EUROSDR NETWORK ON DIGITAL CAMERA CALIBRATION

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ABSTRACT:

This paper documents the status of the actual Phase 1 of the EuroSDR project on "Digital Camera Calibration". This project was officially installed in October 2003 during the 103rd EuroSDR Science and Steering Committee Meetings. Up to now about 35 experts from industry, camera manufacturers, software developers, research and system users already joined this calibration network. Some general remarks on the objectives of the project are given in the introductory part of the paper. Besides that, the paper is mainly based on the detailed Phase 1 report describing current practice and methods for digital airborne camera calibration. Therefore three airborne sensors already in operational use are chosen exemplarily: The Applanix/Emerge DSS as one representative of medium format sensors, and the well-known ZI-Imaging DMC and Leica ADS40 systems, where the latter two both claim to replace the standard analogue airborne frame cameras in near future. The different applied calibration approaches and process steps are described in the second part of the paper.

1. INTRODUCTION

The need of camera calibration is a fundamental requirement in the field of photogrammetric data processing. For airborne sensors this calibration is typically realized under well controlled laboratory conditions, where especially designed calibration setups are used to determine the internal camera characteristics with sufficient accuracy. From such calibration facilities (i.e. multi-collimator or goniometer) the camera distortion parameters are estimated using the obtained discrepancies between measured coordinates or angles versus their a priori known values. Besides this, the focal length and principle point coordinates are chosen to minimize the absolute amount of lens distortions and to realize a symmetric distortion pattern.

However, this classical situation changes with the increasing availability of new digital airborne imaging systems, mainly due to the following two aspects: Comparing digital sensor systems from their system design concepts, there are large variations within the specific system realizations and in comparison with standard analogue cameras: Frame sensor concepts versus line scanning approaches, multi-head systems versus single head sensors, large image format data acquisition versus medium or even small format cameras, pan-chromatic and/or multi-spectral image data recording. All this results in different calibration approaches, which have to be defined individually for each sensor type. Additionally, due to the new parallel multi-spectral imaging capability (which is one of the major selling points for the new digital sensors), calibration should not only be restricted on the geometric aspects but has to be extended on the radiometric part also. The second fact is mainly due to the integration of the imaging sensors with additional sensors for direct sensor trajectory determination like GPS or integrated GPS/inertial modules. The combination of digital imaging sensors with direct orientation components is straightforward, since they provide very accurate information on the sensors movement, which can be used for fast generation of photogrammetric products like ortho images. In case of line scanning systems a tight coupling with GPS/inertial sensors is even mandatory to allow for an efficient image data processing. Hence, calibration has to cover the whole sensor system consisting of imaging part and additional components like GPS/inertial sensors. From this background the need of more complex, extended and more general calibration procedures is evident, where the aspect of in situ calibration will gain in importance, since calibration should cover the whole sensor system not only the optical part.

This today's situation defines the framework of the EuroSDR initiative on "Digital Camera Calibration". Within this project a network is established formed by experts from different expertise. The following sections of this paper will present a short overview on the project goals, history and the ongoing work. In the second part the calibration approaches and process steps for three already operational digital airborne sensors are described, to illustrate differences and complexity of modern digital camera calibration.

2. PROJECT "DIGITAL CAMERA CALIBRATION"

2.1 Project history

In summer 2003 the Steering Committee of EuroSDR has established a core network of some key researchers in the field of digital camera calibration to initiate a research project inside EuroSDR with the goal to derive the technical background for calibration procedures of digital cameras based on scientific theory and empirical investigations. Legal and organizational aspects for certification are put to the background for the time being. Within a very first initial meeting during Photogrammetric Week 2003 in Stuttgart/Germany all larger digital airborne camera producers already signalised their willingness to support this EuroSDR initiative. Based on this motivating kick-off the initiative was officially accepted and established during the 103rd EuroSDR Science and Steering Committee Meetings from October 15-17, 2003 in Munich/Germany. At the time of writing the project is running in its first phase, where already 35 experts from research, industry and users like national mapping agencies joined the network.

2.2 Objectives

The objective of this Digital Camera Calibration project is two-fold:

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

As a result of Phase 1 a report will be compiled based on the support of all project participants, i.e. camera producers and users. Such summary will help to create a common knowledge base for the formulation of future strategies and later experimental work in Phase 2. This status report is helpful for digital camera system users to gain their experience with digital camera calibration aspects. Furthermore, this report should list open problems which need to be solved. All participants of the first initiate meeting welcome the idea, that this report is open to producers, users and customers.

The second phase should focus on the development of commonly accepted procedure(s) for camera calibration and testing. It seems to be necessary to concentrate on some of the technical aspects in a sequential order, starting with geometrical aspects and verification in a limited number of test flights by different camera producers and discussion on radiometric and image quality aspects. One aspect is the design for optimal calibration flight procedures to be tested then empirically. Another aspect is a collection of recommendations of producers on how customers should calibrate and do the processing. It requires a fine definition of goals which should not lead to direct comparisons of cameras, but to individual recommendations for each major camera type. The definition of goals and the design of empirical tests has to be discussed based on the report compiled in Phase 1.

It has to be mentioned that the project itself will focus on the calibration of digital airborne camera systems only. The combination of LIDAR and imaging sensors is not considered since this is a registration and no calibration problem.

3. ASPECTS OF CAMERA CALIBRATION

3.1 Definitions

Before focussing on the topic “Digital Camera Calibration” by presenting the applied methods for three digital systems, the general aspects of traditional camera calibration as mentioned in the Manual of Photogrammetry (Slama 1980) are briefly cited in the following:

- Camera calibration is the process, whereby the geometric aspects of an individual camera are determined.
- It is performed in the order that the photo obtained with the camera is used to produce maps, two allow measurements, whereby ground distances or elevations can be obtained and to make orthophotos.
- It is possible to perform calibration to some order on any camera, but the cameras used to obtain the most accurate geometric data are specially designed for that purpose (namely high-quality lenses, usually at infinity focus). High-quality includes both well defined images and accurate positioning of the image, large aperture possible without introducing excessive distortions, special geometric features like fiducials for determining a coordinate system and for controlling the film behaviour.
- Calibration assumes, that the thing being calibrated is stable between calibrations.
- Calibrated values and their accuracy are reported in a camera calibration certificate with tables and graphs.

Although most of these definitions are generally valid for all types of cameras (i.e. analogue and digital), some remarks should be given related to digital sensors: As already mentioned the multi-spectral capability is one of the major selling points for the new digital sensors, hence the calibrations should not only be restricted to the geometric aspects but to the radiometry part also. Traditional calibration only focuses on the geometry task. The photo interpretation application, which obviously is of increasing future importance, is not considered – especially when thinking on the small to medium format digital sensors non dedicated for airborne use but increasingly used to obtain fast and coloured images for applications in monitoring of land use changes, disaster and risk assessment, forestry and others like real estate search and promotion or tourism. Additionally, those sensors are not specially designed for highest accuracy evaluation which directly covers the point of stability between calibrations. Finally, there is no definition or standard on how the calibrations should be documented.

Since there are different techniques to perform camera calibration the Manual of Photogrammetry (Slama 1980) divides between two basic methods. Their difference is due to the fact, whether the reference values for calibration are presented in object or image space:

- Present an array of targets at known angles to a camera which records their images. The targets may be optical stars (simulating infinite targets) or terrain targets imaged from towers, aircraft or ground. The recorded images are measured and the data reduced from the measurements provide the elements of interior orientation. Many physical controls are necessary.
- Clamp a master grid in the focal plane, measure the observed angles in object space using a visual or goniometer technique. The distortion is computed from the focal length and the difference between the image and object angles.

The parameters of interior orientation are closely related to camera calibration, since a camera is signed as calibrated if the parameters of interior orientation are mathematically defined, namely:

- Focal length f,
- coordinates of principle point x_p and y_p, and
- geometric distortion characteristics of the lens system, i.e. symmetric radial distortions, asymmetric distortions caused by lens decentering.

No matter of the applied method, the accuracy of camera calibration depends on the quality of known geometry of targets being viewed from the camera. This is the reason for the complex and costly equipment used for laboratory calibration methods.

3.2 Laboratory calibration

From classical photogrammetric point of view the laboratory calibration is the standard methodology used for analogue airborne frame sensors. The results of such lab calibrations are documented in the well known calibration certificates. In order to verify the validity of calibration parameters, this calibration is repeated within certain time intervals, typically each two years.

Special equipment is used, where all measurements are done in very well controlled environmental conditions. The European calibrations done for example at the Zeiss (Germany) and Leica (Switzerland) calibration facilities are based on moving collimators, so-called goniometers: The camera axis is fixed, pointing horizontal or vertical and the collimator is moving around the entrance node of the lenses. The precisely known grid crosses from the illuminated master grid mounted in the focal plane of the camera are projected through the lens. These grid points are coincided with the collimator telescope and the corresponding angles in object space are measured. Besides the already mentioned calibration facilities other goniometers are available for example at DLR Berlin (Germany), Simmons Aerofilms in the UK or at FGI in Finland.
In contrary to the visual goniometer technique, multi-collimators are closer to the practical conditions in photogrammetry, since the relevant information is presented in object space. A fixed array of collimators (typically arranged in a fan with well defined angles between the different viewing directions) is used, where each collimator projects an image of its individual cross hair on a photographic plate fixed in the camera focal plane. The coordinates of these crosses (radial distances) are measured afterwards and from these observations the calibration parameters are obtained. In addition to the goniometer method, the multi-collimator is more efficient and the calibration includes not only the lens but the photographic emulsion on the plate fixed in the camera. Such approach finally leads to the more general system driven view – considering not only one individual component during calibration (i.e. the lens of the tested camera), but including all other important components forming the overall system. Although most of photogrammetric systems users feel sufficient with the traditional system component calibration, the need for overall calibration is already obvious since the 1970 as it can be seen i.e. from Maier (1978). This system calibration gains in importance, especially when including additional sensor like GPS/IMU for the data evaluation process. Typically such overall system calibrations are only possible with systems in situ approaches of calibration.

3.3 In situ calibration

In situ calibrations are characteristic for close range applications: Camera calibration and object reconstruction is done within one process named simultaneous calibration. Within this scenario the system and its valid parameters at the time of image recording (including all effects from the actual environment) are considered in calibration which is different from lab calibration described before. Here the camera is calibrated in the environmental conditions and at the object to be reconstructed. Typically the object reconstruction is the primary goal of this measurement campaign, hence the image block configuration might be sub-optimal for the calibration task. Within other approaches, like test site calibration or self-calibration, the calibration is of primary interest. With the use of 3D terrestrial calibration fields providing a large number of signalised points measured automatic or semi-automatic, the calibration parameters are estimated. In some cases the reference coordinates of the calibration field points are known with superior accuracy (test site calibration), although this a priori knowledge is not mandatory. Typically, the availability of one reference scale factor is sufficient (self-calibration).
Since the in situ calibration is a non-aerial approach classically, appropriate mathematical calibration models are originally developed for terrestrial camera calibration. Substantial contributions in this context were given by Brown (1971, 1966), where physically interpretable and relevant parameters like focal length refinement, principal point location, radial and de-centring distortion parameters and other image deformations are introduced during system calibration. Brown clearly shows (from theoretical and practical point of view), that especially when using image blocks with strong geometry the method of bundle adjustment is a very powerful tool to obtain significant self-calibration or additional parameter sets. Such parameter sets as proposed by Brown are implemented in commercial close-range photogrammetry packages (e.g. Fraser 1997).
Besides this, calibration in standard aerial triangulation often relies on mathematical polynomial approaches as proposed e.g. by Ebner (1976) and Grün (1978). In contrary to the parameter sets resulting from physical phenomena, such mathematical driven polynomials are extending the model of bundle adjustment to reduce the residuals in image space. Since high correlation between calibration parameters and the estimated exterior orientation was already recognized by Brown, the Ebner or Grün polynomials are formulated as orthogonal to each other and with respect to the exterior orientation elements of imagery. Those correlations are especially due to the relatively weak geometry of airborne image blocks with their almost parallel viewing directions of individual camera stations and the normally relatively low percentage of terrain height undulations with respect to flying height. In standard airborne flight configurations variations in the camera interior orientation parameters cannot be estimated as far as no additional observations for the camera stations provided by GPS or imagery from different flying heights (resulting in different image scales) are available. This is of particular interest in case of GPS/inertial system calibration due to the strong correlations of GPS/inertial position and boresight alignment offsets with the exterior orientation of the imaging sensor, which is of increasing interest for digital camera systems supplemented with GPS/inertial components. Normally, the two modelling approaches (physical relevant versus mathematical polynomials) are seen in competition, nonetheless the estimation of physical significant parameters and polynomial coefficients is supplementary and both models can also be used simultaneously, as already pointed out in Brown (1976).

4. DIGITAL CAMERA CALIBRATION

Till now only general aspects of camera calibration are recalled and very few specifications on the calibration of digital cameras were given. Hence, some exemplarily systems already used in airborne photogrammetric applications are introduced in the following, with special focus on the applied calibration steps. Since the individual designs of digital sensor systems are quite different, only representatives of the different system classes are mentioned in the following, namely the Applanix/Emerge DSS, the ZI-Imaging DMC and the Leica ADS40 system. These sensors are representatives of the following classes: Sensor systems based on (1) 2D matrix arrays within a single camera head (typically small to medium sized format) (2) several 2D matrix arrays combined within a multi-head solution (utilizing medium or larger format matrix arrays for each individual camera head) and finally (3) line scanning systems, where several linear CCD lines with different viewing angles and different spectral sensitivity are combined in one focal plane.
The DSS is representing the systems of the first class. This group is a very vital one, since many of the already relatively low-cost semi-professional or professional digital consumer market cameras can be modified for airborne use. Petrie (2003) presents a very good overview on the 2D digital sensors market

segment covering the before mentioned classes (1) and (2). The second and third group is more or less dedicated for high accuracy and large format data acquisition. The Vexcel UltracamD and the Dimac Systems DIMAC sensor are other systems which are related to class (2). Besides ADS40, other actual imaging line scanning systems being used for operational airborne photogrammetric purposes are relatively seldom. The DLR HRSC family and the Starlabo TLS scanner have to be mentioned in this context. Nonetheless, other imaging line scanners are used in close connection with laser scanning systems to support the automatic classification of laser points. One representative of such system integration is the Toposys Falcon laser scanner system (Toposys 2004).

4.1 Applanix/Emerge DSS

The Applanix/Emerge DSS is chosen as representative of digital medium format sensor systems. The optical part is based on a MegaVision 4092 x 4077 pix CCD array digital back mounted at a Contax 645 medium format film camera housing. This housing is stabilized using a proprietary exoskeleton to maintain a more or less fixed interior camera geometry. The camera body itself is rigidly fixed with an Applanix POS/AV 410 GPS/inertial system, providing full exterior orientation elements for direct georeferencing. The dimension of the used CCD matrix is 3.68 x 3.67 cm² (9 x 9 μm² individual pixel size) which is less compared to the size of medium format analogue films (typically between 4.5 x 6 cm² and 6 x 7 cm²). In combination with the two available lens systems of 55mm (standard) and 35mm focal length (optional) the resulting field of view is 37deg and 56deg. Comparing the field of view to the geometry of standard photogrammetric cameras (23 x 23 cm² format) these values correspond to a normal-angle (41deg, 30.5cm focal length) or medium-angle (57deg, 21.0cm focal length) image geometry, respectively.

The geometric calibration of the DSS is done by terrestrial and airborne calibration. Using a calibration cage imposed from different angles the interior orientation parameters of the camera are estimated, namely focal length, principle point and lens distortion parameters. In addition to the camera related parameters, the inherent misalignment between IMU body frame system and DSS camera frame is estimated. After terrestrial calibration the estimated parameters are verified from airborne data. Some more details on the applied calibration procedure, the software and the overall performance are presented in Mostafa (2004).

4.2 ZI-Imaging DMC

The concepts of the ZI-Imaging DMC system were firstly introduced to the photogrammetric users community during the Photogrammetric Week 1999. The official market introduction took place during the ISPRS congress 2000 in Amsterdam. This digital sensor is based on a multi-head solution using four larger format CCD frame sensors (7k x 4k pixels, pixel size 12 x 12 μm²) for the slightly tilted pan-chromatic high resolution camera heads. From the overlapping images a new image is calculated representing an perspective virtual image recorded by a large format 13824 x 7680 array. This virtual image is claimed to be free of any distortions, hence the knowledge of interior orientation of each individual camera head and the relative orientations between the different cameras is essential within the generation of the virtual image. The applied calibration process is divided into two steps: single head calibration and platform calibration. The approach is given in detail in Dörstel et al (2003), Zeitler et al (2002) and should be recalled here in a condensed form.

4.2.1 Single head calibration

The lab calibration of the individual camera heads is done with the goniometer measurement device available at the Zeiss Camera Calibration Centre at Oberkochen/Germany. This calibration unit is typically used for the calibration of analogue RMK airborne cameras. The goniometer is based on the Zeiss theodolite Th2 providing an accuracy of 1 arc sec which results in an image accuracy of 0.6 μm or 1/20 pixels assuming the nominal focal length of 12cm for the PAN camera heads. In contrary to the classical calibration, which was already described in Section 3, the CCD array – rigidly fixed into the camera head – cannot be exchanged by a master grid plate. This does not allow the measurement of reference points on the master grid and the correct auto-collimination of the system. Hence, the projected images of the theodolites cross-hair are measured in the digital imagery via automatic point mensuration approaches. The goniometer measurements are done in four different planes (horizontal and vertical bi-section, two diagonals), where all measurements in each plane are done twice with approx. 180deg rotated camera head. Since this rotation is slightly different from the nominal 180deg value and the auto-collimination cannot be guaranteed, additional three degrees of freedom (3 unknown rotation angles) are introduced in the subsequent calibration adjustment, which are estimated as unknown parameters for each measurement plane. These angles are describing the individual rotation between pixel- or image coordinate system of the camera head and the object coordinates realized by the goniometer for each measurement plane.

The desired calibration parameters are determined via bundle adjustment, where the calibration terms are estimated as additional parameters. In order to use the bundle approach, the goniometer angle measurements are transformed into “object coordinates” obtained via intersection of the measured rays with a virtual plane with constant height. Within the DMC calibration the physical relevant parameter set proposed by Brown slightly modified as given by Fraser (1997) are implemented. Besides the three geometric parameters of interior orientation Δx_p, Δy_p and Δc, the first two (K1, K2) of the three radial symmetric parameters are always significant. In some cases the affinity and shear terms B1 and B2 are also estimated as significant. Due to the high quality lens manufacturing the tangential distortion parameters P1 and P2 are non present and eliminated typically. The accuracy $\hat{\sigma}_0$ after parameter estimation is about 0.15 pixel or 1.8 μm, respectively. Repeating the calibration after certain time interval shows high stability of the individual camera heads. The maximum corrections after re-calibration are documented with 1/10 of a pixel (Dörstel et al 2003). It should be mentioned that the single head calibration parameters refer to the “preliminary” single head images only. Their knowledge is essential for the calculation of the virtual image but they must not been applied on the composed images when using these virtual images for photogrammetric data evaluation, which should be the standard way for DMC image data processing.

The result of the camera lab calibration is documented in one calibration certificate for each camera head. Within this protocol, the estimated values of calibration parameters and their accuracy (STD) are given. Additionally, the applied distortion model formula and some general remarks are mentioned. The certificate consists of three pages.

4.2.2 Platform calibration

The platform calibration is essential for the resampling of the new large format image composite based on the four PAN channels. Due to the fact, that a mechanical part used in high-dynamic environments like a photogrammetric flight never can be realized as absolutely stable, the DMC camera housing was designed to allow for some angular deformation of the individual camera heads relative to each other. These deformations are different for each airborne environment and have to be estimated from the mission data itself. This on-the-fly calibration approach is based on tie point measurements from the overlapping regions of pan-chromatic imagery. Besides that, the precise knowledge of relative positions of the individual camera heads, the calibration parameters from single-head calibrations as described above and first approximations on the relative misorientation between the camera heads are necessary input data required for platform calibration. The calibration is solved within a bundle adjustment approach, where three already mentioned rotation angles plus a focal length refinement for three camera heads relatively to one reference camera head are estimated As mentioned in Dörstel et al (2003) about 30-50 tie points are sufficient to estimate the unknown parameters. The typically obtained accuracy is reported with 1/12 to 1/6 of a pixel.

4.3 Leica ADS40

In contrary to the frame based approach (single or multi-head) described so far, multiple linear CCD lines are used in the Leica ADS40 system. The ADS sensor development was driven by the experiences with digital airborne line scanning systems at DLR, namely the WAOSS/WAAC camera systems, originally designed for the 1996 Mars mission and adopted for airborne use after failure of the mission. First tests with ADS engineering models started in 1997, the official product presentation was done during the ISPRS 2000 conference in Amsterdam. The imaging part of the sensor consists of typically 10 CCD lines with different viewing angles and different multi-spectral sensitivity. Each individual line provides 12000 pix with 6.5 x 6.5 μm^2 pixel size.

During calibration the pixel positions of each individual line are determined. The nomenclature for the different CCD lines is like follows: pan-chromatic forward (PANF), nadir (PANN) and backward (PANB) lines, multi-spectral forward (red REDF, green GRNF, blue BLUF) and backward (near-infrared NIRB) lines. The viewing angle relative to the nadir looking direction is also specified by extending these identifiers with the appropriate inclusion of numbers representing the individual viewing angle. For example 28 corresponds to the 28.4deg angle between nadir and forward looking direction of the PANF channels - the resulting identifier is PANF28. The other viewing angles are 14.2deg for the backward PAN lines, 16.1deg for the RGB forward lines and 2.0deg for the NIR backward looking CCD line, resulting in 14, 16, 02 code numbers. Since each PAN channel consists of two individual lines, shifted by half a pixel (so-called staggered arrays), this two lines are differed by using character A for the first and B for the second line. For reasons of completeness it should be mentioned, that the ADS is available with a slightly different CCD-line configurations in the focal plane also: In this case the nadir looking PAN staggered lines and the forward looking RGB lines are exchanged, resulting in nadir viewing RGB channels and an additional forward looking PAN channel. Such configuration might be advantageous, when the main focus of applications is laid on the generation of MS ortho-images.

4.3.1 Lab calibration

The lab calibration of the ADS sensor is based on a coded vertical goniometer (CVG) available at SwissOptic (a Leica Geosystems company). All details on the calibration facilities are given in Pacey et al (1999). The CVG was developed from a modified electronic vertical goniometer (EVG), where the photomultiplier is replaced by a digital CCD frame camera and the glass reference plate (with its high-precisely known marks) is replaced with a special glass code plate. These coded targets are located at the two diagonals and the two horizontal and vertical bi-sections of the plate. The spatial distance between neighbouring targets is 10mm. The measurement is done automatically with high precision. From the measured corresponding object angles the calibrated focal length and the distortion function are obtained. The CVG is used for the calibration of classical RC30 cameras as well as for the ADS sensors, although for ADS the calibration procedure has to be modified like follows.

As described in Pacey et al (1999) lens cone and CCD focal plate are calibrated separately first. Afterwards both components are assembled and calibrated using the CVG. In this case the glass code plate cannot be used any longer since the CCDs are fixed in the focal plane now. Therefore, a coded target is projected in reverse direction on to the CCD-line of the tested lens. In order to allow measurements in of-nadir directions an additional mirror scanner is mounted on top of the goniometer arm. With this modification each individual pixel location on the focal plate can be addressed. As written in Schuster & Braunecker (2000) it is sufficient to measure pixels every 2-5deg within the field of view. The values for intermediate pixels are interpolated numerically.

4.3.2 Self-calibration by bundle adjustment

Although a complete measurement and process flow was established for lab calibration a new approach for ADS calibration was introduced recently. This in situ approach is exclusively based on self-calibration, which is – as already mentioned before – a system driven approach including the calibration of all image-relevant system components. In this context especially the inertial measurement unit (IMU) has to be mentioned, which is essential for operational processing of airborne line scanner data. The mandatory relative orientation between IMU body frame and ADS photo coordinate system can only be determined via self-calibration, which is one advantage compared to the lab calibration approach. The applied procedure is given in detail in Tempelmann et al (2003) and should be recalled in the following.

The calibration is based on the orientation fixes approach proposed by Hofmann, which is implemented in the bundle adjustment software. Again the Brown parameter sets are used as calibration terms. Beside that, additional three unknowns are used to model the before mentioned misalignment angles. Although ADS40 comprises line instead of classical frame geometry, many of the Brown parameters are directly transferable. Some of the parameters (modelling platen flatness) are not useful for line scanners and have to be eliminated. Nonetheless, some uncompensated effects remain. These remaining effects, which are non compensated via the Brown parameter set, have to be modelled by additional polynomials. In Tempelmann et al (2003) a 6^{th} degree of order polynomial performs sufficiently well and is recommended for X and Y components of each sensor line. This extended model will be available in the updated bundle software, hence additional polynomial coefficients are directly estimated in the bundle.

In order to realize a sufficiently well overall system calibration, special requirements for the calibration flight pattern are necessary. Due to strong correlations between some of the calibration parameters and exterior orientation elements, the block layout should consist of two flight lines forming a cross, each line flown twice in bi-directional flight directions. In principle, such pattern is sufficient to estimate all parameters (even without additional ground control) except of the focal length distance. To estimate this parameter, the knowledge of a scaling factor is necessary, which can be obtained from introduction of ground control. Alternatively the same calibration block could be flown within a different flying height resulting in two different image scales. Since both blocks are connected via tie points, such block layout not only allows for calibration without any ground control but also has advantages in terms of stronger block geometry, which results in very reliable estimations of calibration parameters. Hence this double cross block layout is the recommended pattern for calibration flights.

Practical tests have shown, that based on this self-calibration procedure an accuracy of 2.5-2.9μm is obtained for all ADS40 systems, which is the accuracy potential to be expected from the automatic tie point matching quality. Since the additional 6^{th} order polynomials are non fully integrated in the bundle adjustment (status 2003) the final self-calibration parameters are obtained from 4-6 iteration steps. It is worth to mention, that starting from the values obtained from lab calibration, only one single iteration step can be saved. From this background first trends are visible to obtain ADS40 camera calibration parameters from self-calibration exclusively. Potentially, ADS40 lab calibration will totally set away in future.

The calibration results are documented in a 5 pages long calibration certificate. Within this document the tested individual system components are given and the layout of the calibration flight with tie points is depicted. The calibrated misalignment angles are given, the results of geometrical calibration (i.e. calibrated x/y coordinates of all pixels of all sensor lines) are not mentioned explicitly – they are attached separately in a digital file, which belongs to the certificate.

5. SUMMARY

Although this report on the today's status of digital airborne camera calibration is only on its first preliminary stage, these comments will be the base of a more detailed report, which will be published within the next months as result of the first phase of the the EuroSDR project on "Digital Camera Calibration". This Phase 1 final report is open to all persons interested in the different methods of digital camera calibration.

Although only the geometrical calibration of three airborne systems was described in more detail in this paper, some general trends are clearly visible:

- System driven calibration approaches are gaining in importance due to the complexity of digital sensor systems consisting of several sub-components.
- A decrease of importance of lab calibration seems to be visible, whereas the importance of in situ calibration (i.e. self-calibration based on distinct calibration flights) is definitely increasing.
- The acceptance of such combined lab and in situ calibration might be low from today's point of view and has to be increased. This fact is caused from some knowledge deficits on the users side, especially when focussing on the full system calibration based on in situ calibration techniques, which are not as common in the traditional airborne photogrammetry field. With their increased future use such methods will be accepted as powerful and efficient tool for overall systems calibration.

All these aspects will be covered and discussed in more detail in the ongoing project. Hence anyone being interested in these topics is cordially invited to actively participate in the EuroSDR network. All relevant information are available from the project WWW side http://www.ifp.uni-stuttgart.de/eurosdr/ .

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