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EuroSDR network on Digital Camera Calibration

Report Phase I (Status Oct 26, 2004)

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Final Report – Phase I

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[1] This Phase I report is based on the paper presented at the ISPRS commission congress 2004 in Istanbul, Turkey and the publications in ZfV (4(2004)) and PE&RS (December 2004).

Introduction

The need of a camera calibration is a fundamental requirement in the context of photogrammetric data processing. For airborne sensors this calibration is typically realized under well controlled laboratory conditions. In this case, special calibration devices are used to determine the internal camera characteristics with sufficient accuracy. Using such calibration facilities (i.e. multi-collimator or goniometer), the distortion parameters of the lens in use, are estimated based on the computed obtained discrepancies between measured coordinates or angles and their apriori known values. In addition, the focal length and principle point coordinates are chosen to minimize the absolute amount of lens distortions and to realize a symmetric distortion pattern.

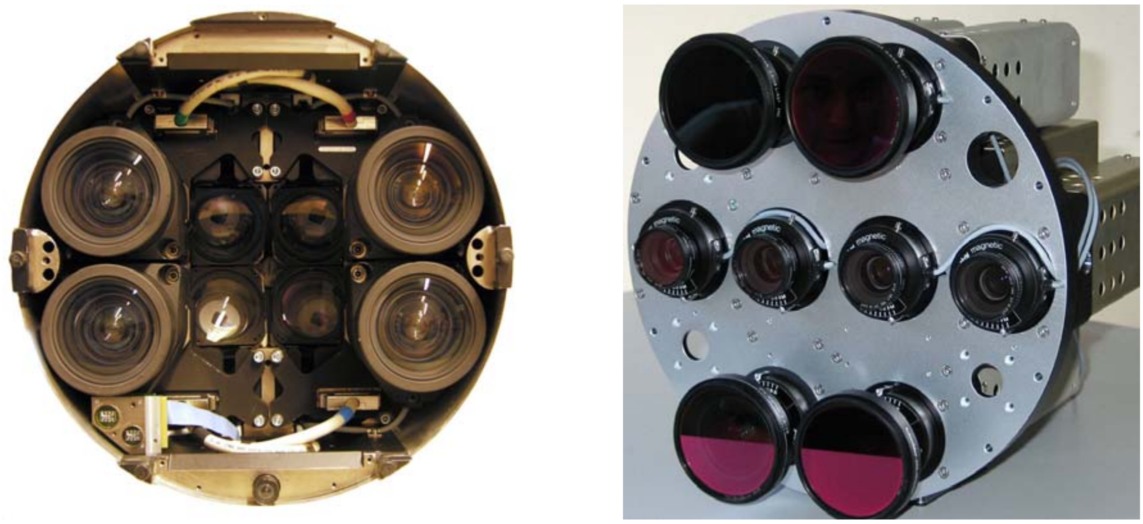
However, this classical technique changes with the increasing availability of new digital airborne imaging systems, mainly due to the following two aspects. First, comparing digital sensor systems from their system design concepts, there are large variations within the specific system realizations and in comparison with standard analogue cameras. These can be summarized as:

- 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
- panchromatic versus multi-spectral image data recording.

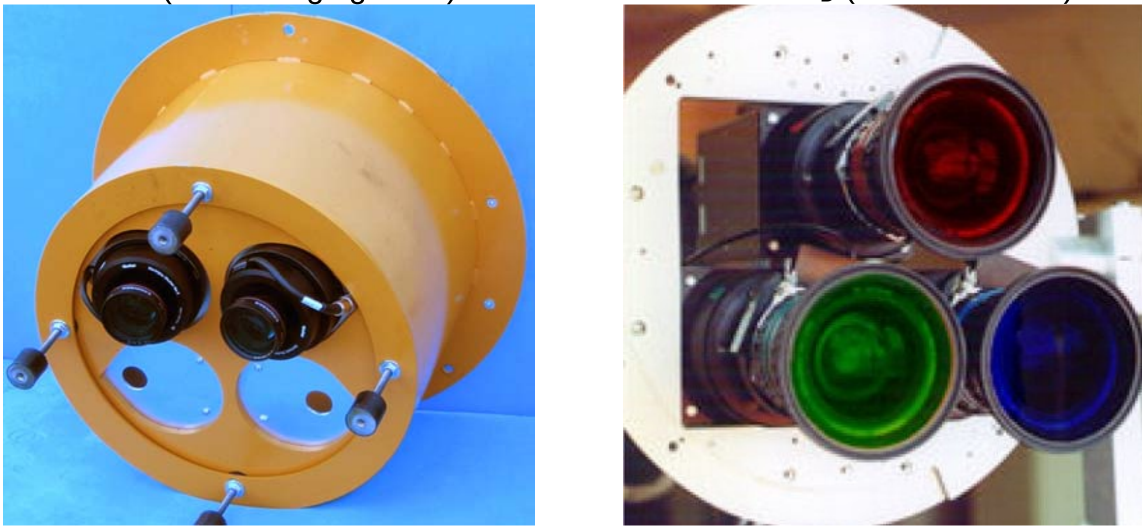
Table 1 summarized these design characteristical differences with respect to the currently available commercial systems. Figure 1 shows the differences in design of multi-head digital cameras compared to each other and to the standard analogue frame sensors. All of the aforementioned differences result 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 to geometric calibration, but should also include radiometric calibration.

#	System	Geometry		Sensor heads		Image format		Image recording		Inertial/GPS components	
		line	frame	single	multi	large	medium	syn-chronous	Syn-topic	optional	man-datory
1	ADS40	☑		☑		☑		☑			☑
2	DMC		☑		☑	☑		☑		☑	
3	Ultracam$_D$		☑		☑	☑			☑	☑	
4	DSS		☑	☑			☑	☑		☑	
5	DIMAC		☑	☑	☑		☑	☑		☑	
6	HRSC-Ax	☑		☑		☑		☑			☑
7	3-DAS-1	☑			☑	☑		☑			☑
8	Starimager	☑		☑		☑		☑			☑

Table 1, Characteristics of modern digital airborne sensor system designs



DMC (© Z/I-Imaging 2004) Ultracam$_D$ (© Vexcel 2004)



DIMAC (© Dimac Systems 2003) IGN (© IGN 2003)

Figure 1, Examples of camera head designs of multi-head frame based airborne digital sensors.

The second fact is mainly due to the integration of the imaging sensors with additional sensors for direct sensor trajectory determination, e.g. GPS or integrated inertial/GPS modules. The combination of digital imaging sensors with direct orientation components is straightforward, since they provide very accurate information of the sensors' movement and which can be used for fast generation of photogrammetric products such as ortho imagery. In the case of line scanning systems a tight integration with inertial/GPS sensors is mandatory for efficient image data processing. The topic of overall system calibration is then important to discuss because calibration has to cover the whole sensor system consisting of both the imaging component and the positioning component. Therefore, the more complex, extended and more general calibration procedures are needed. In this case, the aspect of in-situ calibration gains importance, since calibration should cover the whole sensor system and not only the optical part.

The Digital Camera Calibration Network

The preceding discussion defines the framework of the EuroSDR initiative on “Digital Camera Calibration”. On the 103rd EuroSDR Science and Steering Committee Meetings from October 15-17, 2003 in Munich/Germany the new EuroSDR project on Digital Camera Calibration has been accepted and established officially. The goal is to derive the technical background for digital camera procedures based on scientific theory and empirical research. Legal and certification aspects are put to the background for the time being. Within a first initial meeting in September 2003 all larger digital airborne camera producers already signalized their willingness to support this EuroSDR initiative. In the meantime a network has been established by a core network group who formed this network by selecting a group from experts from around the world with different areas of complementary expertise: currently more than 30 experts from the industry, universities, research institutes, and system users. The members of the network who already have joined the network since September 2003 is given in the Appendix A.

The objective of the Digital Camera Calibration project is twofold:

- 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 this report has been compiled based on contributions from all project participants, which is helpful for digital camera system users to increase their knowledge of digital camera calibration aspects. Additionally, an extensive bibliography of all relevant publications on airborne camera calibration topics is (partially digital) available to all interested users (see Appendix B).

The second phase focuses on the development of commonly accepted procedures for camera calibration and testing. A certain number of well-controlled test flight data sets will be provided for experimental analysis, which can be used by each network member individually. 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 of optimal calibration flight procedures and then to test them empirically. Another aspect is collecting a list of recommendations from the system vendors about how calibration is optimally done with their systems. 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.

Camera calibration aspects

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:

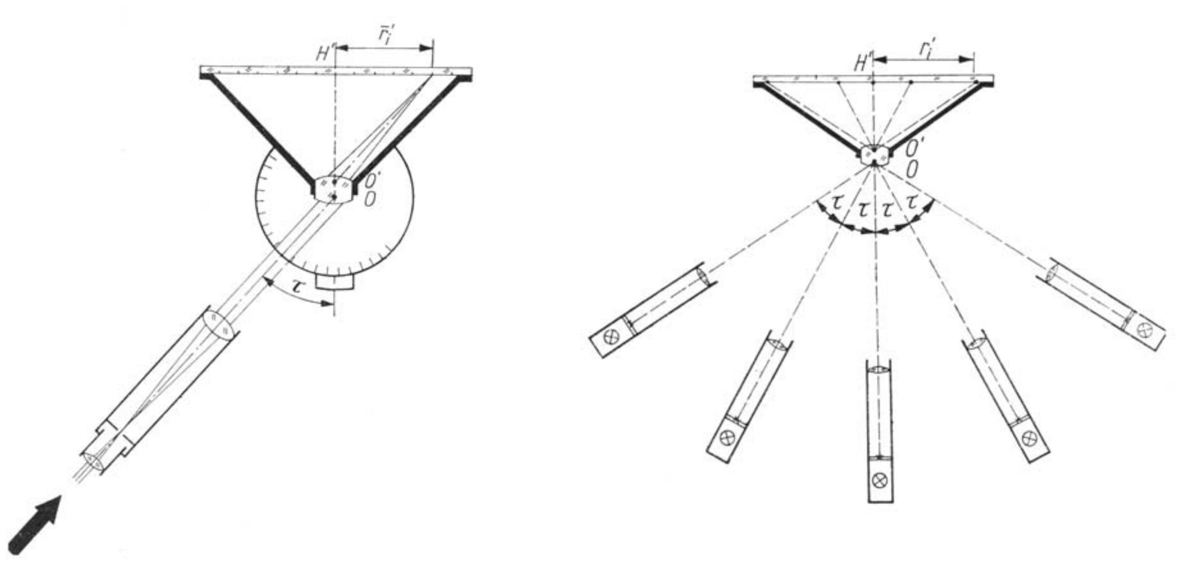
- Focal length f,
- coordinates of principle point x_p and y_p, and
- geometric distortion characteristics of the lens system, i.e. symmetric radial distortions, asymmetric distortions caused by lens decentering.

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.

Laboratory calibration

From classical photogrammetric point of view the component driven 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 (Figure 2a): 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 (Figure 2b). 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.



(a) Goniometer (b) Multi-collimator

Figure 2, Principles of laboratory calibration (Source Bucholtz & Rüger (1973), p. 46)

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.

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).

Although most of the photogrammetric system users still feel it is sufficient to have only a traditional system component calibration, the obvious need for an overall calibration has grown over the last 30 years and continues to gain in importance, especially with the advent and use of additional integrated sensors like GPS and IMU. Against this background the need for an in-situ calibration approach increases since this offers the only possibility to calibrate complex digital sensor systems consisting of several sub-components within true physical environments. The in-situ calibration methodology, originating from the close range application field, solves for the calibration parameters within the object reconstruction process.

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. The slightly different line scanning concept of 3-DAIS-1 was presented at the ISPRS congress by Wehrli Ass. 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).

DSS (Applanix)

The Applanix DSS is one 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 (Figure 3). 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 cm^2 (9 x 9 m^2 individual pixel size) which is less compared to the size of medium format analogue films (typically between 4.5 x 6 cm^2 and 6 x 7 cm^2). 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 cm^2 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 (Figure 4) 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).

Figure 3, DSS medium format camera with proprietary exoskeleton for camera housing stabilization (© Applanix)

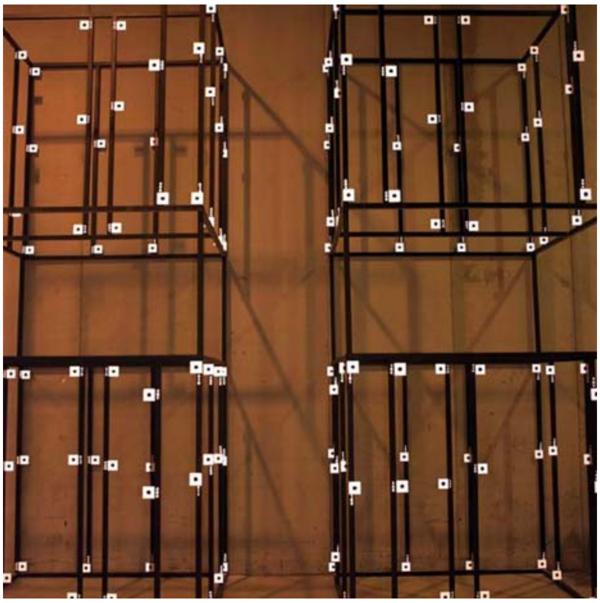


Figure 4, 3D calibration cage used for terrestrial DSS camera calibration (© Applanix)

DMC (ZI-Imaging)

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 μm^2) for the slightly tilted pan-chromatic high resolution camera heads. In Figure 1 the design of optics module is already depicted. Figure 7 shows the camera sensor unit. 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. The colour information is obtained from the four lower resolution colour channels applying appropriate pan-sharpening methods.

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 (Figures 5 and 6). 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 before, 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.

Figure 5, Zeiss goniometer calibration facility (© Zeiss)

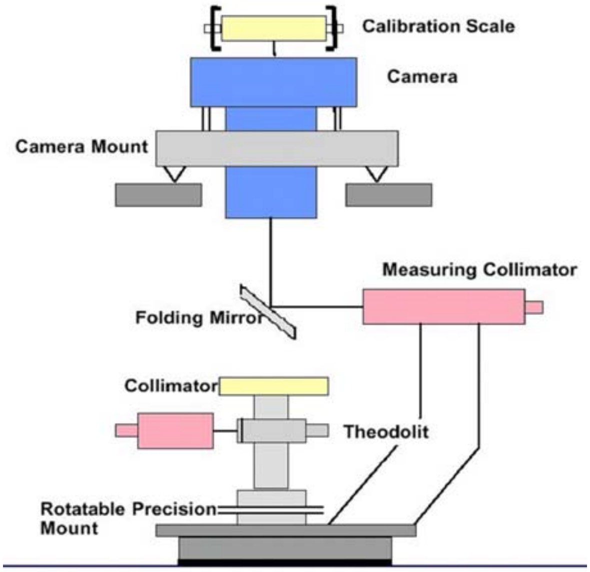


Figure 6, Principle sketch of goniometer (© ZI-Imaging)

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 1.8μm, 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, respectively. 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. An exemplarily calibration protocol is given in Appendix C.

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.

Figure 6, DMC sensor (© ZI-Imaging)

Figure 7, Ultracam$_D$ (© Vexcel)

Ultracam$_D$ (Vexcel)

The Ultracam$_D$ camera design is based on the use of several parallel CCD array sensor (4k x 2.7k pixels each). The sensor unit itself is given in Figure 7, where the different cones are clearly visible. Four optical cones (linearly arranged in Figure 7) are providing the high resolution pan-chromatic images, where the other 4 cones in the edges of the sensor unit are for multi-spectral data acquisition. Each pan-chromatic optical cone has the same field of view, but the CCD arrays are placed in different positions within each focal plane. Therefore, a stitching procedure is necessary to obtain a large format image from the different individual images. Since the pan-chromatic lenses design is based on 9 individual CCD arrays separated in the four different cones the resulting large image format is about 11500 x 7500 pixels. Within the stitching process one cone acts a master cone, to define the image coordinate system. The other images are matched as sub-images parts within this master cone frame. Since the other cones are physically displaced from the master cone, the individual image cones are triggered with certain time delays to physically realize one projection center for all 4 different pan-chromatic image cones. This new mode of image acquisition is called syntopic image recording in contrary to the more common typical synchronous data acquisition mode (each cone is triggered at the same time) used for example within the DMC sensor system. The time delay between the individual image cone triggering is dependent on the actual flying speed of the aircraft. Since the cones are physically displaced by 7cm the recording needs to be delayed by 0.001s from another, based on an aircraft speed of 70m/s.

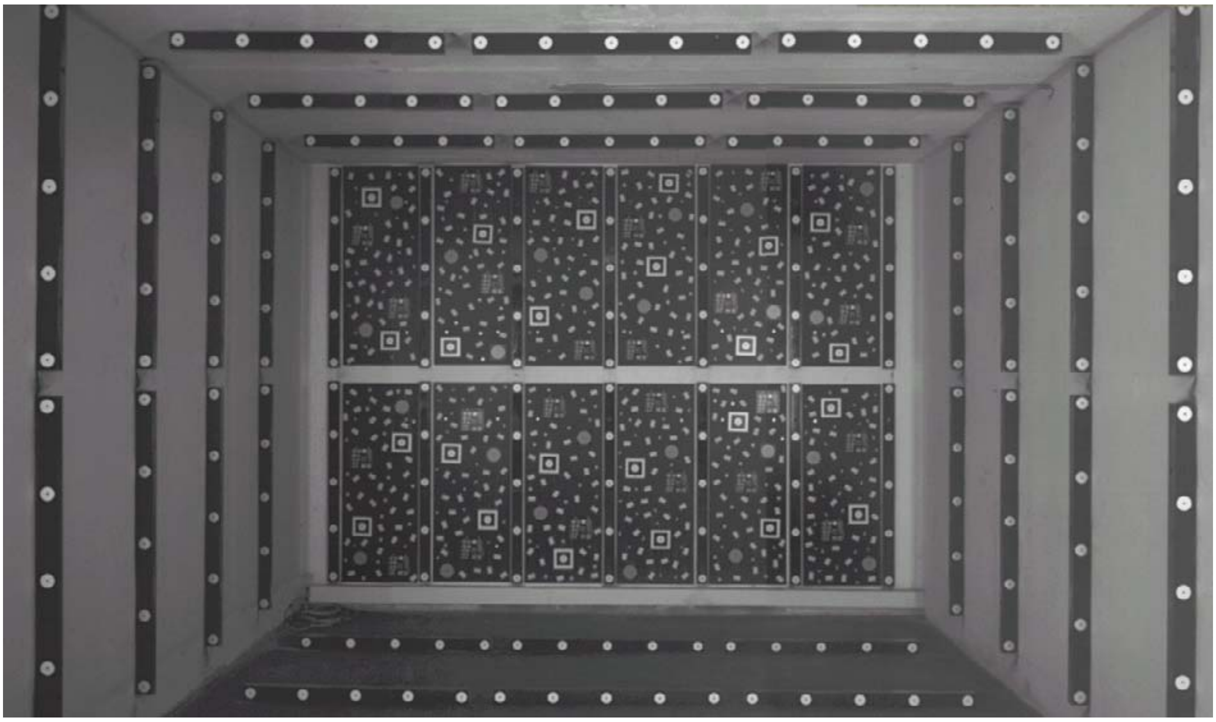


Figure 8, Terrestrial calibration site used for UltracamD lab calibration (© Vexcel)

The lab calibration part for the Vexcel Imaging Ultracam$_D$ large format digital sensor is similar to standard terrestrial close range camera test site calibrations, similar to the DSS lab calibration. A 3D terrestrial calibration field (Figure 8) with sufficient number of 240 targeted and coordinated points is recorded from three different stations with rotated and tilted camera views. Using appropriate bundle adjustment software the calibration parameters are obtained using least squares technique, where typically 84 images are taken for calibration of each individual camera head. For each cone focal length, principal point and distortions are estimated as relevant parameters. Besides that shift, scale, shear and perspective distortions are determined for each CCD. The relative orientations between the individual camera heads of Ultracam$_D$ are estimated for control purposes to detect any tilt between the different optic modules. Since the orientation between pan-chromatic master cone and the three slave camera heads is assumed to be variable, the transformation parameters are determined for each image individually from the mission site imagery itself, quite similar to the DMC approach. This is essential for stitching the individual image patches together to obtain large format imagery from the multi-head systems DMC and Ultracam$_D$. Within this process the distortions parameters from calibration are already considered providing a (theoretically) distortion free image which is used in production then. Again, these values are verified from airborne calibration as a second step. More details on the applied calibration methods can be seen from Kröpfl et al (2004).

The results of geometric individual cone calibration are listed in a quite extensive calibration sheet which is given in Appendix C. Besides that results from radiometric calibration, remarks on the lens resolving power, calibration of sensor electronics and shutter calibration are also documented in this calibration report.

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. The camera sensor unit and the system aircrafts installation for an experimental flight are depicted in Figures 9 and 10.

Figure 9, ADS40 sensor head (© Leica)

Figure 10, ADS40 aircraft installation for experimental test flight (© Leica)

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 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.

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.

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 6th 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 6th 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. An exemplarily calibration protocol is given in Appendix C.

DIMAC (Dimac Systems)

The DIMAC sensor from Dimac Systems, which is a frame based sensor with a flexible combination of up to four individual camera heads, is exclusively calibrated from calibration flight data. In contrast to the DMC and Ultracam$_D$ concept, the images from the different camera heads are kept individually without merging them into a larger format virtual image during data post-processing.

Summary

From the preceding discussion on the geometric calibration using different examples of modern airborne digital systems, the following statements could be summarized:

- System-driven calibration approaches are of increased importance in the future due to the increasing complexity of the digital sensor systems.
- A decreased use of classical lab calibration seems to be evident, whereas the importance of in-situ calibration (i.e. self-calibration with specific calibration flights) are definitely pursued by many vendors.
- The acceptance environment of a combined lab and in-situ calibration has to be increased. There are clear knowledge deficits on the users' side, concerning the features and advantages of system calibration in flight. This is basically due to the fact that these are not as common in the traditional airborne photogrammetry field. With their increasing usage, such methods will be accepted as powerful and efficient tools for overall system calibration.

All these aspects will be discussed in more detail and verified from experimental research in the ongoing project at hand. Generally accepted procedures for calibration shall be tested. The validation of the results will play a very important role. The technical aspects have to be treated with different priority. The geometric aspects will be treated at the beginning and shall be verified in a limited number of test flights. Various administrations and companies have offered material which will be checked by the network for best applicability in this Phase 2. Panchromatic flights shall be used for geometric resolution tests. The influence of 8-bit radiometric resolution compared to original (higher) resolution shall be evaluated with respect to the measurement accuracy. The optimal size of signals needs to be investigated for the calibration flights. The camera stability shall be checked. It has to be decided if point coordinates or derived image products (like in United States) are the optimal criteria for the evaluation, or if a combination of both would make sense. Further investigations concerning radiometric aspects, colour and general aspects of image quality are to be prepared for the second part of Phase 2.

The long-term perspective of the network activities is geared towards the development of optimal calibration setup, which is appropriate for each individual sensor system design. The goal is not to compare between individual camera systems, but to distribute information to a wide range of users that can then be transferred to any new digital camera of comparable system architecture. In general, experiences within this network have already resulted in the fruitful interaction between system providers and system users. It is also expected to see more and more recommendations on system calibration and optimal data processing provided by camera manufacturers. Since camera calibration has a world-wide interest, the EuroSDR initiative has a close link with other calibration activities, mainly in the United States.

With this project EuroSDR wants to support and spread this new technology in cooperation with ISPRS and experts from the US. This project thus supports also new camera vendors in the design of suitable calibration procedures. Further experts in the network are always welcome.

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Appendix A

Network members (Status October 2004)

#	Organization	Network member
System providers		
1	ADS 40, Leica Geosystems	Mr. U. Tempelmann, Mr. P. Fricker
2	DMC, Z/I-Imaging	Mr. C. Dörstel, Dr. M. Madani
3	Ultracam$_D$, Vexcel	Dr. M. Gruber
4	DIMAC, Dimac Systems	Mr. P. Louis, Mr. J. Losseau
5	DSS, Applanix Corp.	Dr. M. Mostafa
6	Starimager, Starlabo Corp.	Dr. K. Tsuno
Industry & other software developers		
7	ISTAR	Dr. P. Nonin
8	MacDonald Dettwiler	Dr. B. Ameri
9	Vito	Mr. J. Everaerts
10	Optical Metrology Centre	Dr. T. Clarke
11	GIP Engineering	Dr. E. Kruck
12	ORIMA	Dr. L. Hinsken
13	DLR Oberpfaffenhofen	Prof. M. Schroeder, Dr. P. Reinartz, Dr. R. Müller, Dr. M. Lehner
University		
14	Ohio State University	Prof. T. Schenk, Prof. D. Merchant
15	ETH Zürich	Prof. A. Grün, Mr. L. Zhang, Mrs. S. Kocaman
16	University of Glasgow	Prof. G. Petrie
17	University of Rostock	Dr. G. Grenzdörffer
18	University of Stuttgart	Dr. N. Haala, Dr. M. Cramer
19	University of Hannover	Dr. K. Jacobsen
20	Humboldt University Berlin	Prof. R. Reulke
21	University of Applied Sciences Stuttgart	Prof. E. Gülch
22	University of Applied Sciences Anhalt	Prof. H. Ziemann
23	Institute de Geomatica Castelldefels	Dr. I. Colomina
24	Agricultural University of Norway Aas	Dr. I. Maalen-Johansen
National mapping agencies & other authorities		
25	Swedish Land Survey	Mr. D. Akerman
26	Finnish Geodetic Institute	Prof. R. Kuittinen, Prof. J. Hyppä
27	British Ordnance Survey	Mr. P. Marshall
28	Swisstopo – Landestopographie	Dr. A. Streilein
29	US Geological Survey	Dr. G. Stensaas, Dr. G. Y. G. Lee
30	ICC Barcelona	Dr. J. Talaya
31	IGN France	Dr. J. Lagrange, Dr. M. Deseilligny

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ADS40 (Leica Geosystems)

ADS40 calibration certificate, sample document

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Appendix C

DMC Calibration protocol of PAN-chromatic camera head (example)

Calibration Certificate N° 02109383

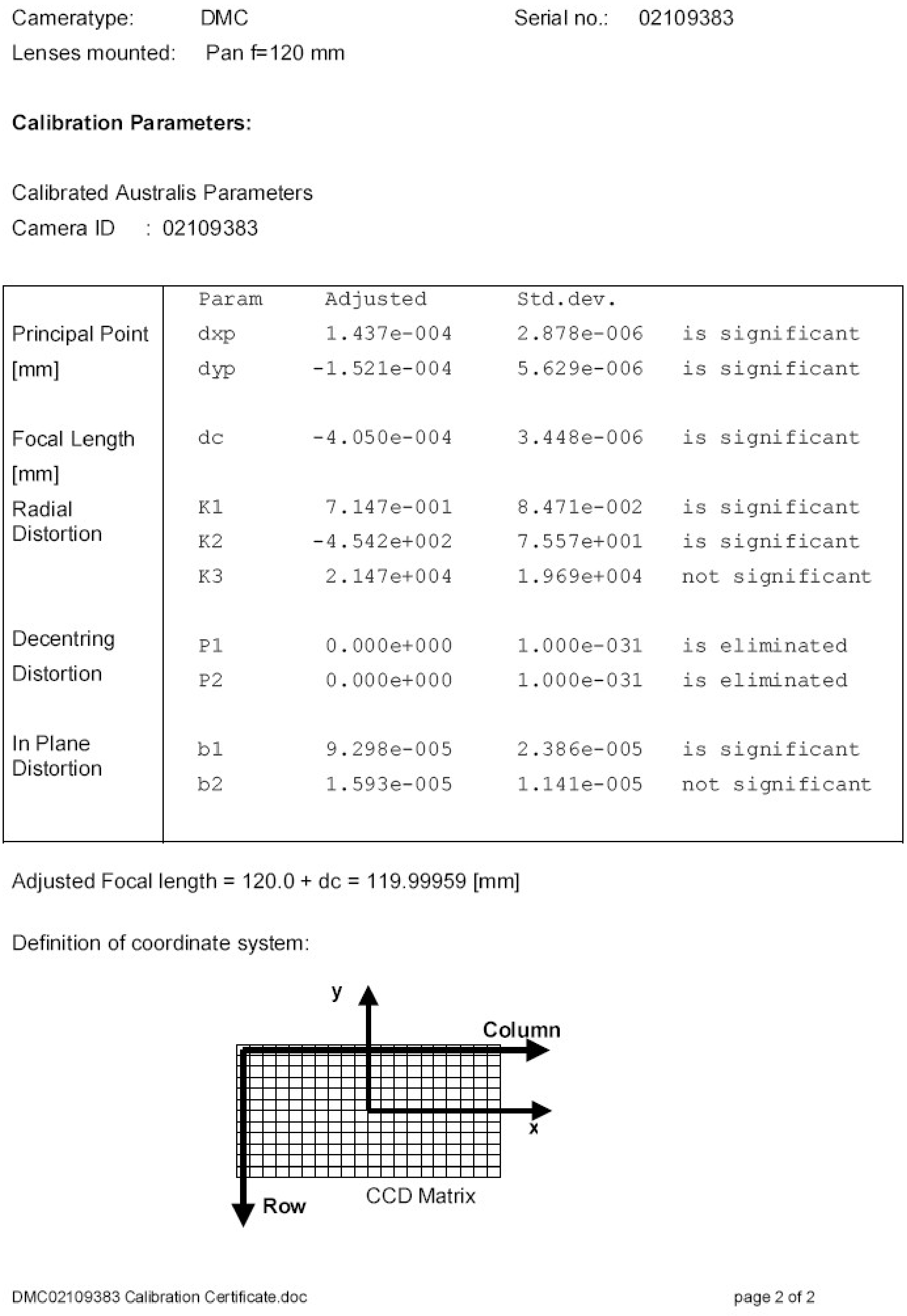
Object	Digital Aerial Survey Camera
Manufacturer	Z/I Imaging D-73431 Aalen
Type	DMC Panchromatic
Serial Number	02109383
Customer	

Calibration performed at:
Deutscher Kalibrierdienst (DKD)
Kalibrierstelle für Meßgrößen der geometrischen Optik
at Carl Zeiss, Oberkochen (DKD Registration No. : DKD-K-0502)

Number of pages of the certificate	3
Date of Calibration	15.05.2003

Certified	Date	Z/I QS Manager	Calibration Performed
	15.05.2003	(M. Raubach)	(J.Hefele)

DMC02109383 Calibration Certificate.doc page 1 of 1



Cameratype: DMC Serial no.: 02109383

Lenses mounted: Pan f=120 mm

Calibration Parameters:

Calibrated Australis Parameters

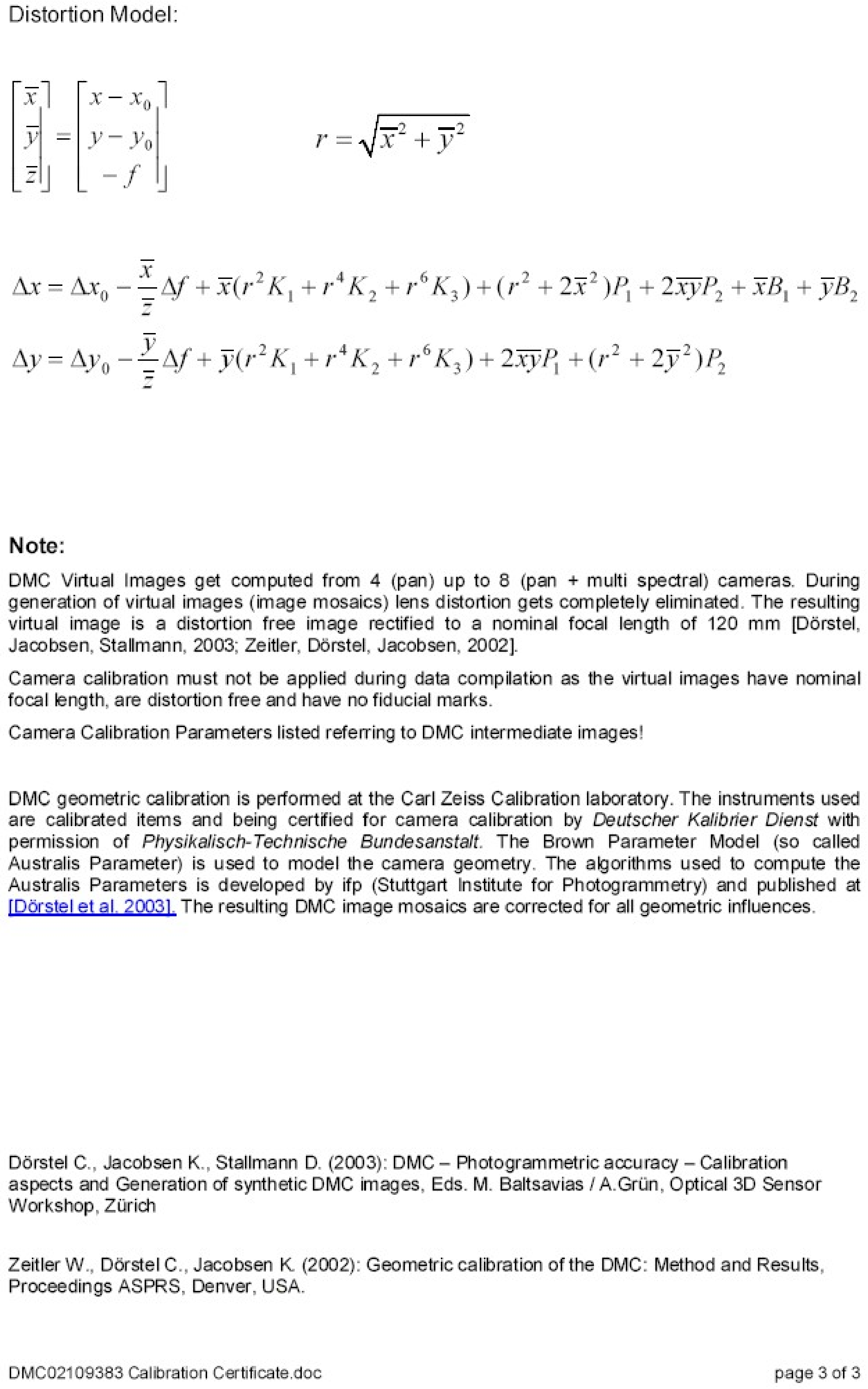
Camera ID : 02109383

	Param	Adjusted	Std.dev.	
Principal Point [mm]	dxp	1.437e-004	2.878e-006	is significant
	dyp	-1.521e-004	5.629e-006	is significant
Focal Length [mm]	dc	-4.050e-004	3.448e-006	is significant
Radial Distortion	K1	7.147e-001	8.471e-002	is significant
	K2	-4.542e+002	7.557e+001	is significant
	K3	2.147e+004	1.969e+004	not significant
Decentring Distortion	P1	0.000e+000	1.000e-031	is eliminated
	P2	0.000e+000	1.000e-031	is eliminated
In Plane Distortion	b1	9.298e-005	2.386e-005	is significant
	b2	1.593e-005	1.141e-005	not significant

Adjusted Focal length = 120.0 + dc = 119.99959 [mm]

Definition of coordinate system:

DMC02109383 Calibration Certificate.doc page 2 of 2



Distortion Model:

$$\begin{bmatrix} \overline{x} \\ \overline{y} \\ \overline{z} \end{bmatrix} = \begin{bmatrix} x - x_0 \\ y - y_0 \\ -f \end{bmatrix} \qquad r = \sqrt{\overline{x}^2 + \overline{y}^2}$$

$$\Delta x = \Delta x_0 - \frac{\overline{x}}{\overline{z}}\Delta f + \overline{x}(r^2 K_1 + r^4 K_2 + r^6 K_3) + (r^2 + 2\overline{x}^2)P_1 + 2\overline{xy}P_2 + \overline{x}B_1 + \overline{y}B_2$$

$$\Delta y = \Delta y_0 - \frac{\overline{y}}{\overline{z}}\Delta f + \overline{y}(r^2 K_1 + r^4 K_2 + r^6 K_3) + 2\overline{xy}P_1 + (r^2 + 2\overline{y}^2)P_2$$

Note:

DMC Virtual Images get computed from 4 (pan) up to 8 (pan + multi spectral) cameras. During generation of virtual images (image mosaics) lens distortion gets completely eliminated. The resulting virtual image is a distortion free image rectified to a nominal focal length of 120 mm [Dörstel, Jacobsen, Stallmann, 2003; Zeitler, Dörstel, Jacobsen, 2002].

Camera calibration must not be applied during data compilation as the virtual images have nominal focal length, are distortion free and have no fiducial marks.

Camera Calibration Parameters listed referring to DMC intermediate images!

DMC geometric calibration is performed at the Carl Zeiss Calibration laboratory. The instruments used are calibrated items and being certified for camera calibration by *Deutscher Kalibrier Dienst* with permission of *Physikalisch-Technische Bundesanstalt*. The Brown Parameter Model (so called Australis Parameter) is used to model the camera geometry. The algorithms used to compute the Australis Parameters is developed by ifp (Stuttgart Institute for Photogrammetry) and published at [Dörstel et al. 2003]. The resulting DMC image mosaics are corrected for all geometric influences.

Dörstel C., Jacobsen K., Stallmann D. (2003): DMC – Photogrammetric accuracy – Calibration aspects and Generation of synthetic DMC images, Eds. M. Baltsavias / A.Grün, Optical 3D Sensor Workshop, Zürich

Zeitler W., Dörstel C., Jacobsen K. (2002): Geometric calibration of the DMC: Method and Results, Proceedings ASPRS, Denver, USA.

DMC Calibration protocol of colour camera head (example)

Calibration Certificate N° 03109058

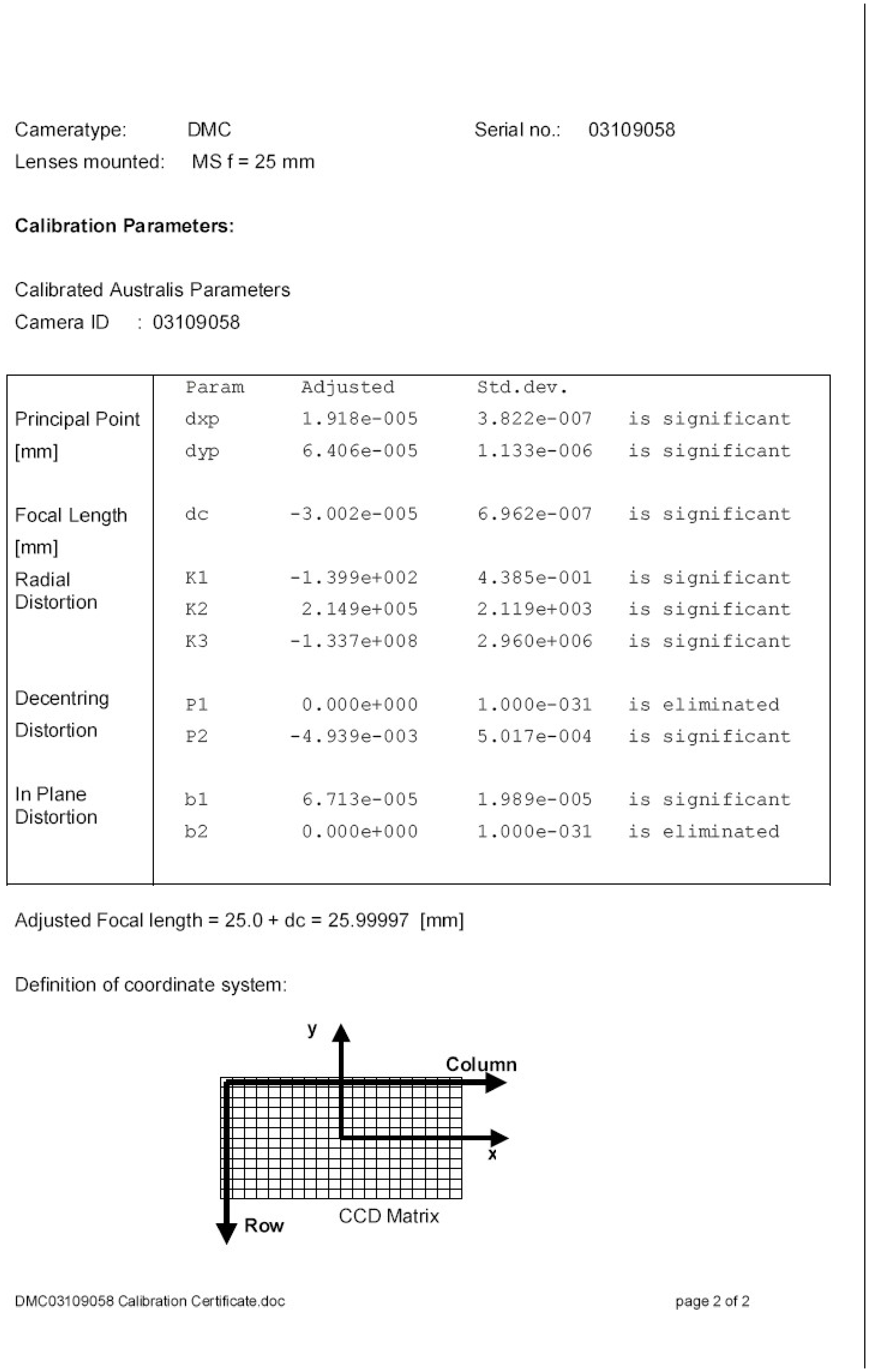
Object	Digital Aerial Survey Camera
Manufacturer	Z/I Imaging D-73431 Aalen
Type	DMC MS-BLUE
Serial Number	03109058
Customer	

Calibration performed at:
Deutscher Kalibrierdienst (DKD)
Kalibrierstelle für Meßgrößen der geometrischen Optik
at Carl Zeiss, Oberkochen (DKD Registration No. : DKD-K-0502)

Number of pages of the certificate	3
Date of Calibration	26.06.2003

Certified	Date	Z/I QS Manager	Calibration Performed
	26.06.2003		
		(M. Raubach)	(J.Hefele)

DMC03109058 Calibration Certificate.doc page 1 of 1



Cameratype: DMC Serial no.: 03109058

Lenses mounted: MS f = 25 mm

Calibration Parameters:

Calibrated Australis Parameters

Camera ID : 03109058

	Param	Adjusted	Std.dev.	
Principal Point [mm]	dxp	1.918e-005	3.822e-007	is significant
	dyp	6.406e-005	1.133e-006	is significant
Focal Length [mm]	dc	-3.002e-005	6.962e-007	is significant
Radial Distortion	K1	-1.399e+002	4.385e-001	is significant
	K2	2.149e+005	2.119e+003	is significant
	K3	-1.337e+008	2.960e+006	is significant
Decentring Distortion	P1	0.000e+000	1.000e-031	is eliminated
	P2	-4.939e-003	5.017e-004	is significant
In Plane Distortion	b1	6.713e-005	1.989e-005	is significant
	b2	0.000e+000	1.000e-031	is eliminated

Adjusted Focal length = 25.0 + dc = 25.99997 [mm]

Definition of coordinate system:

Distortion Model:

$$\begin{bmatrix} \bar{x} \\ \bar{y} \\ \bar{z} \end{bmatrix} = \begin{bmatrix} x - x_0 \\ y - y_0 \\ -f \end{bmatrix} \qquad r = \sqrt{\bar{x}^2 + \bar{y}^2}$$

$$\Delta x = \Delta x_0 - \frac{\bar{x}}{\bar{z}}\Delta f + \bar{x}(r^2 K_1 + r^4 K_2 + r^6 K_3) + (r^2 + 2\bar{x}^2)P_1 + 2\overline{xy}P_2 + \bar{x}B_1 + \bar{y}B_2$$

$$\Delta y = \Delta y_0 - \frac{\bar{y}}{\bar{z}}\Delta f + \bar{y}(r^2 K_1 + r^4 K_2 + r^6 K_3) + 2\overline{xy}P_1 + (r^2 + 2\bar{y}^2)P_2$$

Note:

DMC Virtual Images get computed from 4 (pan) up to 8 (pan + multi spectral) cameras. During generation of virtual images (image mosaics) lens distortion gets completely eliminated. The resulting virtual image is a distortion free image rectified to a nominal focal length of 120 mm [Dörstel, Jacobsen, Stallmann, 2003; Zeitler, Dörstel, Jacobsen, 2002].

Camera calibration must not be applied during data compilation as the virtual images have nominal focal length, are distortion free and have no fiducial marks.

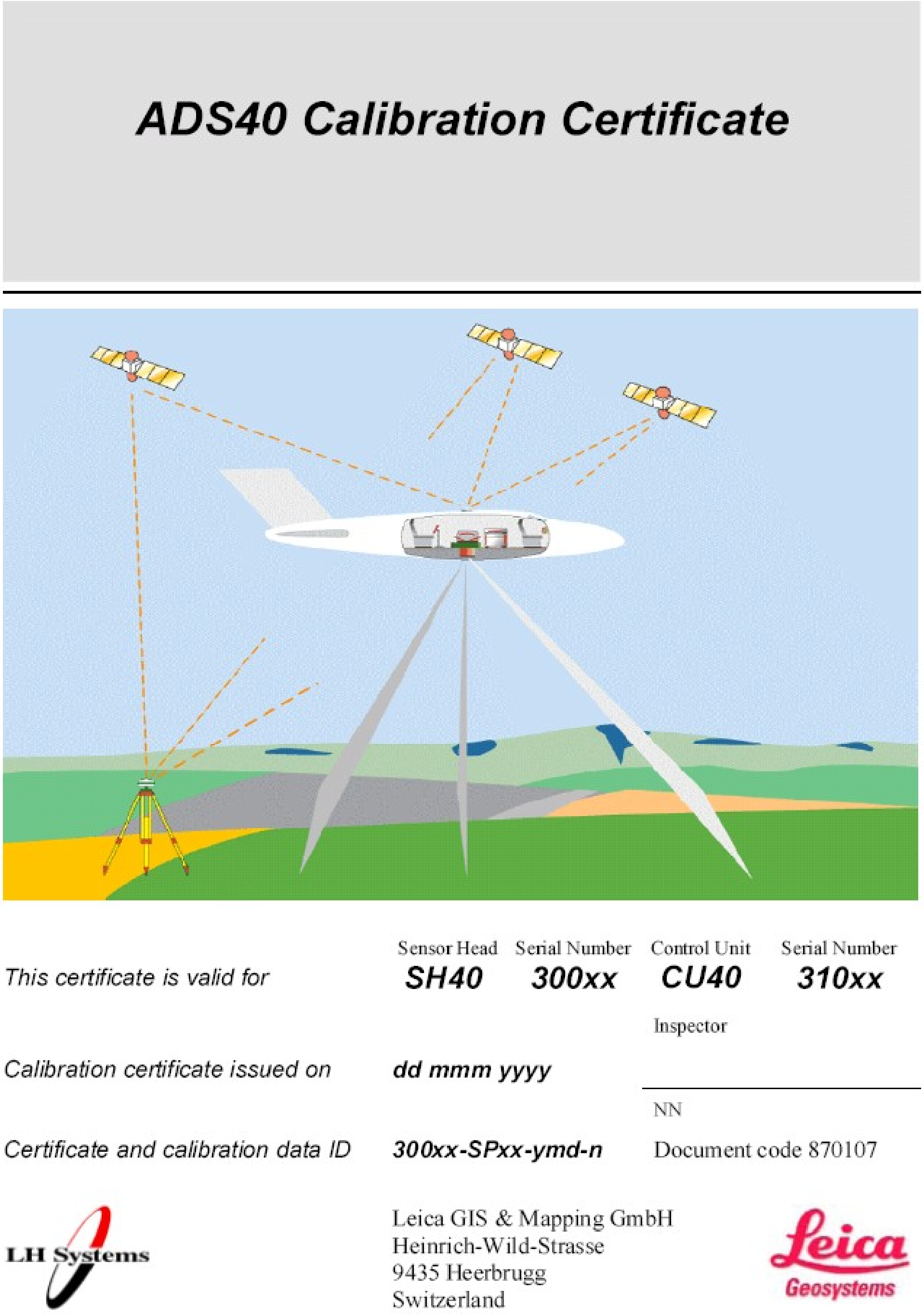
Camera Calibration Parameters listed referring to DMC intermediate images!

DMC geometric calibration is performed at the Carl Zeiss Calibration laboratory. The instruments used are calibrated items and being certified for camera calibration by *Deutscher Kalibrier Dienst* with permission of *Physikalisch-Technische Bundesanstalt*. The Brown Parameter Model (so called Australis Parameter) is used to model the camera geometry. The algorithms used to compute the Australis Parameters is developed by ifp (Stuttgart Institute for Photogrammetry) and published at [Dörstel et al. 2003]. The resulting DMC image mosaics are corrected for all geometric influences.

Dörstel C., Jacobsen K., Stallmann D. (2003): DMC – Photogrammetric accuracy – Calibration aspects and Generation of synthetic DMC images, Eds. M. Baltsavias / A.Grün, Optical 3D Sensor Workshop, Zürich

Zeitler W., Dörstel C., Jacobsen K. (2002): Geometric calibration of the DMC: Method and Results, Proceedings ASPRS, Denver, USA.

ADS40 calibration protocol (example)



ADS40 Calibration Certificate

	Sensor Head	Serial Number	Control Unit	Serial Number
This certificate is valid for	**SH40**	**300xx**	**CU40**	**310xx**

Calibration certificate issued on ***dd mmm yyyy***

Inspector

NN

Certificate and calibration data ID ***300xx-SPxx-ymd-n***

Document code 870107

LH Systems

Leica GIS & Mapping GmbH
Heinrich-Wild-Strasse
9435 Heerbrugg
Switzerland

Leica Geosystems

Components

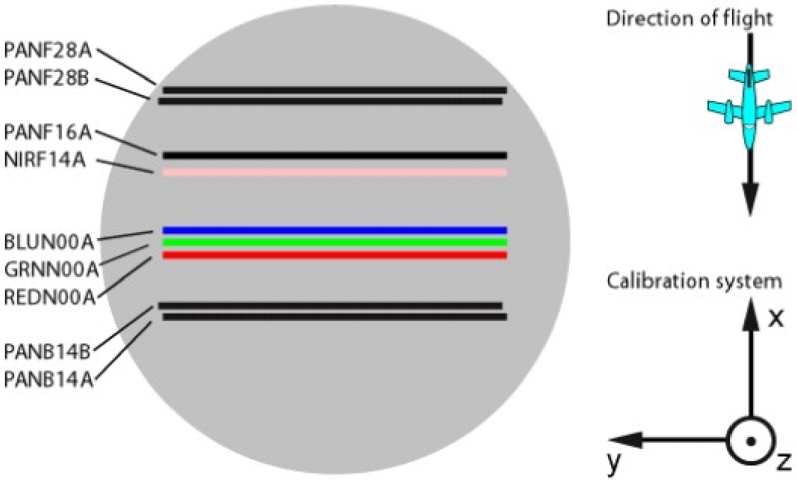
Component	Device	Type	Serial Number
SH40 #30020	Lens system	DO64	21955 / 00xx
	Focal Plate Module cover	FCO	xx
	Focal Plate Module (FPM)	RGB-Nadir-A	xx
	Inertial Measurement Unit	LN200-ADS	xxxxxx
CU40 #31020	POS-system with GPS	POS-OEM	xxx

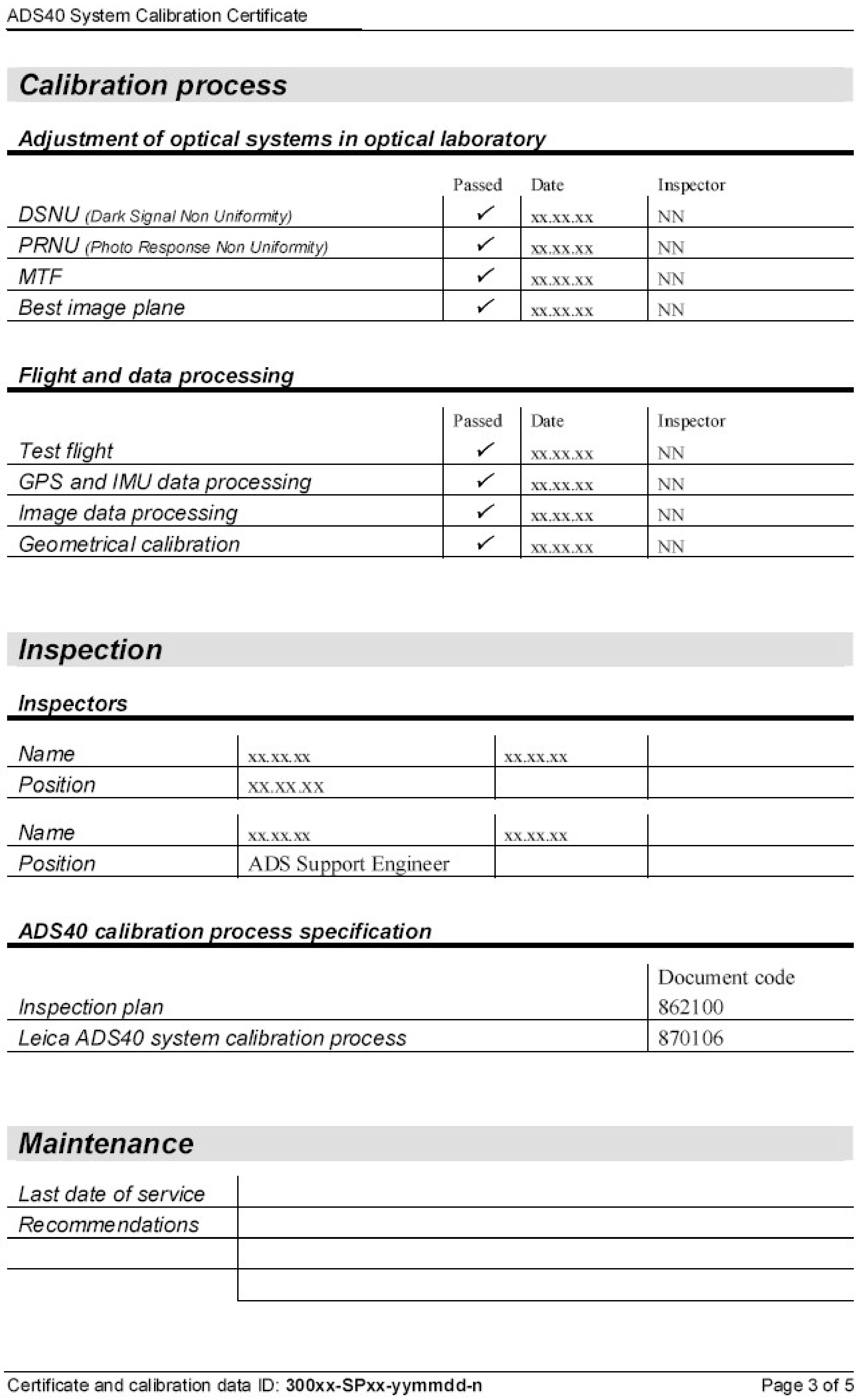
Nominal FPM layout of tested system

End pixel coordinates are center of pixel coordinates.
Middle coordinates are between pixels 6000 and 6001.
All values in [mm]

Line Name	X	Y, Pixel 1	Y, Center	Y, Pixel 12000
PANF28A	34.91	38.44	0.00	-40.24
PANF28B				
PANF16A	18.42	-40.11	0.00	38.75
NIRF14A	16.18	-40.03	0.00	38.73
BLUN00A	0.00	-39.00	0.00	39.00
GRNN00A				
REDN00A				
PANB14A PANB14B	-15.74	-39.59	0.00	38.74

View from top of Sensor Head





ADS40 System Calibration Certificate

Calibration process

Adjustment of optical systems in optical laboratory

	Passed	Date	Inspector
DSNU (Dark Signal Non Uniformity)	✓	xx.xx.xx	NN
PRNU (Photo Response Non Uniformity)	✓	xx.xx.xx	NN
MTF	✓	xx.xx.xx	NN
Best image plane	✓	xx.xx.xx	NN

Flight and data processing

	Passed	Date	Inspector
Test flight	✓	xx.xx.xx	NN
GPS and IMU data processing	✓	xx.xx.xx	NN
Image data processing	✓	xx.xx.xx	NN
Geometrical calibration	✓	xx.xx.xx	NN

Inspection

Inspectors

Name	xx.xx.xx	xx.xx.xx	
Position	xx.xx.xx		
Name	xx.xx.xx	xx.xx.xx	
Position	ADS Support Engineer		

ADS40 calibration process specification

	Document code
Inspection plan	862100
Leica ADS40 system calibration process	870106

Maintenance

Last date of service	
Recommendations	

Certificate and calibration data ID: **300xx-SPxx-yymmdd-n** Page 3 of 5

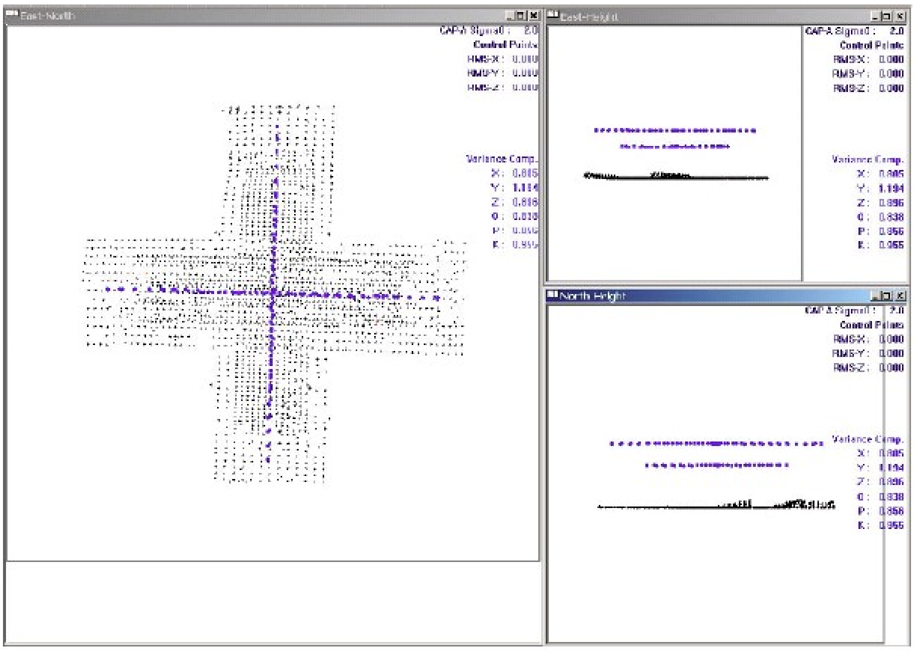
Results of geometrical calibration

Calibrated apparent of x/y-coordinates for all sensor lines are contained on the calibration file attached to this certificate. File: 30020-SP15-031015-1.zip

Stereo lines *(A-lines of staggered panchromatic pairs)*

Included lines	PANF28A PANF16A PANB14A
Calibration method	Estimation of additional parameters in simultaneous bundle adjustment
Sigma naught of bundle adjustment	2.0 micron
Mean local redundancy	> 0.5
Accuracy of calibrated apparent pixel coordinates	±1.0 micron

Final bundle adjustment result after elimination of tie point blunders and before introduction of ground control:

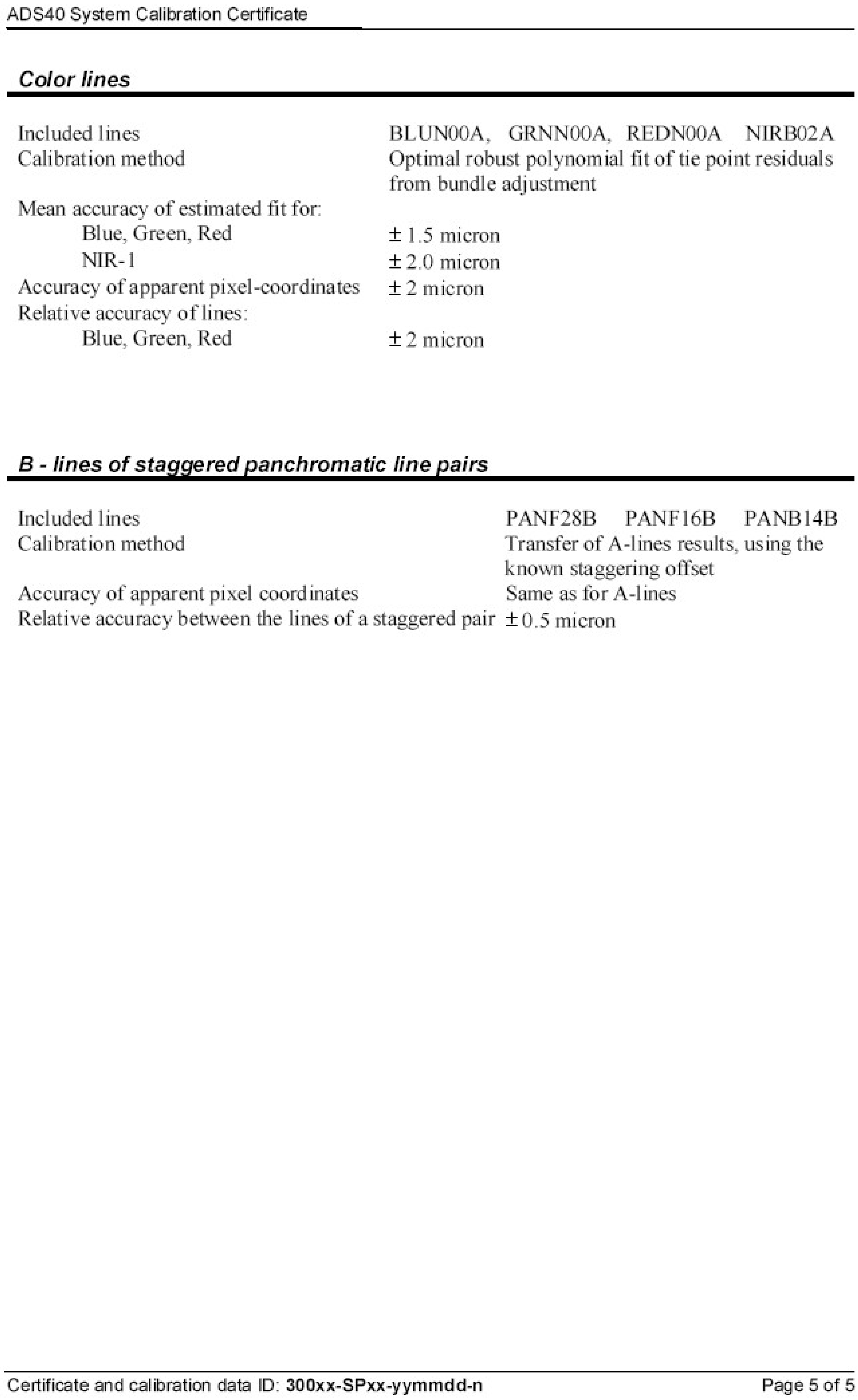


CAP-A Sigma0 : 2.0
Control Points
RMS-X : 0.000
RMS-Y : 0.000
RMS-Z : 0.000

Variance Comp.
X : 0.885
Y : 1.194
Z : 0.896
O : 0.838
P : 0.856
K : 0.955

IMU misalignment

Misalignment results in [rad]:	ω =	-0.0047520958	±0.0000044550
	ϕ =	-0.0122040885	±0.0000041843
	κ =	-0.0119988404	±0.0000079528



ADS40 System Calibration Certificate

Color lines

Included lines	BLUN00A, GRNN00A, REDN00A NIRB02A
Calibration method	Optimal robust polynomial fit of tie point residuals from bundle adjustment
Mean accuracy of estimated fit for:	
Blue, Green, Red	± 1.5 micron
NIR-1	± 2.0 micron
Accuracy of apparent pixel-coordinates	± 2 micron
Relative accuracy of lines:	
Blue, Green, Red	± 2 micron

B - lines of staggered panchromatic line pairs

Included lines	PANF28B PANF16B PANB14B
Calibration method	Transfer of A-lines results, using the known staggering offset
Accuracy of apparent pixel coordinates	Same as for A-lines
Relative accuracy between the lines of a staggered pair	± 0.5 micron

Certificate and calibration data ID: **300xx-SPxx-yymmdd-n** Page 5 of 5

UltracamD calibration protocol (example, only excerpts given here)

VEXCEL

UltraCam D, Serial Number UCD-SU-1-00xx

Calibration Report

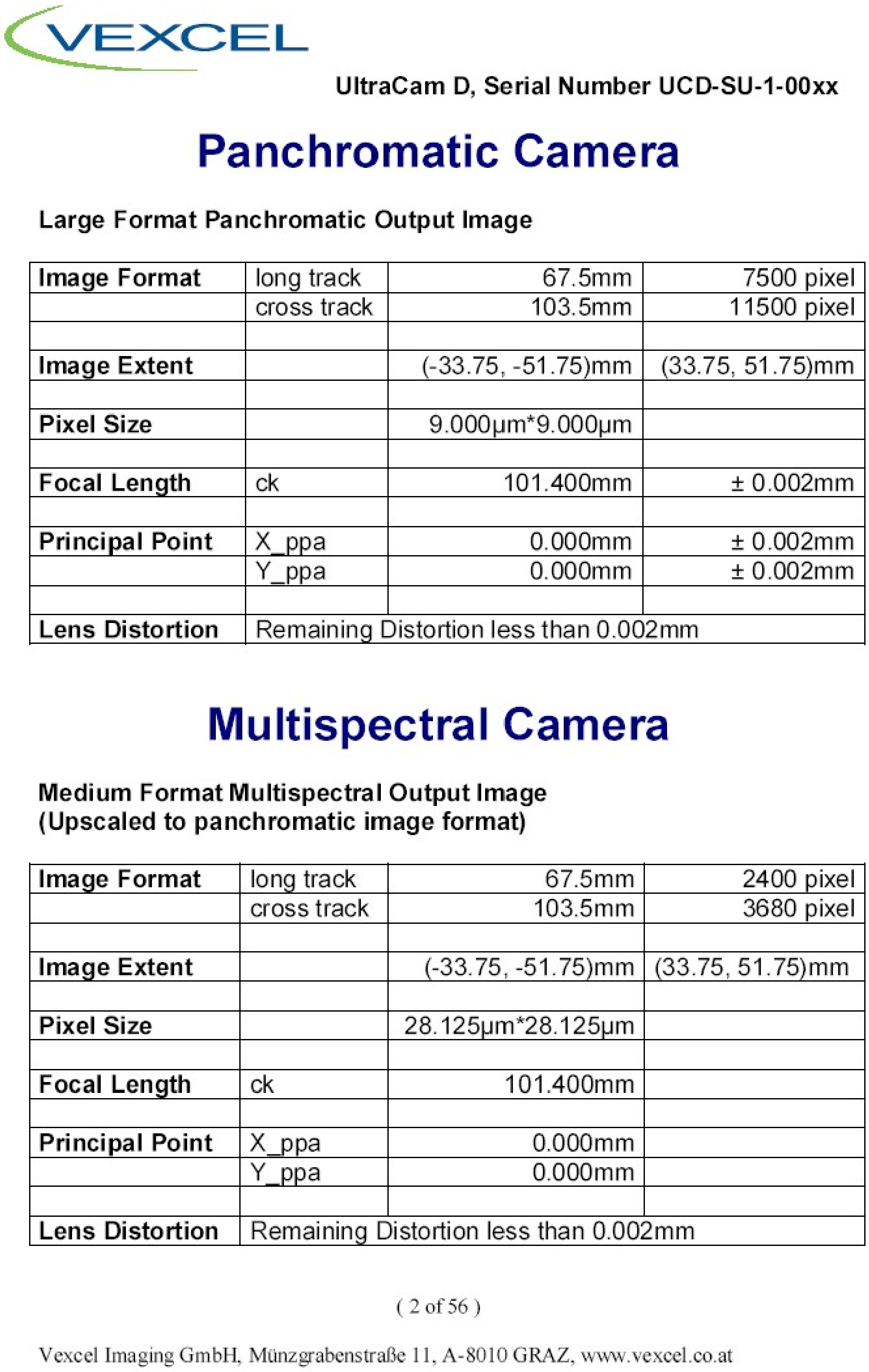
Geometric Calibration

ULTRACAM$_D$
Large Format Digital Aerial Camera

Camera:	UltraCam D, S/N UCD-SU-1-00xx
Manufacturer:	Vexcel Imaging GmbH, A-8010 Graz, Austria
Panchromatic Camera:	ck = 101.400mm
Multispectral Camera:	ck = 101.400mm
Date of Calibration:	Jun-12-2004
Date of Report:	Junl-14-2004
Camera Revision:	1.0
Revision of Report:	1.0

(1 of 56)

Vexcel Imaging GmbH, Münzgrabenstraße 11, A-8010 GRAZ, www.vexcel.co.at



UltraCam D, Serial Number UCD-SU-1-00xx

Panchromatic Camera

Large Format Panchromatic Output Image

Image Format	long track	67.5mm	7500 pixel
	cross track	103.5mm	11500 pixel
Image Extent		(-33.75, -51.75)mm	(33.75, 51.75)mm
Pixel Size		9.000µm*9.000µm	
Focal Length	ck	101.400mm	± 0.002mm
Principal Point	X_ppa	0.000mm	± 0.002mm
	Y_ppa	0.000mm	± 0.002mm
Lens Distortion	Remaining Distortion less than 0.002mm		

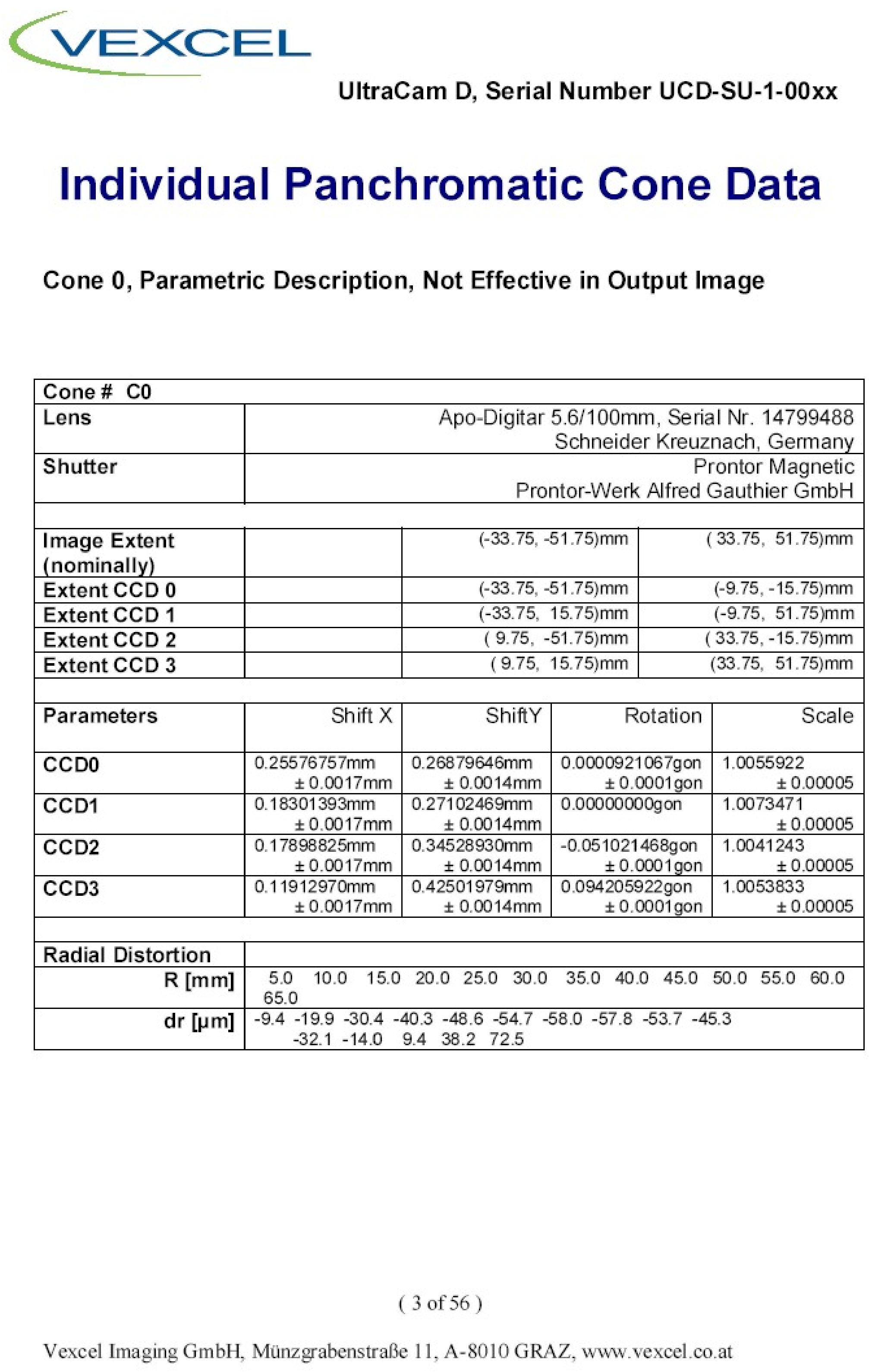
Multispectral Camera

Medium Format Multispectral Output Image
(Upscaled to panchromatic image format)

Image Format	long track	67.5mm	2400 pixel
	cross track	103.5mm	3680 pixel
Image Extent		(-33.75, -51.75)mm	(33.75, 51.75)mm
Pixel Size		28.125µm*28.125µm	
Focal Length	ck	101.400mm	
Principal Point	X_ppa	0.000mm	
	Y_ppa	0.000mm	
Lens Distortion	Remaining Distortion less than 0.002mm		

(2 of 56)

Vexcel Imaging GmbH, Münzgrabenstraße 11, A-8010 GRAZ, www.vexcel.co.at



UltraCam D, Serial Number UCD-SU-1-00xx

Individual Panchromatic Cone Data

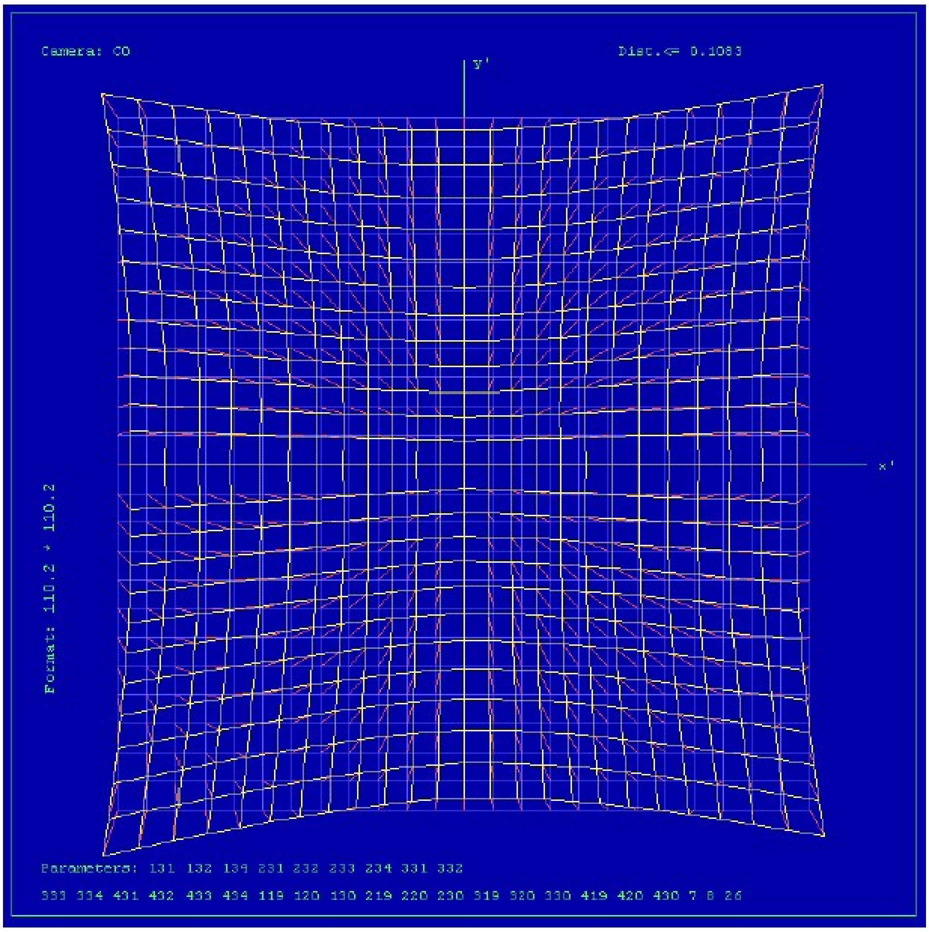
Cone 0, Parametric Description, Not Effective in Output Image

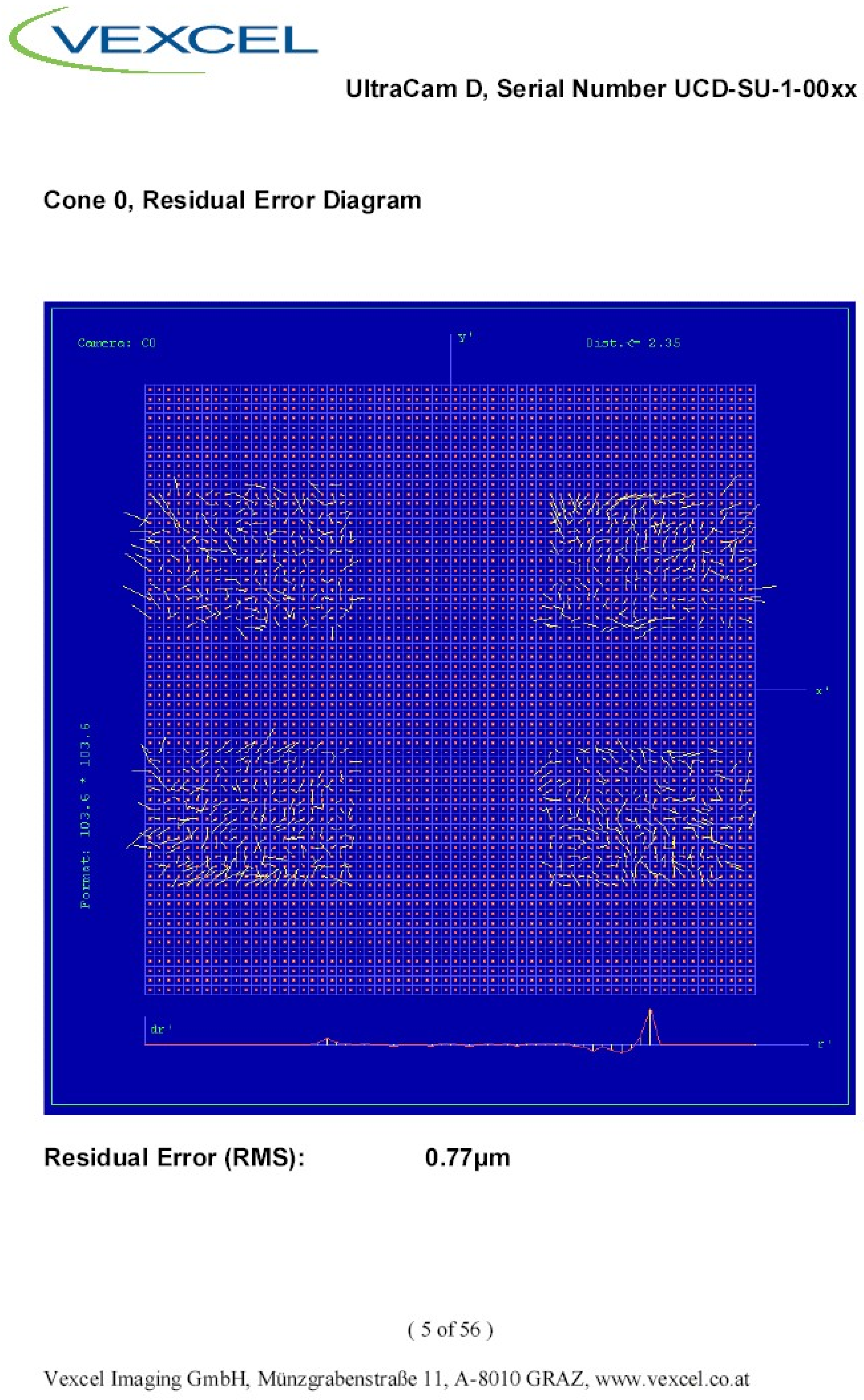
Cone # C0				
Lens	Apo-Digitar 5.6/100mm, Serial Nr. 14799488 Schneider Kreuznach, Germany			
Shutter	Prontor Magnetic Prontor-Werk Alfred Gauthier GmbH			
Image Extent (nominally)		(-33.75, -51.75)mm		(33.75, 51.75)mm
Extent CCD 0		(-33.75, -51.75)mm		(-9.75, -15.75)mm
Extent CCD 1		(-33.75, 15.75)mm		(-9.75, 51.75)mm
Extent CCD 2		(9.75, -51.75)mm		(33.75, -15.75)mm
Extent CCD 3		(9.75, 15.75)mm		(33.75, 51.75)mm
Parameters	Shift X	ShiftY	Rotation	Scale
CCD0	0.25576757mm ± 0.0017mm	0.26879646mm ± 0.0014mm	0.0000921067gon ± 0.0001gon	1.0055922 ± 0.00005
CCD1	0.18301393mm ± 0.0017mm	0.27102469mm ± 0.0014mm	0.00000000gon	1.0073471 ± 0.00005
CCD2	0.17898825mm ± 0.0017mm	0.34528930mm ± 0.0014mm	-0.051021468gon ± 0.0001gon	1.0041243 ± 0.00005
CCD3	0.11912970mm ± 0.0017mm	0.42501979mm ± 0.0014mm	0.094205922gon ± 0.0001gon	1.0053833 ± 0.00005
Radial Distortion				
R [mm]	5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0 55.0 60.0 65.0			
dr [µm]	-9.4 -19.9 -30.4 -40.3 -48.6 -54.7 -58.0 -57.8 -53.7 -45.3 -32.1 -14.0 9.4 38.2 72.5			

(3 of 56)

Vexcel Imaging GmbH, Münzgrabenstraße 11, A-8010 GRAZ, www.vexcel.co.at

Cone 0, Distortion Diagram, Not Effective in Output Image





UltraCam D, Serial Number UCD-SU-1-00xx

Cone 0, Residual Error Diagram

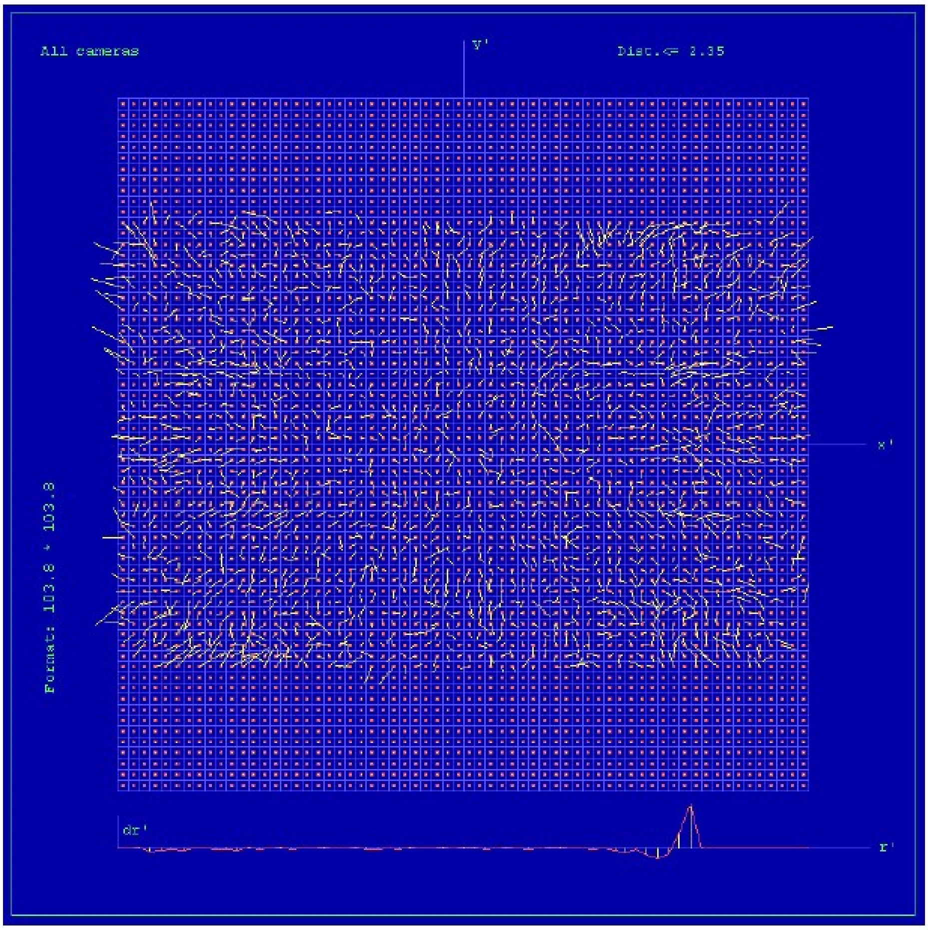
Residual Error (RMS): 0.77µm

(5 of 56)

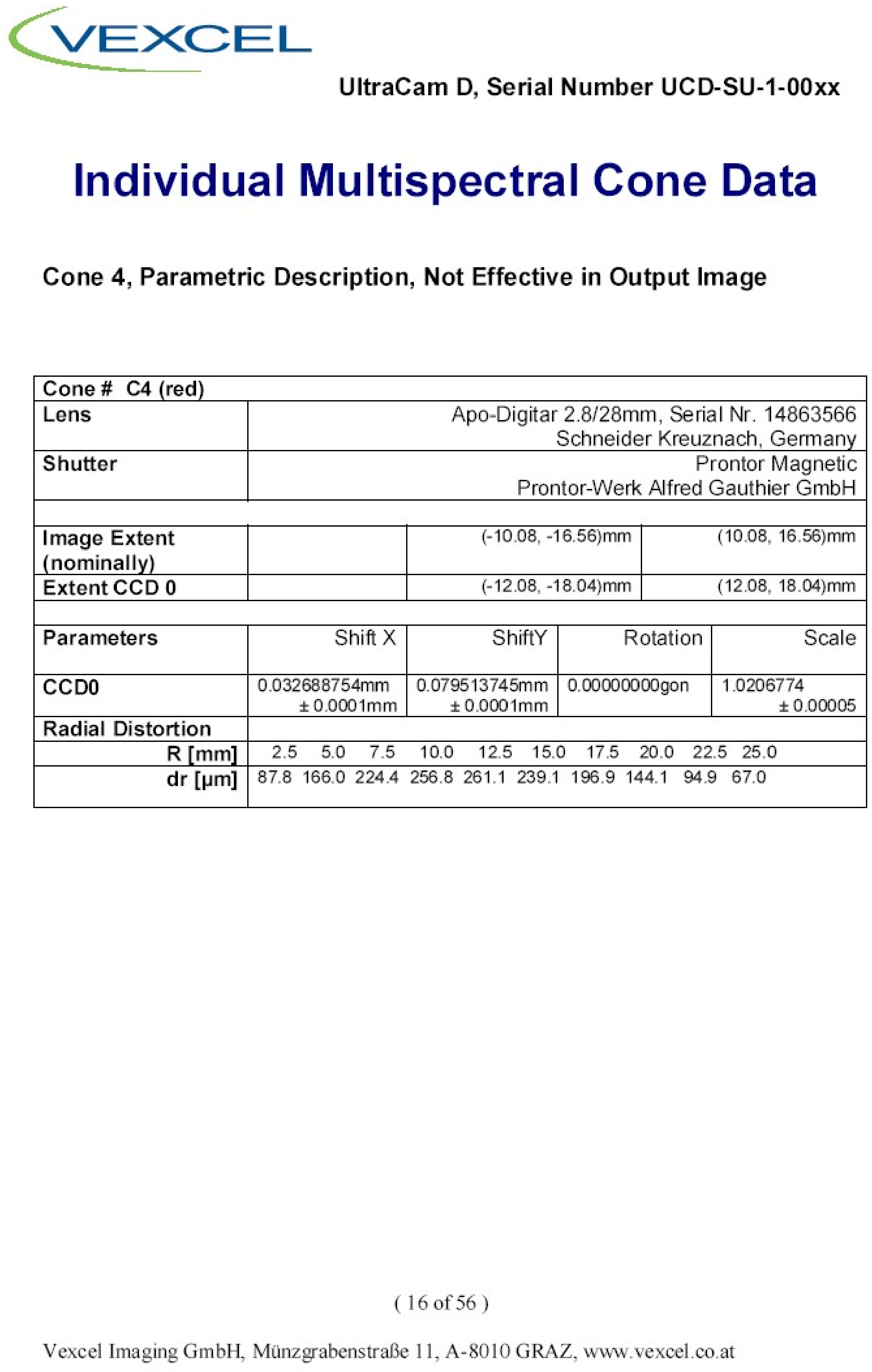
Vexcel Imaging GmbH, Münzgrabenstraße 11, A-8010 GRAZ, www.vexcel.co.at

SKIPPED Calibration of pan-chromatic cones 1 – 3

Full Pan Image, Residual Error Diagram



Residual Error (RMS): **0.66µm**



UltraCam D, Serial Number UCD-SU-1-00xx

Individual Multispectral Cone Data

Cone 4, Parametric Description, Not Effective in Output Image

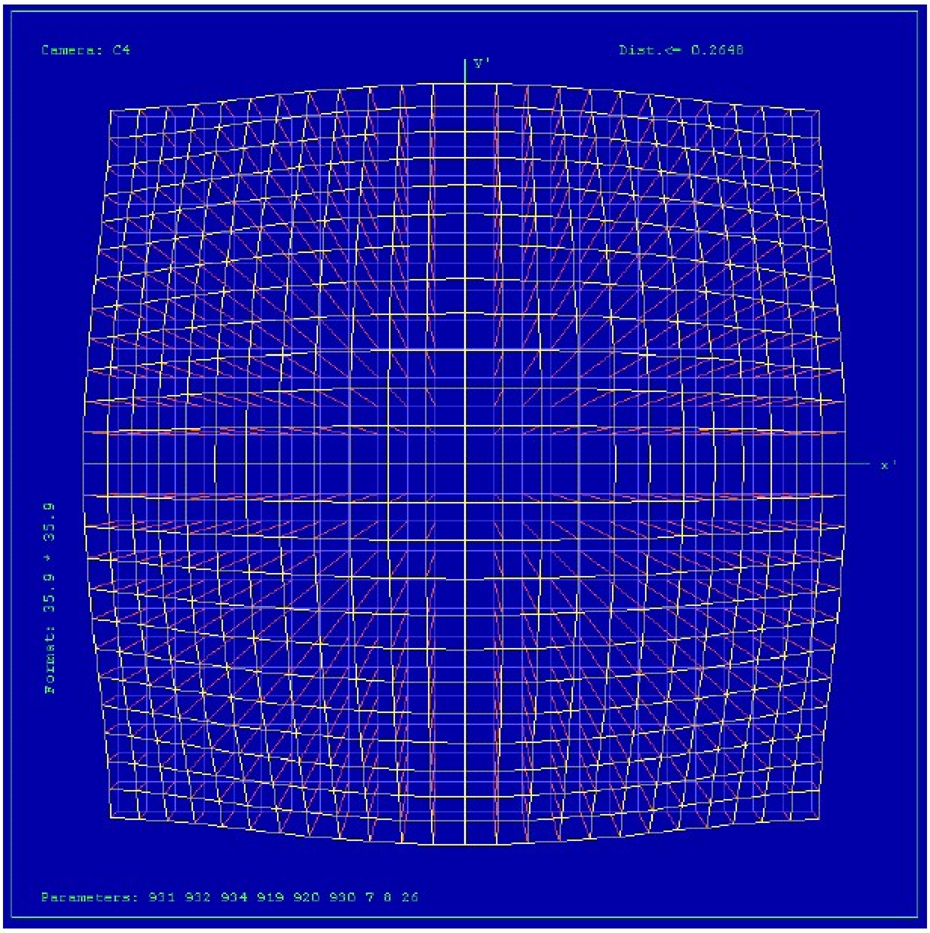
Cone # C4 (red)				
Lens	Apo-Digitar 2.8/28mm, Serial Nr. 14863566 Schneider Kreuznach, Germany			
Shutter	Prontor Magnetic Prontor-Werk Alfred Gauthier GmbH			
Image Extent (nominally)		(-10.08, -16.56)mm		(10.08, 16.56)mm
Extent CCD 0		(-12.08, -18.04)mm		(12.08, 18.04)mm
Parameters	Shift X	ShiftY	Rotation	Scale
CCD0	0.032688754mm ± 0.0001mm	0.079513745mm ± 0.0001mm	0.00000000gon	1.0206774 ± 0.00005

Radial Distortion										
R [mm]	2.5	5.0	7.5	10.0	12.5	15.0	17.5	20.0	22.5	25.0
dr [µm]	87.8	166.0	224.4	256.8	261.1	239.1	196.9	144.1	94.9	67.0

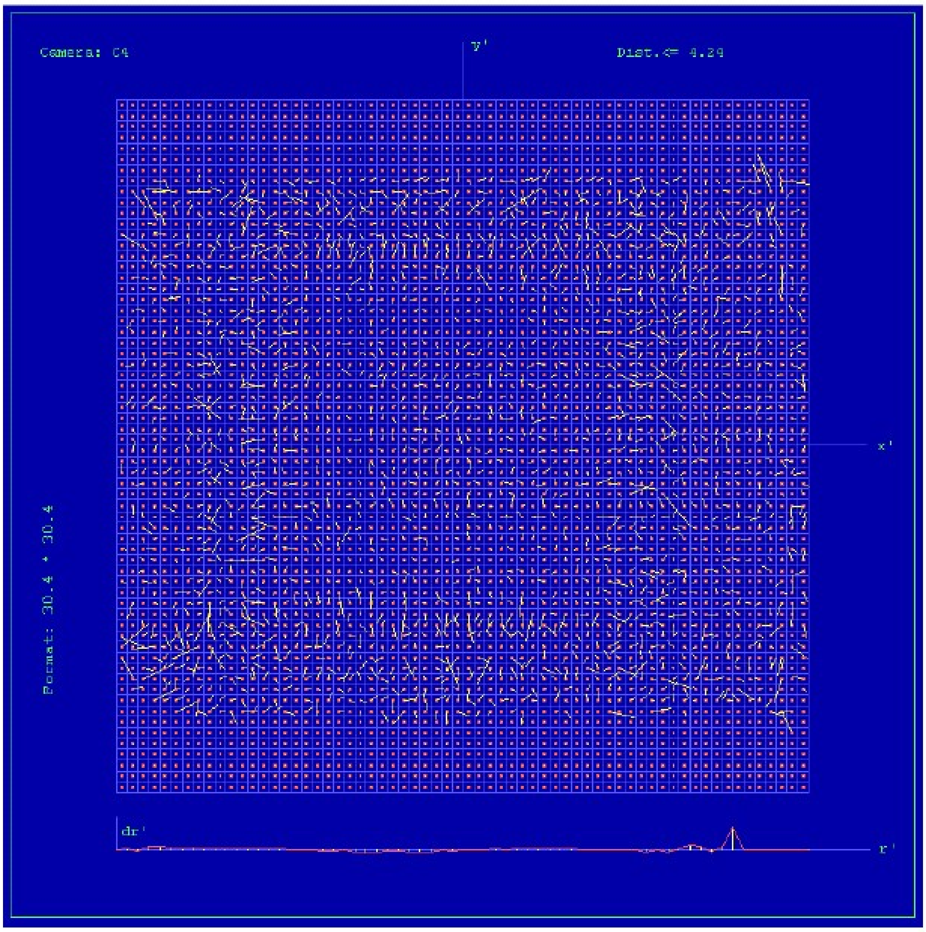
(16 of 56)

Vexcel Imaging GmbH, Münzgrabenstraße 11, A-8010 GRAZ, www.vexcel.co.at

Cone 4, Distortion Diagram, Not Effective in Output Image



Cone 4, Residual Error Diagram



Residual Error (RMS): **1.10µm**

SKIPPED Calibration of colour cones 5 – 7

Explanations:

1) Calibration Method:

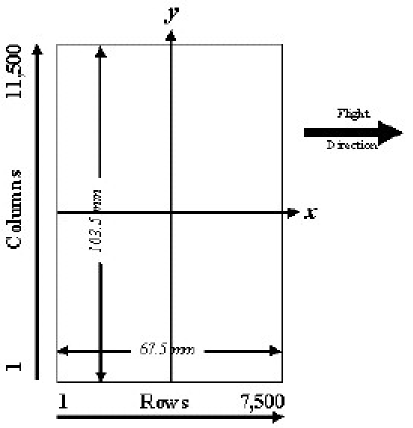
The geometric calibration is based on a set of 84 images of a defined geometry target with 240 GCPs.

Number of point measurements for the panchromatic camera :	13424
Number of point measurements for the multispectral camera :	60056

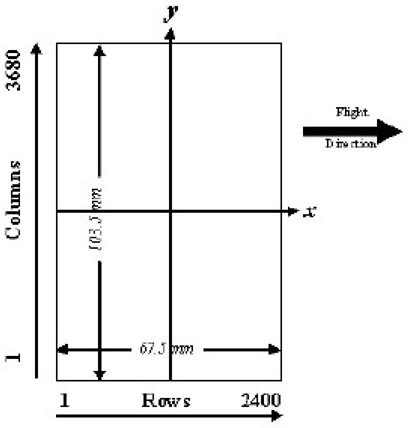
Determination of the image parameters by Least Squares Adjustment.
Software used for the adjustment: BINGO (GIP Eng. Aalen, Germany)

2) Image Coordinate System:

Output image Coordinate System: pan 7500 pixel by 11500 pixel
MS 2400 pixel by 3680 pixel



Panchromatic Image Format



Multispectral Image Format

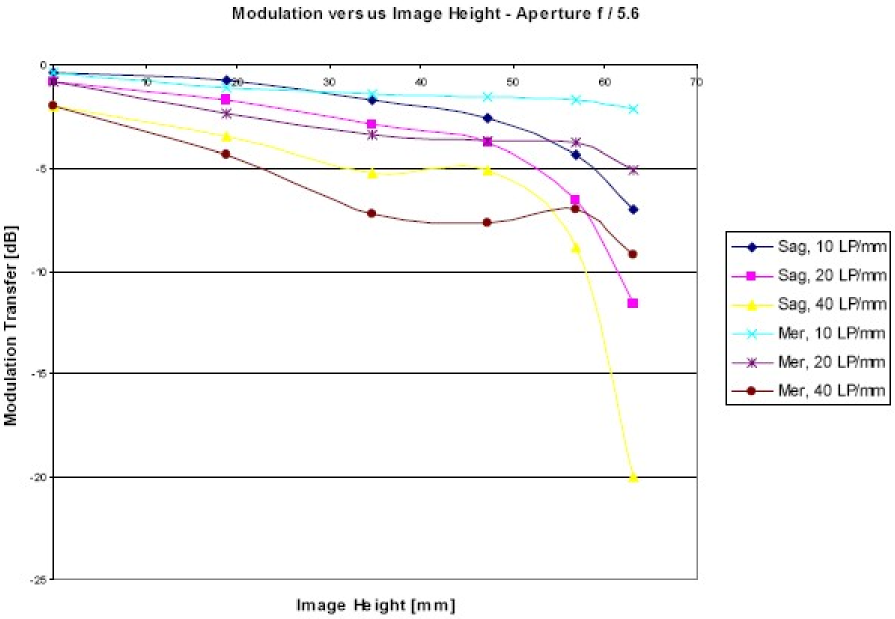
==

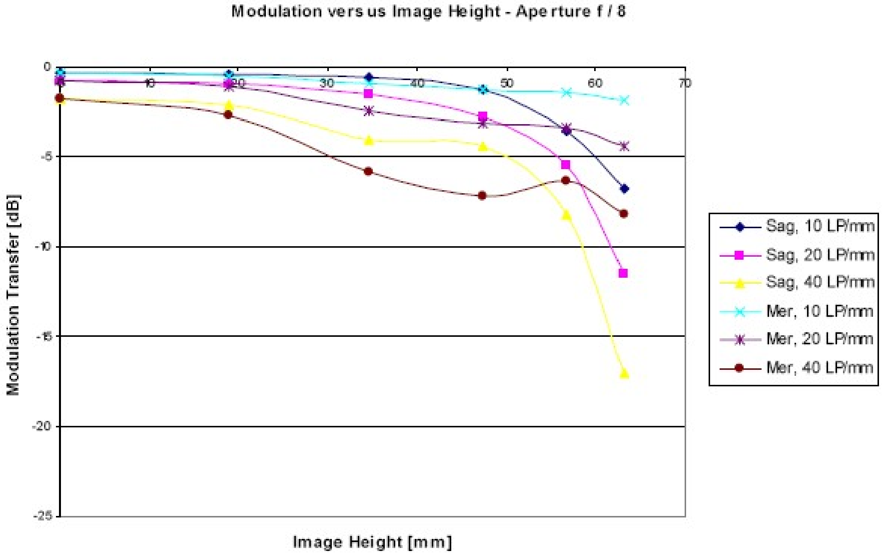
Lens Resolving Power

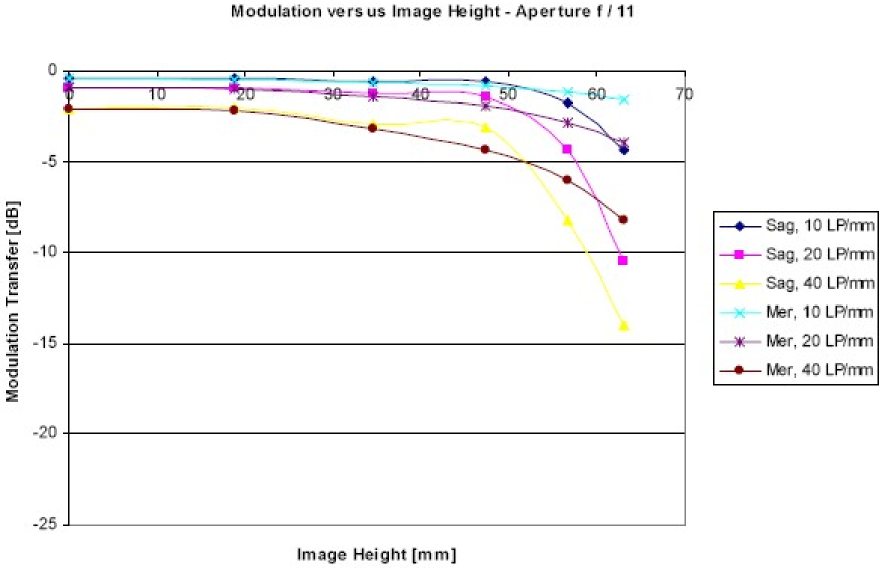
The following curves show the development of the modulation transfer function across different image heights of the panchromatic cones.

The curves are given for the meridonial (tangential) and sagital (radial) component of signals at frequencies of 10, 20 and 40 line pairs per millimeter.

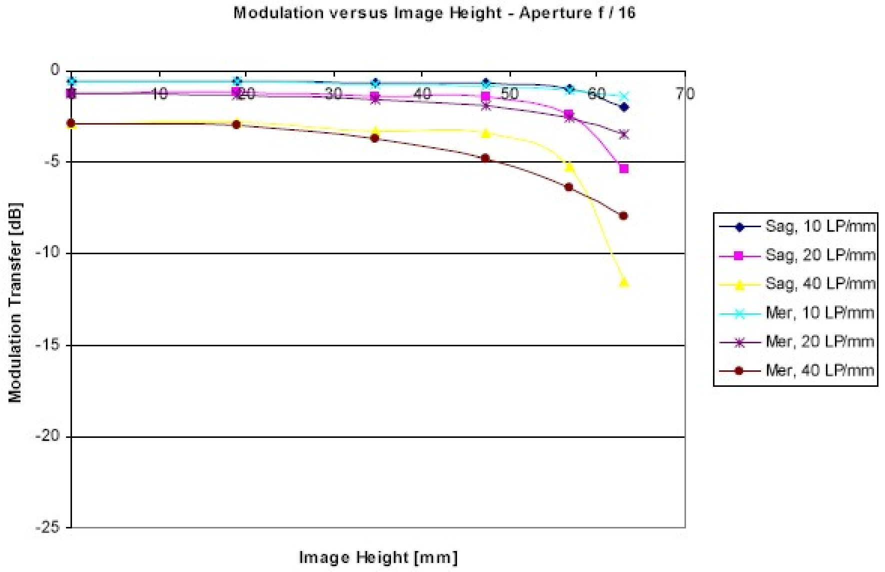
As the MTF is a function of the specific aperture size used, one set of curves is given for each aperture size.

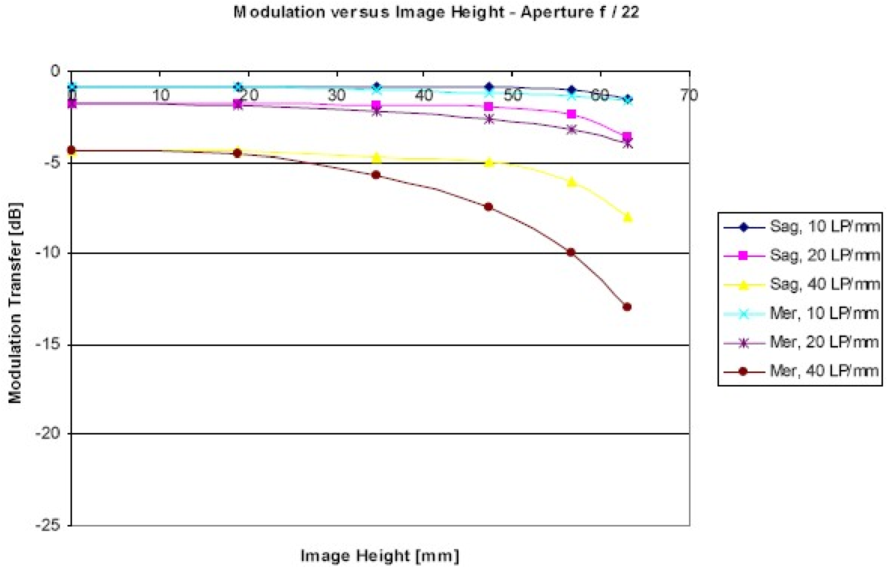



Modulation versus Image Height - Aperture f / 8
Modulation Transfer [dB]
0
-5
-10
-15
-20
-25
10
20
30
40
50
60
70
Image Height [mm]
Sag, 10 LP/mm
Sag, 20 LP/mm
Sag, 40 LP/mm
Mer, 10 LP/mm
Mer, 20 LP/mm
Mer, 40 LP/mm

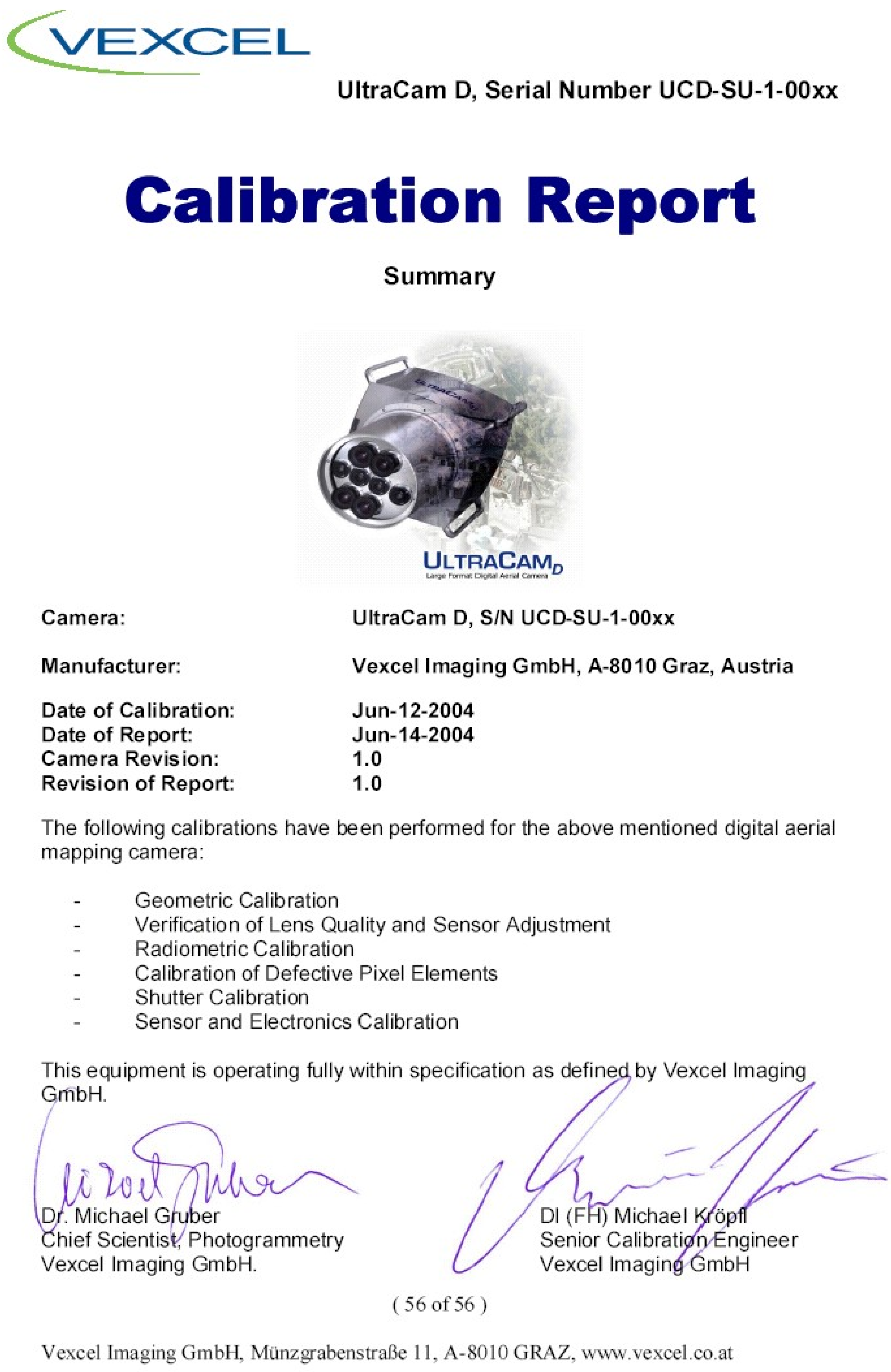

Modulation versus Image Height - Aperture f / 11
Modulation Transfer [dB]
0
-5
-10
-15
-20
-25
0
10
20
30
40
50
60
70
Image Height [mm]
Sag, 10 LP/mm
Sag, 20 LP/mm
Sag, 40 LP/mm
Mer, 10 LP/mm
Mer, 20 LP/mm
Mer, 40 LP/mm

UltraCam D, Serial Number UCD-SU-1-00xx





SKIPPED calibration report on radiometric calibration (pp. 32-50)
SKIPPED calibration report on shutter calibration (pp. 51-52)
SKIPPED calibration report on electronics and sensor calibration (pp. 53-55)



UltraCam D, Serial Number UCD-SU-1-00xx

Calibration Report

Summary

Camera:	**UltraCam D, S/N UCD-SU-1-00xx**
Manufacturer:	**Vexcel Imaging GmbH, A-8010 Graz, Austria**
Date of Calibration:	**Jun-12-2004**
Date of Report:	**Jun-14-2004**
Camera Revision:	**1.0**
Revision of Report:	**1.0**

The following calibrations have been performed for the above mentioned digital aerial mapping camera:

- Geometric Calibration
- Verification of Lens Quality and Sensor Adjustment
- Radiometric Calibration
- Calibration of Defective Pixel Elements
- Shutter Calibration
- Sensor and Electronics Calibration

This equipment is operating fully within specification as defined by Vexcel Imaging GmbH.

Dr. Michael Gruber Chief Scientist, Photogrammetry Vexcel Imaging GmbH.	DI (FH) Michael Kröpfl Senior Calibration Engineer Vexcel Imaging GmbH

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