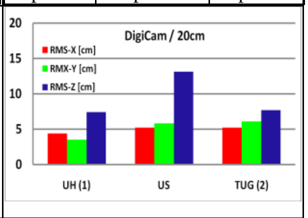
Since the participants of the DGPF-test used individual measurements of the control and tie points and different programs for bundle block adjustment programs, either with or without direct sensor orientation and integrated sensor orientation (ISO), a direct comparison of the results achieved i snot feasible. However, it demonstrates the wide range of possible solutions in photogrammetric projects. This also reflects the situation of later operational processing where each evaluation is based on the available process chain and, maybe even more important, the expertise of each user. Table 2 gives an overview on the different strategies used by the participants for evaluation of the camera systems. Note that for several camera systems different parameter sets, GCP configurations and integration methods for GPS/IMU data have been tested. The figures in Table 2 give the RMS values at independent check points with the dimension [cm]. For better interpretation, some key information about the evaluation strategy used is given below each graph. The exact meaning for each abbreviation is given in the Table 3. More details on these investigations are presented in (Jacobsen et al., 2010).



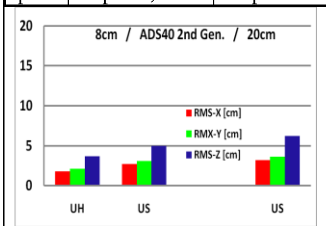


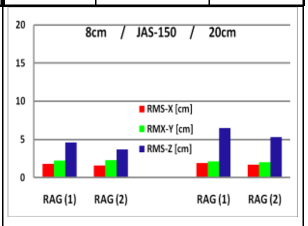
14GCP nDS apB12	14GCP nDS apG44	8GCP GPS apE16	5GCP ISO apBRs	9GCP nDS apB12	4GCP ISO apG44	8GCP GPS apE16





9GCP nDS apB12	4GCP ISO apG44, cr0	8GCP GPS apE16	15GCP apB12x4 nDS	4GCP apE12x4 ISO	5GCP apBRs ISO





9GCP 0ap ISO	4GCP apO6 ISO		4GCP apO6 ISO, cr0	4GCP apBN12 ISO	9GCP apBN12 ISO	4GCP apBN12 ISO	9GCP apBN12 ISO

Table 2 RMS values from check point analyses.

nDS	No direct sensor orientation
GPS	Combined adjustment with GPS
ISO	Integrated sensor orientation
0ap	No self calibration
apE12	12 additional param. (Ebner)
apE16	12 Ebner + 2 radial + 2 tang.
apG44	44 additional parameters (Grün)
apB12	12 additional param. (BLUH)
apB20	apB12+parameters 81–88
apBN12	12 additional param. (BINGO)
apBRs	Brown subset with 5 parameters

Table 3: Abbreviations used in the graphical presentations.

The results of the different block adjustments in Table 2 show the large varieties of the solutions. It's not possible to directly compare the results of the different camera systems because the flight conditions have been different and also the end lap is varying between 60% and 80%. Even more, for one camera system results depend upon the different configurations used, as just based on GCPs, use of combined adjustment with relative kinematic GPS-positions of the projection centres or integrated sensor orientation, using the integrated GPS/inertial trajectory information for exterior orientation plus image and ground control points.

In order to illustrate the performance of area based cameras, not overlaid by effects from direct sensor orientation, block adjustments without GPS/IMU data have been made by the Leibniz University Hannover (UH). Nevertheless, even though additional GPS/IMU sensors are in principle only optional for large format frame based sensors DMC and UltraCamX, almost all of the systems are equipped with such devices. These integrated systems are mandatory part of the line scanning sensors and also advantageous for multi-head medium format sensors, where the images are not merged to form a large format virtual image. The Vienna University of Technology (TUV) preferred combined block adjustments with GPS-coordinates of the projection centres. From their investigation results from that were more accurate than using GPS/IMU data in integrated sensor orientation. The block adjustments of the University of Stuttgart (US) and Graz University of Technology (TUG) in most cases have been performed as integrated sensor orientation. Note that different direct sensor orientation equipment was used and this may dominate the results more than the camera geometry itself. For adjustments of University of Stuttgart no cross-strips were introduced even though mostly available for all the flights. By these means, a more operational like environment was simulated where often no cross-strips are flown, especially when integrated GPS/inertial systems are available.

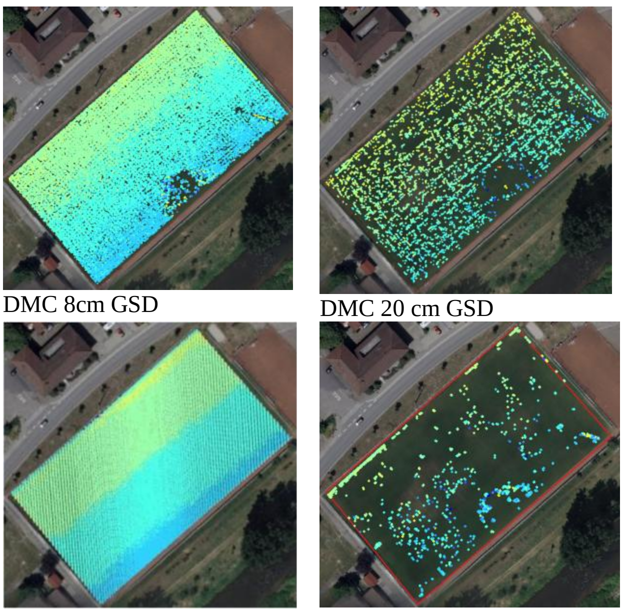
During the investigations, different sets of additional parameters were used. These sets may be based on a pure mathematical justification, as the 12 Ebner parameters (Ebner 1976) in order to eliminate the systematic effects in a grid of 3 x 3 Gruber points or the 44 Grün parameters (Grün 1976) based on 5 x 5 points. Another option is the use of parameter sets which can model physical justified effects like radial symmetric and tangential lens distortion, principal point offset or focal length refinement by a reduced number of additional parameters. The most common known parameter set of this type is the one introduced by Brown (Brown, 1971), which was extended for the program system BLUH by Jacobsen (Jacobsen et al 2010). In addition to the standard parameter sets, specially designed parameters have to be used for the large format digital cameras DMC and UltraCam. They are able to handle small geometric deformations caused by the stitching process by operating on well defined image regions covered by the individual sensor units. Integrated sensor orientation causes an advantage for blocks with less strong image connections. In case of blocks having a limited size and good image connections, a non optimal modeling of systematic errors can cause a negative influence because proper weighting and separation of systematic errors from random errors are more difficult.

Since the investigations at the different institutions were done independently but all using the same data, the analyses provide a wide range of solutions and accuracy. Even though these results are not easy to compare, they very well illustrate the spectrum of possible solutions which is also expected in later operational applications. However, it is important to note that during block adjustment sub-GSD-accuracy was generally reached for the horizontal component of the ground coordinates and in most cases also achieved for the vertical component.

4. DSM GENERATION

Digital photogrammetric cameras can capture high dynamic images at a good signal-to-noise ratio. Compared to the use of scanned analogue images, these features are especially advantageous with respect to the accuracy, reliability and density of automatic point transfer. Thus, follow-up products like Digital Elevation Models, which are based on the use of automatic image matching, will potentially benefit, if digital photogrammetric camera systems are used. In order to evaluate the quality of such a photogrammetric product as aspired by the competence team on digital surface models, the analysis can of course not be restricted to image collection but has to pay attention to the respective software for the following data processing. Commercial software systems aiming at the generation of elevation data from image matching were already introduced more than two decades ago (Krzystek, 1991). Nevertheless, the improvements in the available quality of aerial imagery triggered a renaissance in software development to optimally benefit from these advancements. As an example, digital airborne camera systems can capture largely overlapping images at a relatively little additional effort. Such high redundant multi-image information as available in the DGPF test and depicted Figure 1 is especially beneficial in situations, were standard stereo matching is hindered due to occlusions. Algorithms which fully exploit this potential of digital aerial cameras by extending the traditional stereo to a multiple image matching have been implemented just recently. Such commercial software systems, which were employed during the DGPF test were Next Generation Automatic Terrain Extraction (NGATE) from BAE Sytems (DeVenecia et al., 2007) and MATCH-T DSM from INPHO GmbH (Lemaire, 2008).

Within the test, these software systems were used to compute DSM grids with 0.2m/0.25m and 0.5m raster width for the 8cm and 20cm GSD flights in the central of 5.0 x 2.7 km² area of the test field. One option to determine the quality of the resulting DSM is to investigate their vertical differences with respect to the signalized reference points. This was realized using 60 control points in the test area. For the LiDAR DSM from the ALS 50 measurements, the RMS value was 3.3cm. This is almost in the order of the vertical reference point accuracy. Compared to this accuracy, the RMS values of the DSMs from the DMC, UltraCamX, Quattro DigiCAM and ADS 40 were only slightly larger. They correspond very well to the vertical component of the preceding block adjustment, which gave an accuracy of ½ GSD.



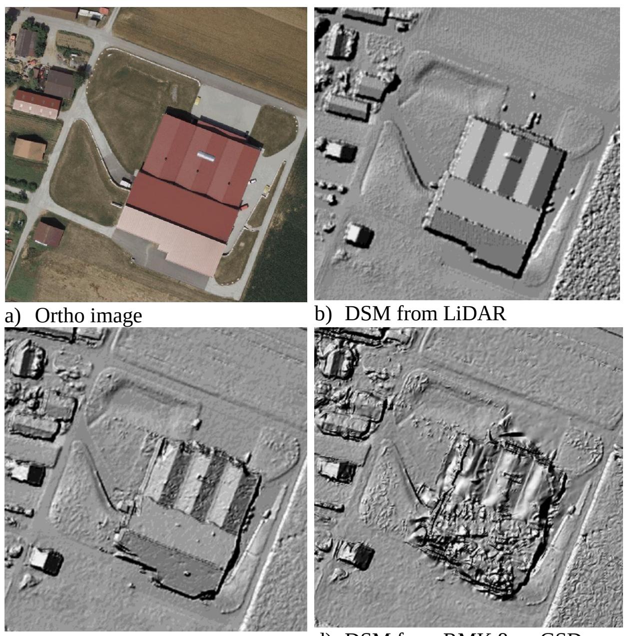
DMC 8cm GSD | DMC 20 cm GSD

ALS 50 LiDAR | RMK 8cm GSD

Figure 4: Point clouds from image matching for planar test area.

Typically, the available ground control points were installed at paved areas like small roads or parking lots. Such flat neighborhoods are of course beneficial for the filtering and interpolation process during DSM raster generation. For this reason, the results might give too optimistic accuracies for regions of higher geometric complexity.

To evaluate the matching quality while avoiding the influence of interpolation processes 3D point clouds were used. Such point clouds can be optionally generated from modern photogrammetric software systems as an alternative to the traditional 2.5D DSM raster representations. An example based on the software MATCH-T DSM is given in Figure 4. In order to generate the point cloud on top left and top right DMC 8cm and 20cm GSD imagery was used, respectively. The bottom right shows the point cloud from image matching the for scanned RMK 8cm GSD imagery. Since the matched 3D points were restricted to a planar area at a sports field, geometric accuracy can be determined using deviations to an approximating plane (Haala, 2009). The results showed a considerable advantage of point matching for the GSD 8cm blocks compared to the GSD 20cm blocks for all digital camera systems. For the GSD 8cm images a point density of about 20 pts/m² was reached. This is even higher than the available LiDAR measurements depicted on the bottom left of Figure 4. However, the standard deviation for the LiDAR data is better than 2cm, almost without any gross errors, while an average of 5.5cm for the single points is achieved from image matching. Usually matching problems occurred due to time dependent shadow movement which can hinder automatic point transfer especially for high resolution images from different strips. The GSD 20cm blocks of the tested digital camera systems resulted in standard deviation of 14.1cm, while the average point density was much lower compared to the 8cm GSD blocks. In contrast to the sufficient point density from images captured by the digital camera systems the matching of scanned RMK images gives less than 1 pt/m². Obviously, the higher radiometric quality of digital images allows for much denser point matching while RMK-Top15 imagery is not as suitable for the automatic derivation of high accurate surface models. This supremacy was verified for all digital camera systems. However, the result is especially relevant for the DMC and RMK images, since they were recorded almost simultaneously at identical conditions.



a) Ortho image | b) DSM from LiDAR

c) DSM from DMC 8cm GSD | d) DSM from RMK 8cm GSD

Figure 5 Comparison of shaded DSM from different data sets.

As it is also demonstrated in Figure 5, especially height data generated from the largely overlapping, high resolution GSD 8cm image blocks seems at least to be comparable to 3D data from LiDAR measurement. The bottom left picture of Figure 5 shows a shaded DSM from image matching using the DMC 8cm GSD block, while the shaded DSM from LiDAR measurement is depicted in the top right. The corresponding result for the scanned RMK data is on the bottom right. The advances of digital airborne camera systems compared to scanned analog images for matching are clearly visible. For comparison, the top left image of Figure 5 additionally shows the corresponding ortho image. Further investigation in built-up areas also showed that the level of detail of the image matching DSMs is high and 3D object edges are reconstructed well. On top of the buildings the difference to the LiDAR DSM is very small, while blunders are limited to buildings borders (Haala et.al. 2010). Currently area covering flights are mainly collected at 20cm GSD, however, the results clearly indicate the benefit of high resolution and largely overlapping imagery for DSM generation at least in built-up areas.

5. CONCLUSION

The DGPF test can be seen as a benchmark to compare airborne sensor performance. This is often requested from the photogrammetric community and actually was one of the user driven motivations of the test. Still, the main objective of this project was not to directly compare different sensors but to evaluate their specific strengths and weaknesses, since they are relevant when choosing a sensor system for specific applications. During geometric evaluation by the test participants, the digital frame cameras DMC, UltraCamX and Quattro-DigiCAM as well as the line scanning cameras ADS40 and JAS-150 confirmed their potential. The image geometry itself is somehow mixed with the influence of integrated sensor orientation or by combined block adjustment with GPS-coordinates of the projection centres, but this is realistic for operational application.

Of course the limited test site does not allow a direct extrapolation to large blocks. However, it could be clearly demonstrated that there is no more reason to use analogue photos instead of original digital images. Even with the wide angle RMK Top15 under approximately comparable conditions not the same vertical accuracy has been reached as with the large format digital aerial cameras. In addition, the lower image quality from analogue scanned images became obvious at the manual identification of the control and check points. This was also verified during DSM generation, which is becomming competitive to LiDAR measuerements, if high resulition, highly overlapping images from digital camera systems are used. While aiming at a joint evaluation of the different digital camera systems for DSM generation it has to be considered, that due to the test period of more than 2 months, there were significant changes in vegetation as well as atmospheric conditions and illumination. Elevation data from image matching is still compromised to errors. Potential problems, which can still result in partly varying geometric quality are for example caused by changing illumination or moving shadows. Despite the very promising results, current matching software does not yet fully exploit the complete potential of the new generation of aerial images. Thus, further developments, investigations and tests are still required in the field of multi image matching to broaden potential applications.

The DGPF project will officially be closed in July 2010. This of course will not terminate the deeper scientific evaluations. Since the high scientific value of this reference and empirical data sets is generally recognized it was already decided to make the data available for international and other research projects, too. Interested persons are cordially invited to contact the DGPF executive team members directly. We thus hope that this valuable and comprehensive data will become one of the standard empirical data sets used and cited for the next years.

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