GEOMETRIC ASPECTS CONCERNING THE PHOTOGRAMMETRIC WORKFLOW OF THE DIGITAL AERIAL CAMERA ULTRACAM$_X$

Richard Ladstädter[a], Michael Gruber[b]

[a] Institute of Remote Sensing and Photogrammetry, Graz University of Technology, Austria
Steyrergasse 30, A-1810 Graz, Austria, richard.ladstaedter@tugraz.at
[b] Vexcel Imaging / Microsoft Photogrammetry, Anzengrubergasse 8, A-8010 Graz, Austria
michgrub@microsoft.com

KEY WORDS: Photogrammetry, Digital, Camera, Calibration, Aerial

ABSTRACT:

In this paper we give a detailed description of the photogrammetric workflow recommended for the large format digital aerial camera UltraCamX. This includes image pre-processing, automated aerotriangulation (AAT) and the derivation of the final product (DTM, orthophotos, etc.) High quality geometric camera calibration is a prerequisite for photogrammetric applications. We will therefore also describe the initial camera calibration performed by Vexcel and the temperature dependent model (TDM), which compensates for systematic sensor drift during OPC post-processing. Geometric properties of the image also depend on the (variable) flight conditions (e.g. radial distortion caused by refraction). Self-calibration should therefore be applied in the final bundle adjustment to achieve the highest possible accuracies. We present self-calibration parameters suitable for the UltraCamX, consisting of traditional parameter sets and parameters specially designed for the UltraCamX. Geometric corrections described by these parameters must be applied to avoid systematic errors in the final product. To document this, we simulate systematic errors in the exterior orientation parameters and the DTM surface caused by systematic image errors.

1. INTRODUCTION

UltraCamX is the large format digital aerial mapping camera of Vexcel Imaging GmbH and was introduced into the international mapping market in 2006. The camera is based on Vexcel's well-known multi-cone design concept (Gruber, 2007). This concept was actually presented in 2003 together with the UltraCamD camera system (Leberl et al., 2003). It is further noteworthy that Vexcel Imaging GmbH was acquired by Microsoft Corp. in 2006 and continues to manufacture, offer and maintain the camera system.

The geometric calibration and the evaluation of the geometric performance of this camera has always been an important part of ongoing product maintenance at Vexcel. A comprehensive overview of the individual steps of this procedure is given in this contribution.

Figure 1. UltraCamX digital aerial camera system

1.1 Camera description

UltraCamX is a digital large format frame camera. Therefore it is based on photogrammetric knowledge from many decades but also introduces new concepts of camera design. The main parameters of the camera and the design of the sensor head are given below.

The most considerable advantages of UltraCamX are:

- Large image format of 14430 pixels cross track and 9420 pixels along track
- Excellent optical system with 100 mm focal length for the panchromatic camera heads and 33 mm for the multi spectral camera heads
- Image storage capacity of 4700 frames for one single data storage unit
- Almost unlimited image harvest due to exchangeable data storage units
- Instant data download from the airplane by removable data storage units
- Fast data transfer to the post processing system by the new docking station

The camera consists of the sensor unit (see Fig. 1, right side), the onboard storage and data capture system (see Fig. 1, left side), the operator interface panel and two removable data storage units. The system is also equipped with software for operating the camera and processing the image data after the flight mission.

1.2 Workflow Overview

The complete workflow, including initial camera calibration by Vexcel, comprises the following steps:

- Camera calibration using the in-house 3D test field
- Processing of level00 images to level02 (stitching and TDM correction)
- Automatic aerotriangulation (AAT)
- Self-calibration in the final bundle adjustment
- Applying self calibration results to the photogrammetric production chain.

In the following sections we will give a detailed description for each of the individual steps with a special focus on geometric quality control.

2. CAMERA CALIBRATION

2.1 The Vexcel test field

Vexcel's new Calibration Laboratory has been in use since July 2006 after moving into a new office building. It consists of a three dimensional calibration target with 367 circular markers (see Fig. 2). These markers are surveyed to an accuracy of about +/- 0.1 mm in X, Y and +/- 0.2 mm in Z and show a well defined circular pattern. The size of the structure is 8.4 m by 2.5 m at the rear wall and 2.4 m in depth. The calibration target consists of 70 metal bars with 280 markers mounted on the rear wall, ceiling and floor, four additional vertical bars with 16 markers in the center and 98 markers attached to the rear wall. The mean distance between markers is about 30 cm.

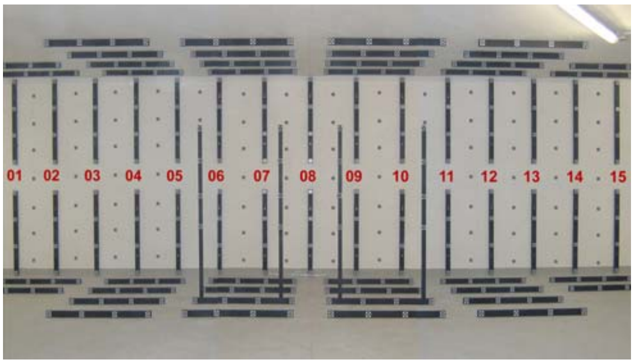

Fig. 2: The UltraCam calibration laboratory

Data capture involves taking 84 images from three different camera stations by tilting and rotating the camera. Software is used to compute sub-pixel accurate image positions of each marker in each image of the entire set of images. This results in a dense and complete coverage of coordinate measurements over the entire image format. One single calibration dataset consists of almost 90 000 measured image points.

The computation of the unknown camera parameters is based on the least squares bundle adjustment method by BINGO (Kruck, 1984). The specific design of the UltraCamX sensor head made modifications in the bundle software necessary. 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.

2.2 Computing of calibration parameters

The unknown parameters which are estimated within the bundle adjustment procedure can be separated in 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 investigating the correlation between those parameters 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, Ladstädter, 2006). It was therefore necessary to reduce the entire set of parameters in order to avoid such correlation. This was done by introducing principal distance and principal coordinates of all eight cones of the UltraCamX 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 lab calibration is documented by the sigma_o value of the bundle adjustment. This value was in the range of 0.4 µm to 0.5 µm for all calibrations of the panchromatic camera cones performed in the new calibration laboratory (see Fig. 3). This is a slight but significant improvement compared to the results achieved in the old calibration laboratory, which was in use until mid-2006.

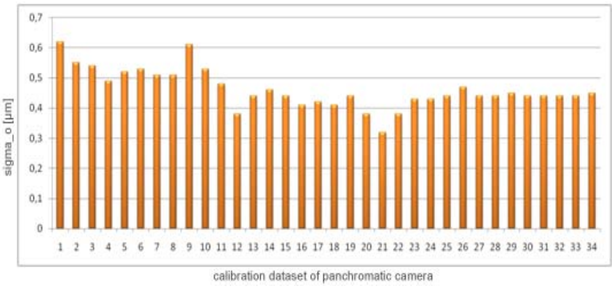

Fig. 3: Results of the bundle adjustment after the estimation of camera parameters (panchromatic camera).

2.3 Testflights

After the geometric laboratory calibration, the performance of each UltraCamX is verified by a flight mission over a well-known test area. A flight pattern with high overlap (80% overlap, 60% sidelap) and cross strips offers a redundant dataset which allows the interior geometry of the camera to be investigated.

Automatic tie point matching was done using INPHO's aerial triangulation software package MatchAT. A cross check and additional self-calibration options were performed using BINGO.

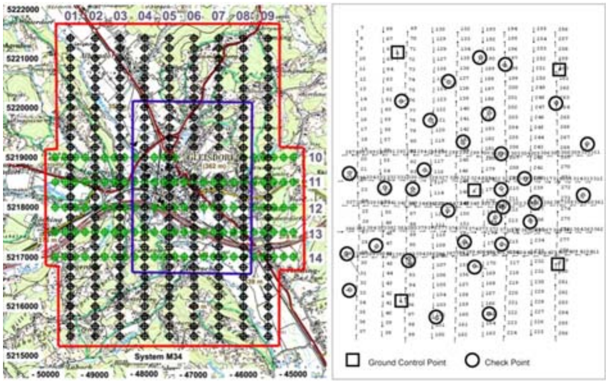

Fig. 4: Test area near Graz, Austria. Flight plan with 14 flight lines (404 images).

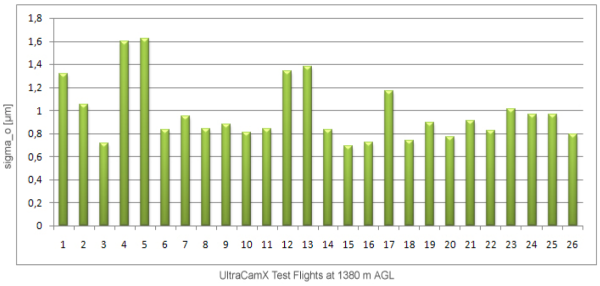

Fig. 5: Sigma_o values obtained from the automatic aerotriangulation of several UltraCamX test flights at 10 cm GSD (1380 m AGL).

The sigma_o value reflects the quality level of image coordinate measurements of an aerial triangulation project. Such values have been computed for several UltraCamX test flights (cp. Mansholt, Ladstädter 2008). The sigma_o values of the flight missions shown in Figure 6 are close to or smaller than 1 µm at that huge redundancy of high overlaps and additional cross strips.

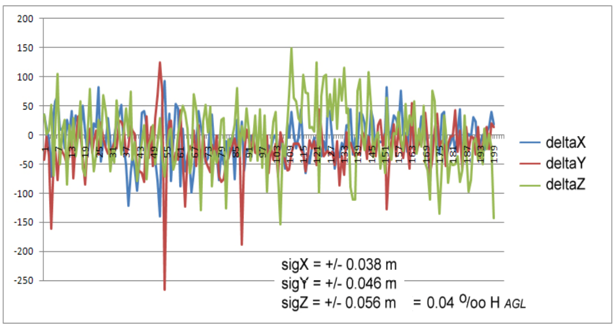

Fig. 6: Check point residuals after the bundle adjustment.

Another widely accepted method for verifying the geometric performance of mapping cameras is the use of check points. We used the result of 6 individual flight missions and 6 individual cameras to analyze the geometric performance of these cameras. Averaging of 199 check point measurements yielded a deviation of 38 mm, 46 mm and 56 mm in X, Y and Z, respectively. The vertical accuracy of that dataset corresponds to 0.04 ‰ of the flying height (cf. Fig. 6).

3. THE STITCHING PROCESS

The results from the test field calibration are stored in a data set (GeoCalibParam) needed for the post processing of each frame using Vexcel's OPC (Office Processing Center) software (see Fig. 7). These calibration parameters allow so-called image layers to be reconstructed for each of the four UltraCamX cones.

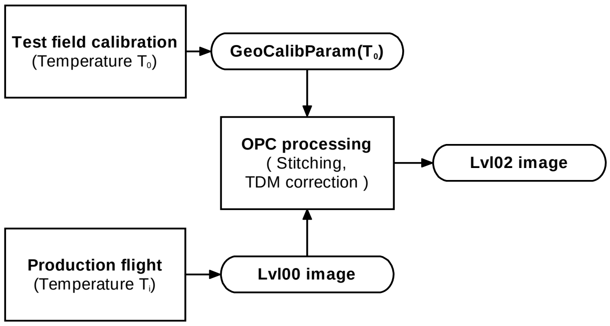

Fig. 7: Stitching process with integrated TDM correction

Level00 pixel data from four sensors are used to build layer 0 (denoted as "M" for master cone in Fig. 8, left side), two sensors for layers 1 and 2 and one for layer 3. Stitching points are matched at high precision between layer 0 and layers 1, 2 and 3. Using these points, layers 1-3 can be transformed into layer 0, resulting in a full frame image (see Fig. 8, right side).

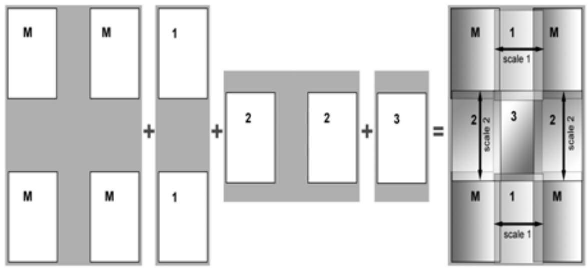

Fig. 8: Scheme of the UltraCam stitching concept

It is important to note that the position of a sensor within a layer has been determined very accurately during camera calibration. However these positions are only valid for a temperature T_0, which is also recorded during calibration.

A different temperature T_i is measured during a flight mission, depending on air temperature and flying height. Such thermal changes cause symmetric expansion/shrinking of the backplanes of the UltraCamX cones. The CCD sensors mounted on the backplane will therefore "drift away" from their calibrated positions when the flight temperature deviates from the calibration temperature. If this effect is neglected in the stitching process, systematic image deformations will be visible in the images.

A temperature dependent model (TDM) was therefore developed to correct geometric errors introduced by sensor drift (cp. Ladstädter, 2007). This correction model was successfully introduced into the OPC post-processing software.

A parameter *dC* describing the temperature difference between calibration time and flight time is deduced from the stitching scales $scale_1$ and $scale_2$ (see Fig. 8) and the 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.

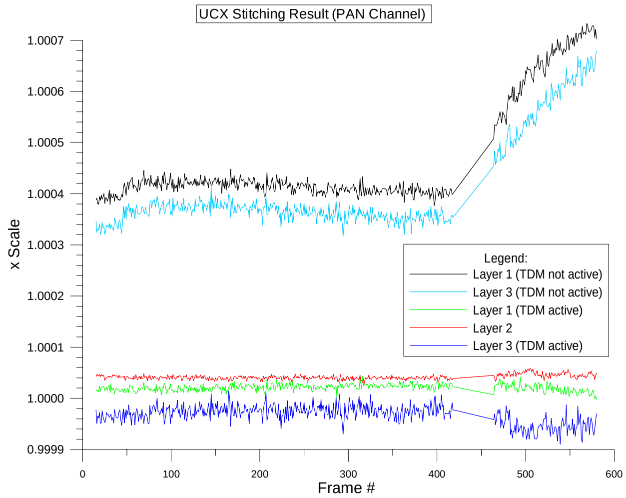

Fig. 9: Stitching scales before and after TDM correction

The stitching scales are expected to be close to 1.0 after the self- calibration. The effect of the TDM correction can be seen from Fig. 9. Images from an UltraCamX test flight have been processed once with TDM switched off and a second time with TDM activated. Without TDM, the stitching scales deviate significantly from 1.0 and show a high correlation with the changing temperature. Note that images 1 to 420 belong to different flying height than images 450-580.

With TDM corrections applied, however, stitching scales are close to 1.0 and are nearly independent from the varying camera temperature. Note also that the scale parameter for layer2 is not affected by the temperature effect and therefore identically for both stitching variants.

We state that the level02 image produced by the OPC software has a very high geometric quality due to the sub-pixel accurate stitching procedure and the enhancement from the TDM correction. No further geometric corrections are applied when images are processed to level03 to be used within a photogrammetric production workflow.

4. AUTOMATED AEROTRIANGULATION

Modern software packages for automated aerial triangulation (AAT) can handle highly redundant image data sets produced by digital camera systems. Strips can be flown at high overlap (80%) with no additional costs. Tie point measurement is fully automated which allows to measure hundreds of points per image. A single point can be measured at least in five images in a single strip flown at 80% overlap. If this point is covered by a second strip and/or additional cross strips point manifolds of 10 or even more are reached. As it can be seen from Fig. 10, the estimated height error can be strongly reduced using five or more rays for point reconstruction.

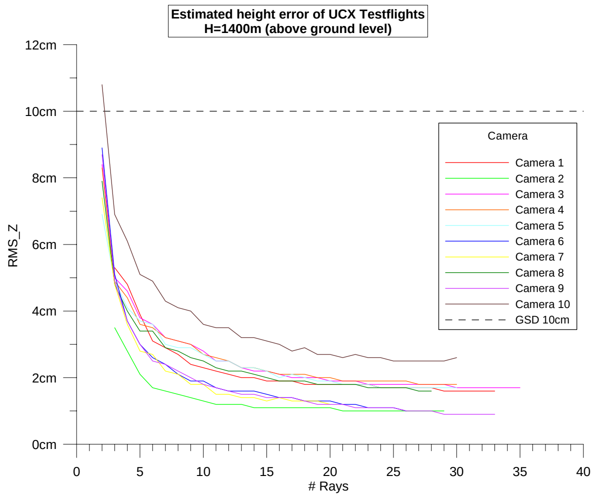

Fig. 10: Estimated height errors and number of rays

A detailed description of AAT results obtained from UltraCamX test flights using the MatchAT software can be found in this volume (Mansholt, Ladstädter, 2008).

5. SELF-CALIBRATION

Using self-calibration has always been good photogrammetric practice to achieve the highest possible accuracy in the bundle adjustment. Traditional parameter sets have been developed for analog cameras, describing e.g. radial lens distortion or affine film deformation. These traditional parameter sets are still valid for digital large format cameras like the UltraCamX.

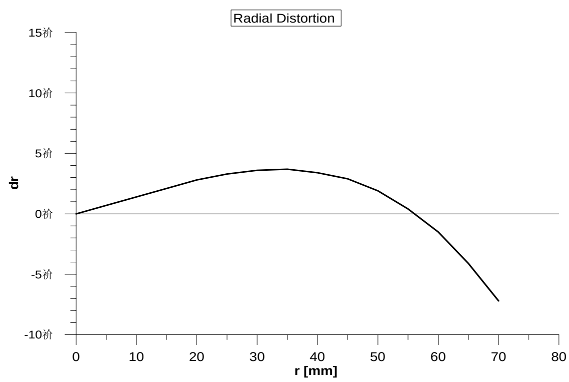

Fig. 11: Radial distortion curve (3.5µm at 35mm)

On the other hand, new specially designed parameter sets are necessary to describe small but systematic errors caused by the stitching process. As has already been mentioned in section 2.2, these parameters can describe shifts, rotations and scales for a certain image region corresponding to a single CCD sensor. Such parameters are implemented in the bundle adjustment software BINGO (Kruck, 1984) and also in the program BLUH, developed by the University of Hannover (Jacobsen, 2007).

We investigated the effect of small, but systematic image errors on reconstructed object points using simulated point measurements and assuming a maximum radial distortion of 3.5µm (see Fig. 11). Such a distortion curve has been determined in various UltraCamX test flights (cp. Mansholt, Ladstädter, 2008). Two effects were observed:

- Systematic height errors in the exterior orientation (EO) parameters of an image strip or block, if no GPS data or sufficient GCP's are used.
- Systematic height errors in the DTM derived from a stereo model (using only two rays, see Fig. 13).

In the first case we observe large systematic height errors in the middle of the strip/block. In this simulation we used a single strip with 30 images at 80% overlap and only four ground control points (GCP) in the corners of the strip. No GPS data is used and radial distortion parameters are switched off in the bundle adjustment. Because of the systematic image errors, a bending of the strip takes place. Erroneous Z-values of the projection centers will propagate into the DTM heights (see Fig. 12). Systematic height errors of +3m have been obtained in the middle of the strip.

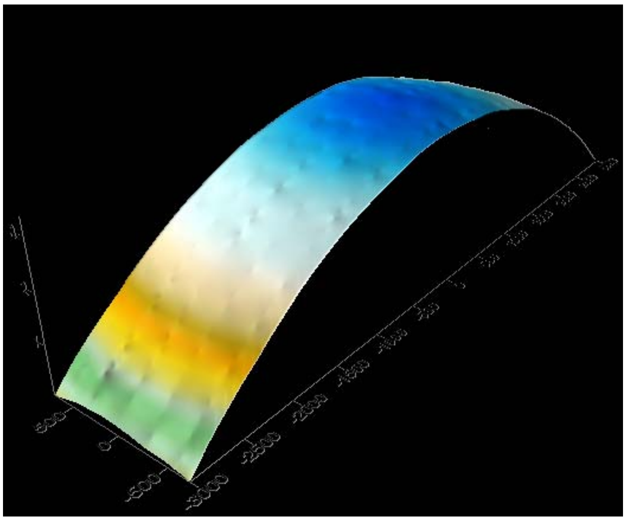

Fig. 12: Simulation of a single strip (30 images, 80% overlap). Systematic DTM errors caused by distorted EO parameters (Z-values).

In the second case we simulate the effect of radial distortion onto reconstructed points within individual stereo models. We use the same configuration as in the previous simulation (30 images, 80% overlap), but this time we assume error free EO parameters. Each point of the DTM is reconstructed using only two rays (from the stereo partners located next to this specific point). This time we observe systematic height errors are along the Y-axis, reaching up to 20cm (see Fig. 13).
Similar effects have also been documented for real projects (cp. Jacobsen, 2007).

6. CONCLUSIONS

The geometric performance of the large format digital camera UltraCamX is based on the initial in-house camera calibration as well as on the stitching procedure which is performed during image post-processing. Image residuals from the test field calibration and the stitching procedure show a precision level of less than 1/10 of a pixel. Nevertheless small but systematic errors may still exist in the final image. Small radial symmetric distortions are typically observed, caused by atmospheric refraction.

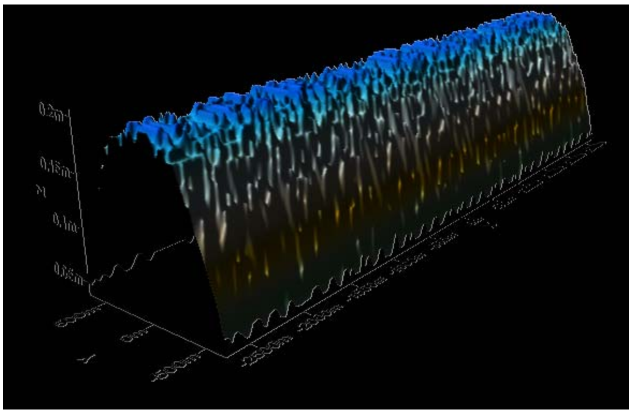

Fig. 13: Simulation of a single strip (30 images, 80% overlap). Systematic DTM errors caused by a simulated radial distortion using correct EO parameters.

Within a photogrammetric block, systematic distortions in the images will produce geometric displacements in the final photogrammetric product. Even when the magnitude of such distortions in the images is quite small they cannot be neglected.

One effective method to overcome such effects is to introduce self calibration parameters in the bundle adjustment. Most of the commercially available software products offer such parameters; especially radial symmetric parameters are well known and widely used. Specially designed parameter sets for UltraCamD/X images are offered e.g. by the bundle adjustment package BINGO and can be used to achieve the highest possible accuracy.

REFERENCES

Gruber, M., 2007: UltraCamX, the new digital aerial camera system by Microsoft Photogrammetry, Proceedings of the Photogrammetric Week 2007, Stuttgart.

Gruber, M. & Ladstädter, R., 2006: Geometric issues of the digital large format aerial camera UltraCamD. International Calibration and Orientation Workshop EuroCOW 2006 Proceedings, 25-27 Jänner 2006, Castelldefels, Spanien.

Gruber M., Leberl, F., Perko, R. 2003: Paradigmenwechsel in der Photogrammetrie durch Digitale Luftbildaufnahme? Photogrammetrie, Fernerkundung, Geoinformation.

Jacobsen, K., 2007: Potential großformatiger digitaler Luftbildkameras, DGPF Tagungsband 16/2007, pp. 589-597.

Kröpfl et al., 2004: Geometric calibration of the digital large format aerial camera Ultracam. The International Archives of Photogrammetry and Remote Sensing, Vol. XXXV/1, p. 42 ff., July 2004, Istanbul, Turkey.

Kruck, E., 1984: BINGO: Ein Bündelprogramm zur Simultanausgleichung für Ingenieuranwendungen.

Möglichkeiten und praktische Ergebnisse, International Archive for Photogrammetry and Remote Sensing, Rio de Janairo 1984.

Ladstädter, R., 2007: Softwaregestützte Kompensation temperaturabhängiger Bilddeformationen für die Vexcel UltraCam, DGPF Tagungsband 16/2007, pp. 609-616.

Leberl F., Gruber, M. 2007: *Microsoft's Virtual Earth Initiative*, Presentation at the Geo-Nord Conference, Hannover, March 2007.

Leberl, F. et al. 2003: *The UltraCam Large Format Aerial Digital Camera System*, Proceedings of the American Society For Photogrammetry & Remote Sensing, 5-9 May, 2003, Anchorage, Alaska

Mansholt, U., Ladstädter, R. 2008: Geometric analysis of Vexcel Imaging UltraCamX test flights, Proceedings of the XXI ISPRS Congress, 3-11 July 2008, Bejing, China (in this volume).