Rainer Sandau (Ed.)
Digital Airborne Camera – Introduction and Technology

Digital airborne cameras are now penetrating the fields of photogrammetry and remote sensing. Due to the last decade's results in research and development in the fields of for instance detector technology, computing power, memory capacity position and orientation measurement it is now possible with this new generation of airborne cameras to generate different sets of geometric and spectral data with high geometric and radiometric resolutions within a single flight. This is a decisive advantage as compared to film based airborne cameras. The linear characteristic of the opto-electronic converters is the basis for the transition from an imaging camera to an images generating measuring instrument. Because of the direct digital processing chain from the airborne camera to the data products there is no need for the processes of chemical film development and digitising the film information. Failure sources as well as investments and staff costs are avoided. But the effective use of this new technology requires the knowledge of the features of the image and information generation, its possibilities and its restrictions.

This book describes all components of a digital airborne camera from the object to be imaged to the mass memory device. So the image quality influencing processes in nature are described, as for instance the reflection of the electromagnetic sun spectrum at the objects to be imaged and the influence of the atmosphere. Also, the essential features of the new digital sensor system, their characteristics and parameters, are addressed and put into the system context. The complexity of the cooperation of all camera components, as for instance optics, filters, detector elements, analogue and digital electronics, software and so forth, becomes transparent. The book includes also the description of example systems.

Audience This book will be of interest to managers, operators, data users dealing with new digital airborne cameras. Students in the fields of photogrammetry and remote sensing will also find valuable information in this book.

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Preface

Digital airborne cameras are now penetrating the market of photogrammetry and remote sensing. Owing to rapid progress in the last 10 years in fields such as detector technology, computer power, memory capacity, and measurement of position and orientation, it is now possible to acquire, with the new generation of digital airborne cameras, different sets of geometric and spectral data with high resolution within a single flight. This is a decisive advantage over aerial film cameras. The linear characteristic of the optoelectronic converters is at the root of this transformation from an imaging camera to a measuring instrument that captures images. The direct digital processing chain from the airborne camera to the derived products involves no chemical film development or digitisation in a photogrammetric film scanner. Causes of failure, expensive investments and prohibitive staff costs are avoided. The effective use of this new technology, however, requires knowledge of the characteristics, possibilities and restrictions of the formation of images and the generation of information from them.

This book describes all the components of a digital airborne camera, from the object to be imaged to the mass memory device on which the imagery is written in the air. Thus natural processes influencing image quality are considered, such as the reflection of the electromagnetic energy from the sun by the object being imaged and the influence of the atmosphere. The essential features and related parameters of the new technology are discussed and placed in a system framework. The complex interdependencies between the components, for example, optics, filters, detectors, analogue and digital electronics, and software, become apparent. The book describes several systems available on the market at the time of writing.

The book will appeal to all who want to be informed about the technology of the new generation of digital airborne cameras. Groups of potential readers include: managers who have to decide about investment in and use of the new cameras; camera operators whose knowledge of the features of the cameras is essential to the quality of the data acquired; users of derived products who want to order or effectively process the new digital data sets; and scientists and university students, in photogrammetry, remote sensing, geodesy, cartography, geospatial and environmental sciences, forestry, agriculture, urban planning, land use monitoring and other fields, who need to prepare for the use of the new cameras and their imagery.

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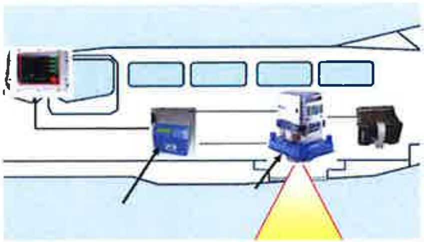

Fig. 7.2-7 DMC system installed in an aircraft

includes two 300 GB SCSI disk drives. A set of 3 FDS can store up to 4,400 images, where one FDS is connected to 2 panchromatic camera heads (each 7 k × 4 k) or to 4 multispectral camera heads (each 3 k × 2 k). The data interface is a high speed 1 Gb copper-based fibre-channel interface. The FDS is certified to be operated at up to 8,000 m altitude in an unpressurized environment. Special environmental tests following the RTCA/DO 160 aircraft standard guarantee high reliability and high data safety for the user.

In the aircraft, each FDS is installed in a special designed carrier ("FDS shoe") and can be easily removed without unplugging any cables or connectors. The "shoe" can be mounted to the aircraft seat rails for crash load safety.

For image data post-processing the FDS is either connected directly to the post-processing software servervia fibre-channel connection or hooked up to a field copy station for mobile data copy to removable hard disk drives or USB disk drives.

7.2.7 System Calibration and Photogrammetric Accuracy

The DMC is certified by USGS (United States Geological Service) to meet the US national mapping standards and accuracy. The basis for this high quality level is a robust mechanical and optical design and an intensive quality test program. Extensive environmental testing is part of the manufacturing process. Each camera system undergoes a laboratory calibration, where focal length, lens distortion and other characteristics are precisely measured. After this laboratory calibration, each camera system is subject to a burn-in flight to perform the platform calibration. Finally all calibration data are stored on a calibration CD and delivered with the system to the customer. The user can repeat at any time a verification flight to check platform calibration. The DMC is fully field serviceable and each component can be exchanged on-site.

The mapping accuracy of the DMC is:

for X,Y 5 μm*photo scale, e.g.2.5cm@6 cm GSD

for Z0.05% of flying height above terrain, e.g. 3 cm @ 6 cm GSD

This high accuracy leads to the possibility of flying at higher altitudes compared to film cameras while meeting the same mapping requirements.

7.3 UltraCam, Digital Large Format Aerial Frame Camera System

7.3.1 Introduction

UltraCam is a large format digital aerial frame camera. The design is unique and based on a multi cone concept. The camera is produced by Vexcel Imaging GmbH, a wholly-owned subsidiary of Microsoft Corporation.[1] The first UltraCam was presented in May 2003 at the 2003 ASPRS Annual Conference in Anchorage, Alaska, in its initial implementation as the 85-megapixel UltraCam$_D$ system (Leberl et al., 2003). Three years later, at the 2006 ASPRS Annual Conference in Reno, Nevada, the 136-megapixel format UltraCamX was introduced.

Fig. 7.3-1 Large scale aerial image at 3 cm GSD. This 700 pixel by 500 pixel sub-area of an UltraCam image covers only 21 m by 15 m on the ground

The new UltraCamX was developed with the experience and success of the UltraCam$_D$ during the three previous years, undergirded by a rapid evolution of the digital sensor market and a transition to the fully digital photogrammetric workflow. A review of the period since the ISPRS Congress in 2000 in Amsterdam, when the first digital large format aerial cameras were presented, shows a rather slow initial acceptance of the new technology. It was not until 2004 that a significant number of digital large format aerial cameras was sold by the then three competing vendors, so

[1] Microsoft Corporation operates though Vexcel Imaging GmbH. The Austrian team is denoted as "Microsoft Photogrammetry". In this text, we will use both "Vexcel" and "Microsoft".

that worldwide count of systems in operation reached a significant number. Since 2004 digital cameras began to have a major impact on the global perspective of the photogrammetric all-digital workflow and value systems.

7.3.2 UltraCamX Produces the Largest Format Digital Frame Images

7.3.2.1 Overview of the UltraCamX

The UltraCamX camera system is the most recent implementation of the basic UltraCam imaging principle. It takes advantage of the most valuable developments of the industry in the technologies of sensors, data storage and data transfer as well as Vexcel's in-house experience and know-how. As will be reviewed later, some essential elements of the camera technology were special custom developments for the UltraCam.

The significant advantages of the UltraCamX include:

- large image format of 14,430 pixels cross-track and 9,420 pixels along-track
- image repeat rate based on a data rate of 3 gigabits per second
- excellent optical system with 100 mm focal length for the panchromatic camera heads and 33 mm for the multispectral camera heads, for an exact 1:3 pan-sharpening ratio
- image storage capacity of 4,700 frames for one single data storage unit
- almost unlimited image harvest due to exchangeable data storage units
- instant data download from the airplane by means of removable data storage units
- fast data transfer to the post-processing system using the new docking station.

The camera consists of the Sensor Unit, the onboard storage and data capture system, the operator's interface panel and two removable data storage units. This airborne configuration is shown in Fig. 7.3-2. It is complemented by an elaborate software system for mission planning and in-flight camera operation, the Camera Operating Software COS.

Of course, there is also an integral systems component in the office, be it a field office or the main home office. This addresses the processing of the acquired imagery into deliverable imagery, in the form of the Office Processing Center OPC.

7.3.2.2 The UltraCamX Sensor Unit

The UltraCamX Sensor Unit consists of eight independent camera cones, as shown in Fig. 7.3-3. Four of these contribute to the large format panchromatic image; the other four, to the multispectral image. The sensor head of the UltraCamX is equipped with 13 FTF5033 high performance CCD sensor units, each producing 16 megapixels of image information at a radiometric bandwidth of more than

Fig. 7.3-2 The UltraCamX digital aerial camera system with the Sensor Unit (*right*) and the airborne Computing Unit including two removable Data Units (*left*). The camera is operated in the air through the Interface Panel (*middle*)

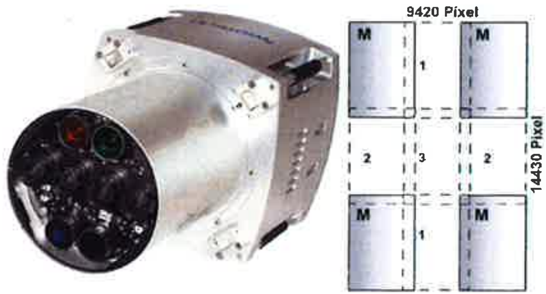

Fig. 7.3-3 The UltraCamX sensor head (*left*) consists of eight camera heads, four of them contributing to the large format panchromatic image. These four heads are equipped with nine CCD sensors in their four focal planes. The focal plane of the so called Master Cone (M) carries four CCDs (*right*)

12 bits. The CCD elements have a pixel size of 7.2 μm square. A single image trigger results in a readout of 13 * 16 * 2 = 416 MB, since each pixel is recorded on to 16 bits. The A/D converter uses a 14-bit approach.

Each camera cone is equipped with a high performance optical system designed by LINOS/Rodenstock specifically for the UltraCam. The focal length of the panchromatic camera is 100 mm, that of the multispectral camera is 33 mm. As mentioned previously, this set of two lens types supports a pan-sharpening ratio of 1:3.

The image format of 14,430 pixels cross-track by 9,420 pixels in the flight direction results in a high rate of productivity in the air. At a 25% side overlap between strips, the UltraCamX covers a strip width at more than one mile or 1,650 m at a pixel size on the ground of 6″. Table 7.3-1 summarizes the salient items of the UltraCamX specifications.

Table 7.3-1 Technical Data and Specifications of the UltraCamX Sensor Unit

Technical data for UltraCamX Sensor Unit	
Panchromatic channel	
Multi-cone multi-sensor concept	4 camera heads
Image size in pixel (cross-track * along-track)	14430 * 9420 pixel
Physical pixel size	7.2 μm
Physical image format (cross-track * along-track)	103.9 * 67.8 mm
Focal length	100 mm
Lens aperture	$f = 1/5.6$
Angle of view (cross-track/along-track)	55°/37°
Multispectral channel	
Four channels (red, green, blue, near infrared)	4 camera heads
Image size in pixel (cross-track * along-track)	4992 * 3328 pixel
Physical pixel size	7.2 μm
Physical image format (cross-track * along-track)	34.7 * 23.9 mm
Focal length	33 mm
Lens aperture	$f = 1/4$
General	
Shutter speed options	1/500–1/32 s
Forward motion compensation	TDI controlled, 50 pixels
Frame rate per second	1 frame in 1.35 s
A/DC bandwidth	14-bit (16,384 levels)
Radiometric resolution	>12 bits/channel

7.3.2.3 The UltraCam X Storage System

The data storage system of the UltraCamX improves the end-to-end workflow of the airborne mission over the previous UltraCam$_D$ arrangement and achieves an improvement in the working conditions of the crew. The system contains two independent Data Units for redundant image capture. The Data Units can capture up to 4,700 images, each consisting of 206 raw input megapixels, which are converted into deliverable images with 136 megapixels each and – most valuable for large-scale missions – can be exchanged for additional Data Units within a few minutes. Thus one can collect a virtually unlimited number of images during a single flight mission, simply by swapping data units in flight. Compared to the UltraCam$_D$, the UltraCamX Data Unit has a capacity that is four times larger, since the number of images per Data Unit has increased from 2,700 to 4,700, and the size of each image, from 86 megapixels to 136 megapixels.

The downloading of the acquired images is accomplished by simply disconnecting the Data Units from the camera system on completion of a flight mission and shipping the raw data to the field office or the home office where the post-processing takes place. A quality control step can be performed in the field, however, either airborne while still returning to the airport, or on the ground upon arrival at the airport, using a laptop computer.

The downloading of the image data is supported by a Docking Station (Fig. 7.3-4), which supports the complete data transfer of 4,000 images within 8 h through four parallel data transfer channels. This results in a 24-h cycle of flying, data download, copying and QC.

Fig. 7.3-4 UltraCamX on board Computing Unit (*left*) and Data Unit attached to the Docking Station (*right*). The download of image data to the post-processing station is supported by four parallel data streams

7.3.2.4 The UltraCam Software Components

The Camera Operating System COS and the Office Processing Center OPC are the two software components required to operate the camera and process the raw image data into a deliverable image product on completion of a flight mission. Figure 7.3-5 presents a typical view of the Graphical User Interface for the OPC software.

7.3.3 UltraCam Design Concept

The UltraCam large format frame camera is based on a unique design of the sensor head. It is composed of eight individual "cones" and 13 CCD sensor arrays. A cone in turn is built with an optical lens and one or more CCD arrays with the associated electronic components. Each CCD feeds into a separate data stream, resulting in

Fig. 7.3-5 COS GUI (*left*) enabling the on board quality control of each picture and OPC GUI (*right*) addressing an entire flight mission with many images

Fig. 7.3-6 Full set of 13 UltraCam CCD-sensor and electronics components. Nine units are used for the large-format panchromatic image; four units are responsible for the multispectral bands

13 parallel data tracks (Fig. 7.3-6). This type of parallel architecture supports fast image capture and data readout.

7.3.3.1 The Large-Format Panchromatic Sensor

Four camera heads and 9 CCD sensor arrays contribute to the large-format panchromatic image. Figure 7.3-7 illustrates the assembly of a large-format image from four separate exposures, each consisting of one or multiple CCD tiles. There are several advantages of this design:

- The Master Cone defines the image format and operates with one shutter exposure for the four CCDs.
- FMC is correctly implemented (the optical axes are parallel)
- Syntopic exposure enables large-scale urban missions.

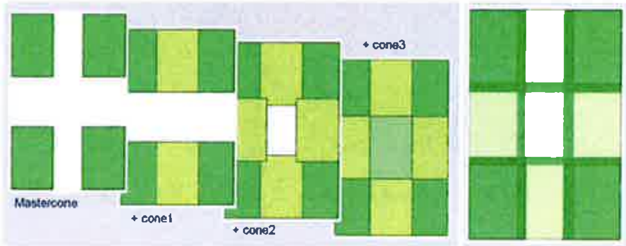

Fig. 7.3-7 UltraCamX panchromatic camera heads. The Master Cone and three slave cones contribute nine CCD arrays to the full frame (*left*). Overlap areas between CCD tiles are used to control the stitching process to sub-pixel accuracy (0.1 pixel) (*right*)

The nine tiles must be "stitched" into a single, seamless image. Stitching is a core function of the OPC software and employs the overlaps between the individual tiles. The result of the stitching process is reported and documents the geometric quality of each frame. An accuracy level of 0.1 pixel can be achieved.

The four cones of the panchromatic part of UltraCam are aligned in parallel with the flight path. This enables a special exposure concept – the so-called "Syntopic Exposure". Each shutter is triggered after a short delay in such way that all four cones take the exposure at one and the same position as the aircraft moves forward.

7.3.3.2 The Four Band Multispectral Sensor

The UltraCamX is equipped with four individual sensor heads for visible light (red, green and blue) and near infrared light. Figure 7.3-8 presents the spectral sensitivities of the four channels. Whereas the panchromatic image is composed of 3 × 3 CCD tiles, the colour image bands consist of single CCD tiles. The final colour image is compiled from a combination of the panchromatic and the four colour channels. This process is denoted as "pan-sharpening" and has already been widely used in remote sensing applications.

Figure 7.3-9 summarizes the concept of the output of five separate channels, namely the panchromatic and four colour bands and a resulting pair of (a) colour and (b) false-colour infrared images.

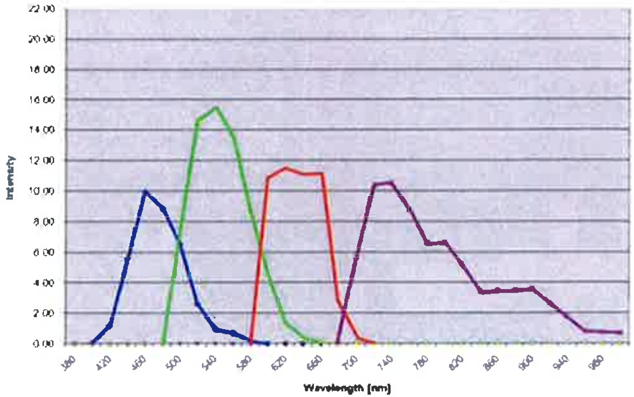

Fig. 7.3-8 UltraCamX multispectral cones. Volume filters are used to separate the four bands

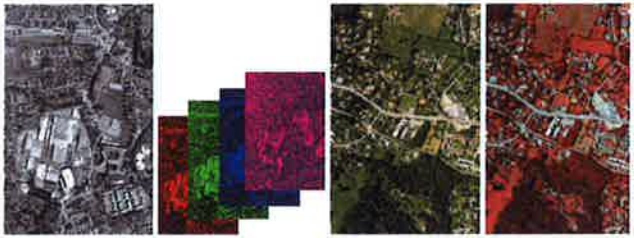

Fig. 7.3-9 Sample image data set with a panchromatic band and four colour bands, as well as the resulting pair of colour and false-colour infrared images

7.3.4 Geometric Calibration

7.3.4.1 The UltraCam Calibration Laboratory and Image Measurements

Vexcel's Calibration Laboratory has been in operation since July 2006 and represents a second-generation solution. It consists of a three-dimensional calibration target with 394 circular marks. These marks are surveyed to an accuracy of about ±0.1 mm in X and Y and ±0.2 mm in Z and have a well defined circular pattern. The entire structure is 8.4 m by 2.5 m at the rear wall and 2.4 m in depth. Rear wall, ceiling and floor carry 70 metal bars with 280 marks; four additional vertical bars in

the center of the structure carry 16 marks; 98 marks are mounted on the rear wall. The mean distance between marks is about 30 cm (Fig. 7.3-10).

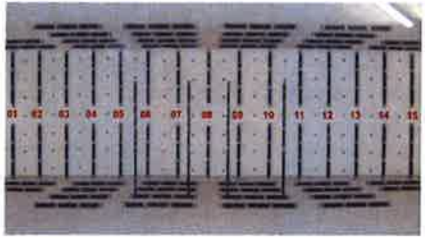

Fig. 7.3-10 The UltraCam calibration laboratory is equipped with a three dimensional target containing 394 marks. The entire volume is 8.4 m by 2.4 m by 2.5 m

During the data capture 84 images are taken from three different camera stations in such a way that the camera is tilted and rotated. In this set of 84 images almost 18,500 image positions of the surveyed marks can be recognized from the four panchromatic camera heads and about 17,500 image positions from each of the four color camera heads, as well.

Software is used to compute image positions of each mark in each image of the entire set of images, with sub-pixel accuracy. This results in a dense and complete coverage of coordinate measurements over the entire image format. Figure 7.3-11 shows the distribution of measured points in an image. One single calibration dataset consists of almost 90,000 measured image points.

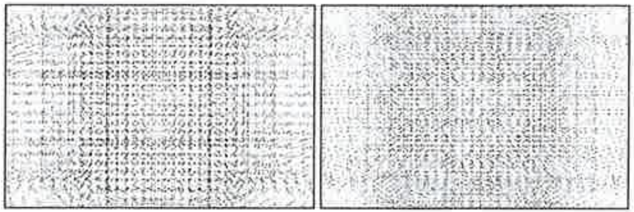

Fig. 7.3-11 The automatically detected image positions cover the entire frame of the camera. About 18,500 points are detected in the panchromatic channel (*left*) and 17,500 points are detected in each of the four colour bands (*right*). A single image trigger will therefore produce a total of about 90,000 points

7.3.4.2 Computing the Camera Parameters

The computation of the unknown camera parameters is based on the least squares bundle adjustment method of BINGO (Kruck, 1984). The specific design of the UltraCamX sensor head required some modifications to the software. It was most important to introduce the ability to estimate the positions of multiple CCD sensor arrays in one and the same focal plane of a camera head.

The unknown parameters which are estimated within the bundle adjustment procedure can be separated into three groups:

- The traditional camera parameters to define the bundle of rays (principal distance and coordinates of the principal point)
- The specific UltraCam parameters for each CCD position in the focal plane of each camera cone (shift, rotation, scale and perspective skew of each CCD)
- Traditional radial and tangential lens distortion parameters (for each lens cone).

When the correlation between these parameters is investigated, it is obvious that CCD scale parameters are correlated with the principal distance of each cone and CCD shift parameters are correlated with the principal point coordinates of each focal plane (Gruber and Ladstädter, 2006). It was therefore necessary to reduce the entire set of parameters in order to avoid such correlation. This was done in such a way that principal distance and principal coordinates of all eight cones of the UltraCamX were introduced as constant values. It is further noteworthy that there exists an additional correlation between the CCD rotation parameter and the angle kappa of the exterior orientation. This correlation could be resolved by removing one and only one CCD rotation parameter of the parameter set of each camera head (Kröpfl et al., 2004).

The resulting quality of the geometric laboratory calibration is documented by the $\sigma 0$ value of the bundle adjustment. This value was observed at a level of ± 0.4 to $\pm$ 0.5 µm for all calibrations of the panchromatic camera cones carried out in the new Calibration Laboratory (Fig. 7.3-12). This is a slight but significant improvement compared to the results achieved from the initial Calibration Laboratory, which was in use until mid 2006.

7.3.4.3 Post-Processing for Stitching and Additional Improvements

The results from the laboratory calibration are stored in a data set, which is used during the post-processing of each frame exposed by the camera. During this post-processing we apply parameters to describe dimensional changes of the camera body which may be caused by the change of environmental parameters during a flight mission (e.g. any thermal effect). Such thermal changes cause symmetric expansion or shrinking of the backplanes of the UltraCam cones. The CCDs mounted on the backplanes will therefore "drift away" from their calibrated positions when the temperature during flight deviates from the temperature at calibration

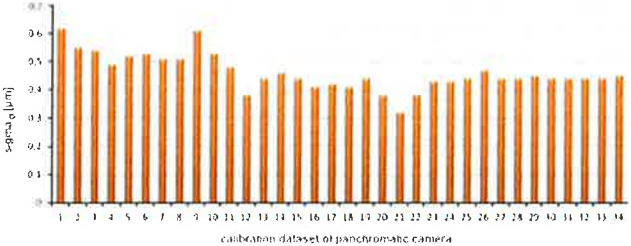

Fig. 7.3-12 A subset of 34 cameras was investigated and is illustrated. Results of the bundle adjustment after the estimation of camera parameters (panchromatic camera) are documented by the σ_0 values of the adjustment. They are in the range of ± 0.4 to ± 0.5 µm. Slightly larger values (± 0.5 to ± 0.6 µm) were observed from the initial Calibration Laboratory, which was in use until mid-2006

time. If this effect is neglected in the "stitching" process, systematic deformations will be visible in the images.

These self-calibration parameters are computed from the stitching scales 1 and 2 and the well known distances between the stitching zones. Sensor drifts can now be modelled and compensated. Finally, a second stitching procedure is performed using the modified calibration parameters. The stitching scales are expected to be close to 1.0 after the self-calibration has been applied. This self-calibration method has been introduced successfully into the post-processing software of the UltraCam digital camera system (Ladstädter, 2007).

7.3.5 *Geometric Accuracy at the 1 µm Level*

7.3.5.1 Aerial Triangulation by σ_0

The first step is the geometric laboratory calibration of each UltraCam. Then each camera's performance is verified by a flight mission over a well known test area. A flight pattern with high overlap (80% end-lap, 60% side-lap) and cross-strips is used, to offer a highly redundant data set suitable for investigating the interior geometry of the camera. Figure 7.3-13 presents a project overview.

The automatic tie point matching is done using Inpho's aerial triangulation software package MATCH-AT. The adjustment of the aerial triangulation is computed by BINGO, with cross-check and additional self-calibration options.

GPS/IMU systems were used to provide Earth observation parameters and did show excellent results (Kremer and Gruber, 2004).

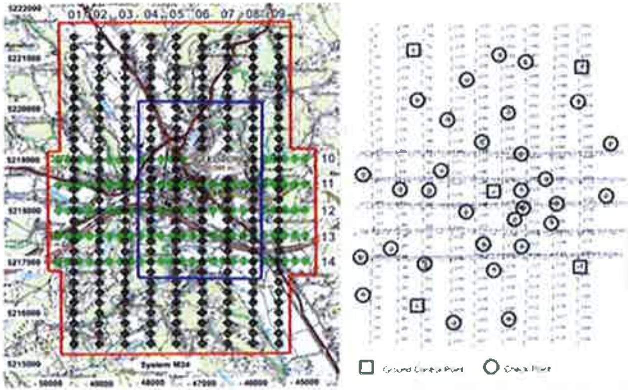

Fig. 7.3-13 Test area near Graz, Austria. Flight plan with 14 flight lines (404 images) and the AAT result after the UltraCamX photo mission (processing by MATCH-AT and BINGO software)

The σ_0 value reflects the quality level of image coordinate measurements of an aerial triangulation project. Such values are computed for each camera. Figure 7.3-14 provides the σ_0 values for 26 UltraCamX image datasets. These values are close to, or oftentimes smaller than ± 1 µm (Fig. 7.3-14), based on a large degree of redundancy from the high overlaps and added cross strips.

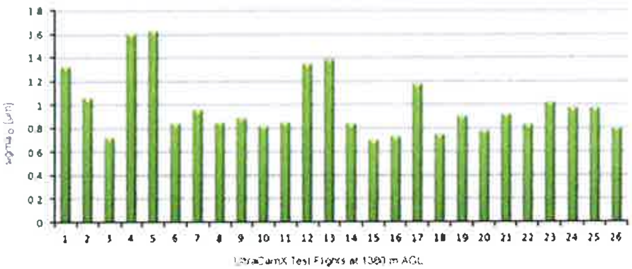

Fig. 7.3-14 Results of the automatic aerial triangulation from several UltraCamX testflights at 10 cm GSD (1,380 m AGL), with σ_0 values are in the range ± 0.7 to ± 1.6 µm. The average value of σ_0 is better than ± 1 µm

7.3.5.2 Aerial Triangulation by Check Points

Another widely accepted method to verify and assess the geometric performance of mapping cameras is the use of check points. We use the results from six individual flight missions and six individual cameras to analyze the geometric performance of these cameras. With an average of 199 check point measurements, deviations of ±38, ±46 and ±56 mm in X, Y and Z respectively were observed at the GSD of 10 cm. The vertical accuracy of this dataset corresponds to 0.04‰ of the flying height (cf. Fig. 7.3-15).

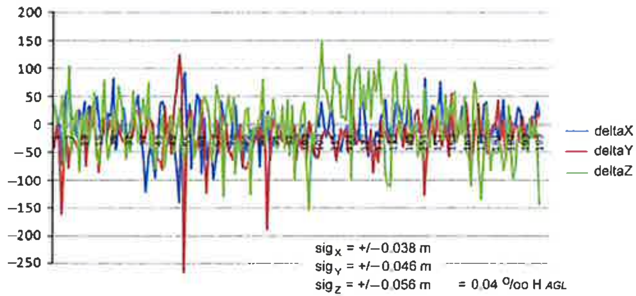

Fig. 7.3-15 Residuals of check points after the bundle adjustment. Results from six individual cameras and flight missions at 10 cm GSD were merged and 199 measurements from 35 checkpoints were analyzed

7.3.5.3 Geometric Improvement by Auto-Calibration

The end-to-end digital workflow of the UltraCam processing chain offers several auto-calibration options. One specific function is already implemented in the post-processing software to reduce the effects of thermal changes during a flight mission (cf. Fig. 7.3-16). In addition, we have observed positive effects when traditional radial symmetric distortion parameters are introduced into the bundle solution. Such parameters are well known in the community, almost every bundle solution offers them and almost any digital workstation is able to accept such parameters. The magnitude of these parameters is small (<0.5 pixel), but their effects are systematic and can therefore not be ignored. In addition to the widely known radial symmetric distortion parameters we have investigated the positive effect of camera-specific parameters. Figure 7.3-17 illustrates how the additional parameters are being used. These parameters are introduced in order to compensate for any asymmetric changes of the geometry of the camera. Again, the magnitude of these parameters is expected to be rather small but will play a role when high accuracy is needed. The remaining

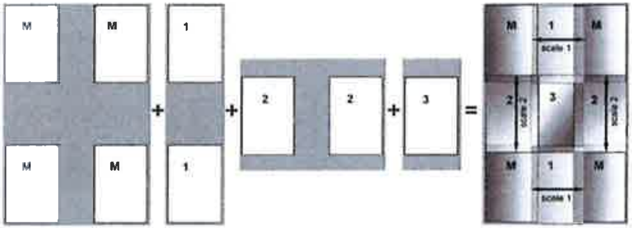

Fig. 7.3-16 Scheme of the UltraCam stitching concept, which is implemented in the image post-processing in order to transform the image information from the four camera heads into one single frame. The two scales shown on the *right* are computed during this step and compensate for any dimensional changes of the camera body

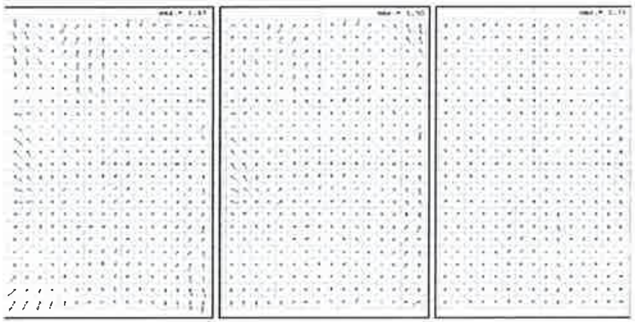

Fig. 7.3-17 Image residuals after the aerial triangulation without additional self-calibration parameters, showing a maximum of 1.67 μm (*left*). Applying radial symmetric distortion parameters (*middle*) and camera-specific parameters (*right*) reduces the remaining image distortions to the sub-micrometre level

residuals in the images have a maximum at ±1.67 μm when no additional self-calibration parameters are applied. When radial symmetric distortion parameters are applied, this value decreases to ±1.5 μm and, finally, when additional asymmetric parameters are also included, to a very accurate value ±0.73 μm.

With the application of automatic self-calibration, users are assured that systematic image errors are stable and do not change during the flight mission for a specific image block. This stability is a clear advantage of the digital camera over the film camera. The achievement of significant increases in accuracy by means of additional parameters testifies to the stability of the errors with time.

7.3.6 Radiometric Quality and Multispectral Capability

The UltraCamX exploits the radiometric quality of the high performance CCD sensor FTF5033 manufactured by DALSA and preserves this quality by means of in-house proprietary electronics circuits. No less than 13 bits of radiometric information can be extracted via the 14-bit analogue/digital converter. Such broad bandwidth allows the resolution of dark and bright areas in one and the same scene, for example from a city area on a bright sunny day with dark shadows in the streets and almost white roofs or other bright objects. The performance in dark image regions shows the full potential of the sensor and its sensitivity. Only ±6 DN @ 16 bit (= ±0.4 DN @ 12 bit) of noise could be detected in shadows.

Figure 7.3-18 shows frame 1,090 from a flight mission over the city of Graz, Austria on 27 March 2007, a clear sunny day. At a flying height of 900 m above ground level a ground sampling distance (GSD) of 6.5 cm was achieved. Two sub-areas of the panchromatic camera image containing very bright objects (umbrellas and welded roofs) as well as dark shadows were analyzed by computing the histogram. Levels of intensity from 350 DN to 7,800 DN @ 16 bit could be detected, yet image areas were not saturated. Such huge dynamic range of 7,450 DN corresponds to almost 77 dB or 12.9 bits.

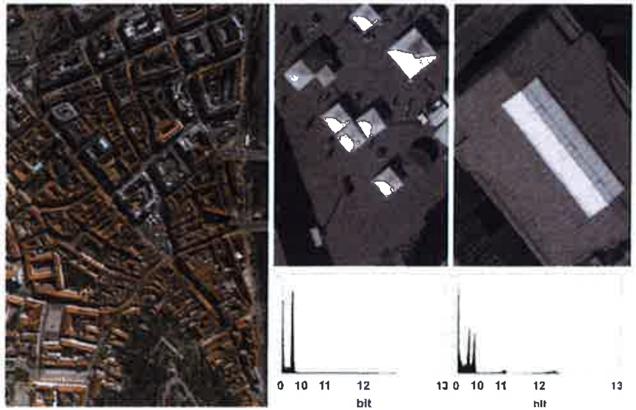

Fig. 7.3-18 Frame 1,090 of an UltraCamX on flight mission over the city of Graz. Two details of the image show a radiometric bandwidth of almost 13 bits. The darkest pixels are at a level of 350 DN and the brightest pixels are at a level of 7,800 DN in a 16-bit representation

The multispectral channels of the UltraCamX offer true colour (red, green and blue) as well as near infrared bands and therefore support multispectral classification, which benefits from a large radiometric range.

7.3.7 The Potential of Digital Frame Cameras

The driving force behind innovation in aerial photogrammetry for about 100 years was to minimize the number of photographs for a given project. The reason was simply cost, which was directly proportional to the number of images to be flown, which determined the film to be purchased, processed in a photo-laboratory, perhaps scanned into a digital format, triangulated and finally manually converted into information by photogrammetric procedures. The costs for aerial triangulation, DEM generation and orthophoto processing were a linear function of the number of images in a project. Cutting the number of flight lines in half meant a reduction in the cost of a project by the factor of four. The rapid acceptance of digital cameras is the result first of all of an increase in image quality and secondly of the economic advantages over the continued use of film cameras, simply because there is no longer a need to purchase film, develop it and scan it into pixel arrays. Higher image quality produces a better product, or supports a reduction of flight lines by flying at higher altitudes. This drives aerial photogrammetry away from film-based workflows and towards fully-digital approaches.

The third reason for acceptance, however, is the most important factor: the individual digital image does not produce any variable cost. Therefore the operation of a digital airbornee camera is feasible with only fixed annual costs, independent of the number of images being produced, be this 1,000 or 100,000 images per year. Only the costs for the fuel and fees in using the aerial camera platform are variable. The result is an opportunity to automate photogrammetric procedures that previously could not be efficiently automated. The many past failures to automate photogrammetric procedures can be attributed to, firstly, the limitations of film quality in the form of grain noise and a limited dynamic range; secondly, economy in the use of film, preventing the creation of sufficiently redundant image blocks properly to support automation. Having each terrain point on only two images for stereo does not represent sufficient support for robust automation, where perhaps five images are needed. Of course, producing a larger number of images only makes sense if subsequent processing efforts for those images are also independent of their number. Therefore automation is the prerequisite for a free choice of the number of images, and this free choice is a prerequisite for successful automation.

It is obvious that the future of modern photogrammetry lies in a fully automated workflow. Automated aerial triangulation may use a vast redundancy of 1,000 or more tie points in every image; the creation of a DEM may rely on 80–90% forward overlap and 30–80% sidelap to look in between vertical objects and match five images instead of a mere two; the orthophoto may be in the form of a 3D photo-texture placed on top of the 3D object surface, with classical orthorectification being nothing more than a special case of the more general "three-dimensional orthophoto". Finally, 3D vectors for GIS may be derived from land use classification and from image analysis, which may also support the classical processes of aerial triangulation, DEM generation and 3D orthophoto creation.

Digital large format airborne cameras help photogrammetry to "strike back", so to speak, after a period of retreat where airborne laser scanning took over the generation of point clouds for DEMs and GPS /IMU compromised the role of aerial triangulation. The lack of any variable cost for a digital image changes the rules of photogrammetric imaging and mission planning. This leads to automation opportunities that will invigorate photogrammetric innovation, offer alternatives to airborne laser scanning for the generation of point clouds and re-establish aerial triangulation as the central tool for precise image block formation for subsequent multi-image analyses. All this will also lead to opportunities to create new types of data and thus "content" for the ever-expanding information society.

It will be the "affordability due to automation" that will make the global 3D databases for "locational awareness on the Internet" a practical reality. Photogrammetry may gain in relevance by moving centre-stage in the world of high-bandwidth digital geospatial data creation and broadband Internet-based delivery.

7.3.8 Microsoft Photogrammetry

The acquisition of Vexcel Corporation, Boulder, Colorado and Vexcel Imaging GmbH, Graz, Austria, by Microsoft Corporation, Redmond, Washington raised questions, expectations and guesses in the photogrammetric community when it was announced in May 2006. The acquisition was driven by Microsoft's "Virtual Earth" initiative. The target of this program is to model in three dimensions the human habitat of the world – a few thousand cities and their neighbourhoods as well as rural areas between cities. Photogrammetry is the prime technology to do this job; the UltraCam is the preferred airborne sensor to build an automated 3D urban building modelling pipeline.

7.3.8.1 Aerial Missions

Aerial photo missions are carried out at a large scale (six-inch GSD) at end-laps of 80% and sidelaps of 60%. This results in a much larger set of aerial images than was previously typical in aerial photogrammetry. This highly redundant image data set, however, supports the automatic processes of aerial triangulation, digital elevation modelling and feature extraction. Redundancy also ensures the robustness of the process and the automatic detection of blunders, mismatches and outliers. Another important advantage of the large overlaps is the rigorous reduction of occlusions, a most helpful side effect when working in densely built up areas of city centres (Fig. 7.3-19).

7.3.8.2 Best Visuals for Non-Expert Users

Throughout the history of photogrammetry, geospatial data was produced by experts to be presented to and used by experts. Depending on the mapping scale a specific set of symbols had to be used to ensure that maps remained readable; details visible

Fig. 7.3-19 3D model of Philadelphia, automatically computed from UltraCam images with large overlaps. The photo texture of the 3D scene was also extracted from UltraCam images

and content interpretable. The user had to be trained to read such maps and to match abstract data, for example names and alphanumeric descriptions, with real world objects.

Microsoft's Virtual Earth initiative is designed to overcome this focus on "experts". Three-dimensional representations of the real world, rather than symbolized maps, are presented to users and the user connects with the data via photorealism. Thus anyone should be able to use terrain data in an intuitive, non-expert manner.

7.3.8.3 A 200 Petabyte Database?

The entire Earth needs to be digitized and presented on the World Wide Web. The Earth's land surface consists of ~140 million km^2. If one were to digitize this in two dimensions at a pixel size of 15 cm, the result would be 6.2 petapixels. Given that we need colour, perhaps even four-band colour with near infrared, we will use up to 4 bytes per pixel or ~25 petabytes. With the third dimension, we may have to add another 50% to the data volume and obtain a 3D data set in the range of <40 petabytes.

But this is not the end of the story. Bill Gates, as the leader of Microsoft Corporation and the champion behind Virtual Earth, stated the following on the occasion of his 50th birthday in London in March 2005: "You'll be walking around

in downtown London and be able to see the shops, the stores, see what the traffic is like. Walk in a shop and navigate the merchandise. Not in the flat, 2D interface that we have on the web today, but in a virtual reality walkthrough." This implies that the urban spaces will be modelled "from the street" and that indoor spaces will be part of Virtual Earth. This adds a requirement to model the facades and street level at a resolution of 2 cm, and indoor spaces at perhaps 0.5 cm.

In fact, we are facing the prospect of Internet-based 3D models of the world with a data volume well in excess of 200 petabytes.