# CALIBRATING DIGITAL PHOTOGRAMMETRIC AIRBORNE IMAGING SYSTEMS IN A TEST FIELD

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**ABSTRACT:**

Passive and active digital imaging is rapidly replacing film imaging in photogrammetric data capture. The reliability, accuracy, and efficiency of airborne photogrammetry are based on calibrated, high-quality sensors and rigorous processing. The calibration processes of the digital photogrammetric airborne imaging systems are under development. Central challenges in the development of the calibration are the extensive variation in digital systems, the need for radiometric calibration, and the necessity for accurate system calibration. Test field calibration is a potential approach for determining the system calibration. An investigation was carried out on the need for and feasibility of test field calibration of the geometry, radiometry, and spatial resolution of digital photogrammetric imaging systems. A unified framework and parameterization for the calibration of these properties was devised. A prototype test field calibration methodology was developed and the need for and feasibility of the test field calibration was investigated using empirical image materials. In the empirical study, data sets from the three first-generation commercial digital photogrammetric large-format sensors, ADS40, DMC, and UltraCamD were used. The results proved the feasibility of the test field calibration; a permanent test field can be an efficient, highly automated, and reliable tool for system calibration. The test field calibration was necessary for the evaluated systems to provide the missing or invalid calibration parameters and to assess their measurement capability. The results also showed that calibration of the high quality photogrammetric systems in a test field was feasible.

## 1. INTRODUCTION

The transition from film imaging to digital imaging by active and passive instruments causes a revolution in airborne photogrammetry. Optimal use of this new technology enables fast data captures, high accuracy, a high level of automation, and a huge increase in applications. The users of airborne photogrammetric cameras have traditionally been concerned on geometric issues, but the optimal utilization of the new digital sensors necessitates also the rigorous processing of the spatial resolution and radiometry.

To fulfil the reliability requirement set for the photogrammetry and to obtain high efficiency, calibrated, high quality instruments and rigorous methods are used in the photogrammetry. *Calibration* is defined as a “process of quantitatively defining the system responses to known, controlled signal inputs” (Morain and Zanoni, 2004). The four tasks of the digital photogrammetric airborne imaging system calibration are: 1) sensor component calibration (e.g. the lens or CCD), 2) sensor calibration, 3) image acquisition system calibration, and 4) image product generation system calibration. The first two tasks can be carried out in well-controlled conditions in a laboratory. The calibration of the image acquisition system and the image product generation system can only be performed under airborne conditions either using test fields or on a self-calibration basis, whereby the methods characterize the entire measurement system under operational conditions (*in situ)*. Test field and self-calibration concepts originate from geometric calibration, but they can be generalized to cover spatial resolution and radiometry as follows. The *test field calibration* determines the system calibration using images collected over a *photogrammetric test field*, which is an area with characterized reference targets and measurement devices suitable for calibrating photogrammetric imaging systems. *Self-calibration* does not require characterized reference targets, and it often determines the system calibration from the data of a certain mapping flight.

Calibration processes of the digital photogrammetric airborne imaging systems are under development. Central challenges in the development of the calibration are the extensive variation in digital systems, the need for radiometric calibration, and the necessity for accurate system calibration. The complexity of the calibration task has been widely recognized (ASPRS, 2000; Cramer 2004; 2006; USGS, 2005; Stensaas *et al.*, 2007). A general expectation is that test field calibration would be an efficient tool for dealing with the above issues (ASPRS, 2000; Pagnutti *et al.*, 2002; Cramer, 2004; 2006; Stensaas, 2007), but the performance, need for, and feasibility of test field calibration has not been empirically proven.

An investigation was carried out to evaluate the need for and feasibility of test field calibration of geometry, radiometry, and spatial resolution of digital photogrammetric imaging systems. A unified framework and parameterization for the calibration of these properties was devised. A prototype methodology for test field calibration of digital photogrammetric airborne imaging systems was developed. The need for system calibration was investigated by using empirical image materials in order to evaluate the sufficiency and validity of system calibration provided by sensor manufacturers. The feasibility of system calibration in test field was empirically investigated by evaluating the feasibility of constructing test fields and calibrating the systems at test fields. The investigation provided information on the performance of digital photogrammetric sensors and test field calibration, and gave recommendations for the calibration process of digital photogrammetric systems and the construction of photogrammetric test fields. This article summarizes the key results of these investigations. The detailed results are given by Honkavaara et al. (2006a; 2006b; 2006c; 2008), Honkavaara (2008) and Markelin et al. (2008).

| Sensors | Date | GSD [cm] | Property |
|---|---|---|---|
| UltraCamD | 11.10.2004 | 4 | G |
| UltraCamD | 14-15.10.2004 | 4, 8, 25, 50 | G |
| UltraCamD | 14.5.2005 | 4 | G |
| DMC | 1-2.9.2005 | 5, 8 | G, SR, R |
| ADS40 | 26-27.9.2005 | 15, 25 | R |
| UltraCamD | 1.7., 5.7. 2006 | 4, 8 | R |

Table 1. Empirical image materials. Analysed properties: G: geometry, SR: spatial resolution, R: radiometry.

## 2. MATERIALS AND METHODS

The research approach was to collect image materials in a photogrammetric test field and by analysing the imagery to draw conclusions about the test field calibration.

### 2.1 Materials

The empirical image materials were collected by the first-generation digital large-format photogrammetric sensors in 2004-2006 (Table 1). The empirical study concerned calibration of the geometry of the DMC and UltraCamD, the spatial resolution of the DMC, and the radiometry of the DMC, UltraCamD, and ADS40. The complete system calibration was performed only for the DMC.

### 2.2 Methods

The permanent Sjökulla test field together with some supplementary portable targets is a prototype photogrammetric test field (Honkavaara et al., 2008). The Sjökulla test field was established in 1994. It consists of an image quality test field for radiometric and spatial resolution calibration (Figure 1) and networks of targeted benchmarks for geometric calibration at large, medium, and small imaging scales. Permanent spatial resolution and reflectance targets made of gravel are special features of the Sjökulla test field (Peltoniemi et al., 2007; Honkavaara et al., 2008).

The central calibration quantities are the models and parameters that are needed to the transform the system inputs to the outputs and the quality indicators for these transformations. A comprehensive parameterization developed in this study is presented in Section 3.4.

The calibration process flow is shown in Figure 2; the sub-processes are the image data collection, reference data collection, and analysis (Honkavaara et al., 2008; Honkavaara, 2008).

Geometric calibration is based on self-calibrating bundle block adjustment; central parameters are the interior orientations and the system distortions (Honkavaara et al., 2006a; 2006b; Honkavaara, 2008). To support the geometric calibration, a methodology utilizing simulation and empirical results was developed for the sensor evaluation and photogrammetric product quality prediction (Honkavaara et al., 2006b). The limitation of the flight missions was that accurate exterior orientation information was not collected. The data were not suitable for interior orientation determination because the Sjökulla test field is flat and the blocks were optimized for the calibration with GPS/IMU support.

The spatial resolution was assessed by evaluating the resolving power (RP) and modulation transfer function (MTF). The RP was obtained from the dense resolution bar target (Figure 1) using an automatic method (Ahokas *et al.*, 2000; Honkavaara et al., 2006c). The MTF was obtained from the Siemens star (Figure 1; Honkavaara et al., 2006c) using a method based on the method developed by Reulke *et al.* (2006) and Becker *et al.* (2006). 10% MTF and $\sigma_{PSF}$ were derived from the MTF.

Figure 1. The Sjökulla image quality test field: 1) permanent dense resolution bar target, 2) permanent gray scale, 3) permanent reflectance targets, 4) sparse resolution bar target, 5) permanent circular targets, 6) portable Siemens star, and 7) portable gray scale.

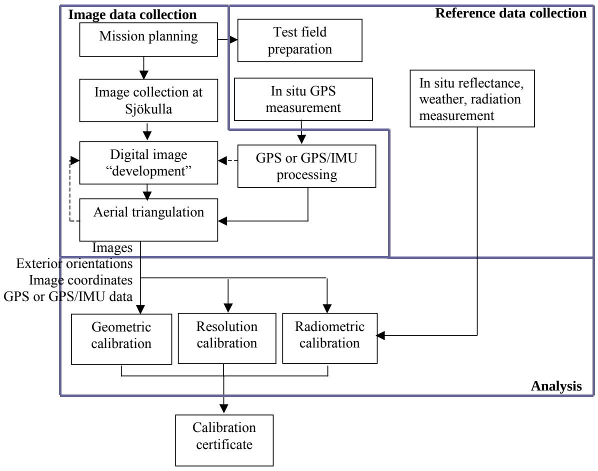



Figure 2. Test field calibration process flow (Honkavaara, 2008).

A portable 8-step gray scale was used as the reflectance reference target for the reflectance based vicarious radiometric calibration (Figure 1; Honkavaara et al., 2008; Markelin et al., 2008). The limitations of the missions were that the atmospheric and illumination data were not collected during the test flights and that the reference targets had not been calibrated comprehensively. The laboratory-determined target spectral reflectance and the MODTRAN 4 default atmospheric models were used (Markelin et al., 2008). Due to these limitations, the calibration could only be performed partially. The results of the linearity and dynamic range evaluations can be considered reliable, while the sensitivity and absolute calibration results should be considered indicative.

## 3. RESULTS AND DISCUSSION

### 3.1 Geometric calibration

The geometry of three technically similar UltraCamDs and one DMC was calibrated (Table 1). In one of the UltraCamD missions, blocks were collected with 4 cm, 8 cm, 25 cm, and 50 cm GSD, and three repetitive blocks with 8 cm GSD were collected during two days; for the other two UltraCamDs, only single blocks with 4 cm GSD were available. The DMC was calibrated using blocks with 5 cm and 8 cm GSD; repetitive blocks with 8 cm GSD were collected on two consecutive days. The following results are based on Honkavaara et al. (2006a; 2006b) and Honkavaara (2008).

A fundamental empirical result was the detection of the distortions in the multi-head images, which caused block deformations; this was verified with all UltraCamD and DMC blocks. The sensor manufacturers did not provide information on these distortions, nor did they provide tools for compensating for them. Examples of the block height deformations for the DMC and UltraCamD are given in Figure 3 (blocks with four image strips, 60% forward and side overlaps, and 12 GCPs). Block height deformations in the central area of the block were estimated by calculating averages and standard deviations in the deformed area (marked by a circle). They were -10.3 cm and 2.2 cm for the UltraCamD, and -4.5 cm and 1.6 cm for the DMC when self-calibration was not performed. With self-calibration (single-head physical model) the corresponding values were -5.2 cm and 1.3 cm for the UltraCamD and 2.0 cm and 1.2 cm for the DMC, respectively. The systematic height deformations in the central areas of the example blocks were for the UltraCamD 2.5 times and for the DMC less than 1 time the theoretical height determination accuracy when self-calibration was performed. Without self-calibration, the values were 4.5 and 1.5, respectively.

Different UltraCamDs had different distortion patterns. One of the tested UltraCamDs did not function correctly, which appeared in the form of exceptionally bad point determination accuracy, poor $\hat{\sigma}_0$, and large systematic distortions. With both DMC and UltraCamD, the repeated blocks showed some similarities (e.g. similar distortion patterns in many cases). This indicated some level of stability, also with respect to altitude, but some unexplained instability appeared as well.

The single and multi-head additional parameters partially compensated for the distortions and improved the point determination accuracy. With self-calibration, the systems provided usually a high geometric accuracy, but without self-calibration in many cases the systematic block deformations were considered to be intolerable in many photogrammetric applications

These results are consistent with other recently published resuts of the first generation systems (e.g. Alamús et al., 2006; Baz et al. 2007; Cramer, 2007b). A significant consequence of the empirical investigations has been that camera manufacturers have started to take action to eliminate distortions (Dörstel, 2007; Gruber, 2007). Improved systems and processing chains are now available but their performance has not been proved by independent empirical tests yet.

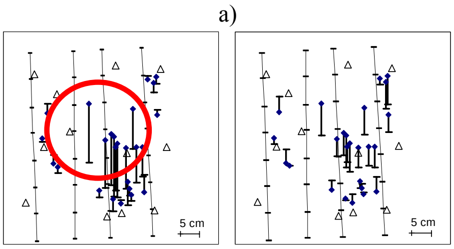
### 3.2 Spatial resolution calibration

In the empirical spatial resolution calibration study, DMC images with 5 cm GSD and 8 cm GSD were used; two blocks with an 8 cm GSD were collected over consecutive days (Table 1). The effect of the distance from the image center, the altitude (500 m and 800 m), and the flying direction were evaluated. The following results are based on Honkavaara et al. (2006c) and Honkavaara (2008).

The resolution of the DMC panchromatic images weakened as the distance from the image center increased; the resolution reduction factor from the image center to the image corner was up to 2 (Figure 4). One important reason for this behavior is the oblique construction of the system. Theoretical evaluation showed that the resolution reduction factors from the nominal 12 μm pixel size, caused by the image tilt, were at their maximum 1.6 in the cross-flight direction and 1.4 in the flight direction in the corners of the image.

The effect of position on spatial resolution was modeled using a linear model as the function of the radial distance from the image center (Figure 4). The intercept indicates the resolution at the image center, and the slope indicates the resolution decrease with the increasing distance from the image center. Evaluation

a)




b)

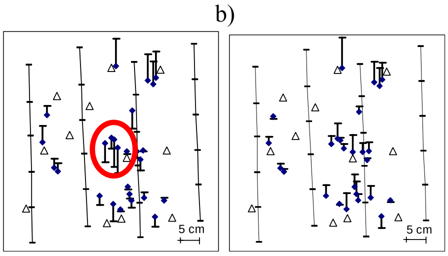
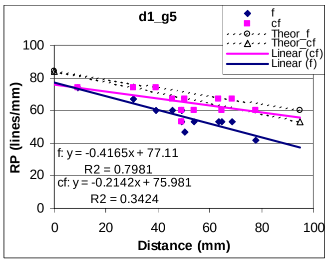



Figure 3. Errors at independent checkpoints in height coordinates: a) UltraCamD, GSD=4 cm. b) DMC, GSD=5 cm. Left: no self-calibration, right self-calibration using single-head physical parameters.

a)




b)

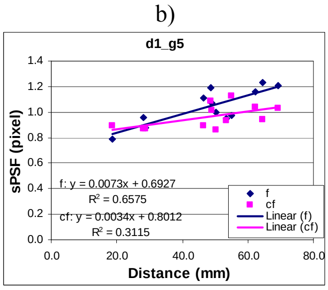



Figure 4. Analysis of a) RP and b) $\sigma_{PSF}$ as a function of the distance from the image center. (f: flight and cf: cross-flight direction

was made in flight and cross-flight directions. The statistics indicated a significant linear fit for the RP, 10% MTF, and $\sigma_{PSF}$ at a 5% confidence level, excluding the $\sigma_{PSF}$ in the cross-flight direction with the imagery with a 5 cm GSD. These regression models can be regarded as spatial resolution models of the DMC panchromatic images.

The empirical spatial resolution analysis showed that the resolution of the panchromatic DMC images was lower than the Nyquist limit, and dependent on the position in image, flying altitude, and direction of flight. The sensor manufacturer did not provide information about these factors. It is likely that selecting the flight parameters of the DMC using the nominal information about the sampling interval will not lead into acceptable results in many photogrammetric applications.

### 3.3 Radiometric calibration

The ADS40, UltraCamD, and DMC were radiometrically test field calibrated. For each sensor two different flying heights were used. The following results are based on Honkavaara (2008) and Markelin et al. (2008).

The systems were linear in response. As an example, a radiometric response plot of one DMC image is shown in Figure 5a. In some cases, however, nonlinearity appeared. Some of the channels of the DMC and UltraCamD were saturated in some images at bright reflectance values, which appeared as nonlinearity (for instance, the green channel of the DMC in Figure 5a). Nonlinearity appeared also with the 20% reflectance target because of the inaccuracy of the reference value (see below).

The A/D-conversion is made with 12 bits for the DMC and with 14 bits for the UltraCamD and ADS40. The DMC used the 12-bit dynamic range entirely, while UltraCamD and ADS40 panchromatic channel indicated a close to 13-bit dynamic range. The dynamic range of the ADS40 multispectral channels was as low as 9-10 bits. Differences in the sensitivity of various channels were the smallest for the DMC and the largest for the ADS40. The solar elevation angle was approximately 28˚ for the ADS40, 35˚ for the DMC, and 50˚ for the UltraCamD.

The absolute radiometric calibration was determined for the DMC and ADS40. Either the linear model with gain and offset parameters or with the gain parameter on its own was appropriate for absolute calibration. The precision of the gain parameters was 1-2% for the DMC (4-8 targets) and 3-5% for the ADS40 (5 targets). The relative empirical accuracy of absolute calibration was evaluated by determining the calibration using subsets of the reference targets and evaluating the accuracy with the remaining targets. This accuracy evaluation is considered to be relative, because the accuracy of the atmospheric correction was not known. The errors in the check reflectance targets are given for one DMC image with 5 cm GSD in Figure 5b; the darkest and brightest targets were used for the calibration. The errors were clearly greater for the 20% target than for other targets, which indicated outlier. The errors in the green channel were clearly larger than the errors in other channels; this was caused by the saturation of the green channel at greater than 45% reflectance. The saturation is an outlier, which caused bias to the calibration parameters and deterioration of accuracy. The errors were less than 6%, excluding the green channel and the 20% target. The RMSEs were 3.3-4.5%. The major source of error was the calibration inaccuracy and non-uniformity of the reference targets. Assuming an atmospheric modelling error of 3-4% (e.g. Biggar

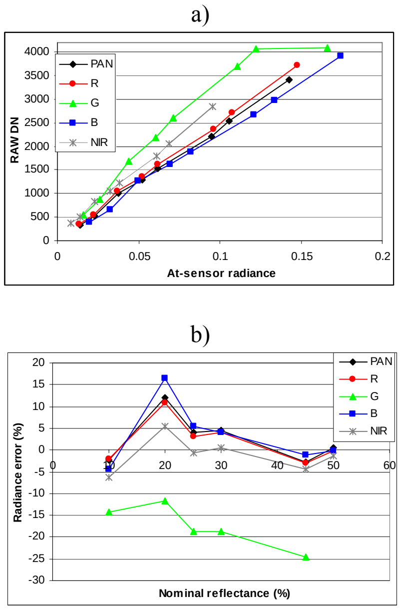



Figure 5. DMC radiometry evaluation, GSD=5 cm. a) DNs plotted as a function of at-sensor radiance. b) Absolute calibration residuals as a % of radiance, 5% and 70% targets were used as a reference (5% and 50% for green channel).

et al., 1994), approximately 6% absolute radiometric accuracy can be expected. This accuracy is similar to values obtained for the remote sensing systems, and it could be further improved by improving the reference target uniformity and calibration.

Sensitivity of the color channels appeared to be a serious limitation for the first generation ADS40 in limited illumination conditions with a high-speed aircraft. The large sensitivity differences in the ADS40 are partially caused by the widths of the bands and the filtering principle. Collection of images with a smaller than 15 cm GSD was not even possible by the system tested. These properties can limit the usability of the 1st generation ADS40 in high latitudes, with a high-speed aircraft; Frickler (2007) states that the 2nd generation ADS40 has an improved sensitivity, but independent empirical results are not yet available. The flying speed and illumination conditions did not cause problems for the DMC and UltraCamD because the exposure time could be increased with the help of forward motion compensation. However, it appeared that for the UltraCamD and DMC, the exposure and aperture settings were critical parameters causing a risk of over-exposure. Missing calibration parameters, radiometric processing chains, and information on radiometric performance are serious shortcomings hindering the quantitative use of the radiometry of the sensors.

### 3.4 Parametrization of the test field calibration

A general parameterization for geometric, spatial resolution and radiometric calibration was devised based on the results (Honkavaara, 2008): a) system calibration model and its parameters; b) accuracy of the calibration model (precisions of parameters, residuals); c) empirical accuracy of output products; d) other performance indicators; e) performance prediction method and its accuracy. The exact parameters are sensor dependent. An interesting quantity here is the performance prediction method. The capability to predict system performance is often advantageous; the predictability could be considered as one requirement for the photogrammetric systems.

### 3.5 Recommendations for calibration process of digital photogrammetric airborne imaging systems

The analysis showed that the comprehensive calibration process should consist of laboratory, test field, and self-calibration, and of product level validations (Honkavaara, 2008). Laboratory calibration was needed, because it is the most accurate method. It enables system evaluation in controlled conditions with all possible settings, and all parameters cannot be determined by test-field calibration. Calibration in a test field is a sophisticated method of assessing the system calibration in controlled conditions, assessing the measurement capability of the system, and determining optimum mission parameters for various applications. Self-calibration is needed, because information about sufficiency of the pre-defined calibration parameters and about system stability are missing. Finally, product level calibration of the geometry appeared to be necessary for applications with high quality requirements. International standardization is required to generate widely accepted calibration procedures (Cramer, 2007a; Stensaas, 2007).

### 3.6 Recommendations for photogrammetric test fields

Recommendations for the reference targets were derived based on the study (Honkavaara, 2008). In principle, any area containing appropriate reference targets and measurement equipment can be considered a photogrammetric test field, but permanent test fields have several advantages in comparison with temporal test fields (Honkavaara, 2008). The permanent targets and measurement equipment will maximize the automation level. When calibration is performed in the same environment under acceptable conditions, object-dependent and condition-dependent variations can be minimized; this enables efficient detection of problems of systems. It is particularly important to be able to build permanent test fields for geometric calibration. Permanent resolution and reflectance targets are also preferable, but the results showed that portable targets are also functional. It is feasible to develop optimal procedures and automated calibration methods for permanent test fields. If systems are calibrated in several test fields, the differences of various test fields should be assessed in order to be able to detect changes in systems. This is feasible for permanent test fields. Finally, the accreditation that is required for testing and calibration laboratories is practical mainly for permanent test fields.

For the users of the test fields, operational and financial issues are of importance. The test fields should be easily accessible. Of great practical importance is the maximum probability of appropriate atmospheric conditions for photogrammetric data collection flights. Reference targets and automatic calibration methods should be standardized so that the processing can be highly automated and objective. The test field should also be suitable for multipurpose product validation (e.g. point determination, digital elevation models, feature extraction, classification, and orthophotos).

### 3.7 On the need for and feasibility of test field calibration

The results showed that the test field calibration of geometry, radiometry, and spatial resolution was needed for the three most high-end digital photogrammetric sensors to determine the invalid or missing calibration parameters, and to assess the system measurement capability (Honkavaara, 2008).

The results showed that the test field calibration of the systems was feasible (Honkavaara, 2008):

- The test field calibration of the geometry was a powerful tool for detecting the precision and bias of the sensor model and output products. The calibration blocks did not enable the determination of the geometric system calibration model. However, current literature and experiences with analog frame cameras indicate that an appropriate sensor model could be determined in a test field.
- Spatial resolution of the DMC panchromatic images could be calibrated in the test field The comprehensive calibration blocks enabled the development of empirical models for spatial resolution which outperformed other tested resolution prediction methods.
- The radiometric study showed that the radiometric response of the ADS40, DMC, and UltraCamD was linear. Calibrating this model in the test field is feasible. The expected calibration accuracy corresponds to results from remote sensing systems. The radiometric data provided by the sensors are easily applicable to quantitative use, thus radiometric calibration is advantageous.

The extent to which the parameters determined in the test field can be utilized in subsequent mapping processes is dependent on the development of models that are accurate and on the stability of the systems.

The results showed that the permanent photogrammetric test fields are feasible (Honkavaara, 2008). Many years of experience in permanent geometric test fields have proven their feasibility. The results of this study showed that construction of a permanent test field for resolution and radiometry is also feasible; experience at Sjökulla shows that gravel is a durable material for these targets. The use of portable reflectance and resolution targets in a permanent test field appeared to be feasible as well.

## 4. CONCLUSIONS AND OUTLOOK

This investigation developed a prototype methodology for the geometric, spatial resolution, and radiometric calibration of the digital photogrammetric imaging systems. It was empirically shown that the test field calibration was necessary and feasible for the first generation digital photogrammetric large-format imaging systems. Furthermore, it was shown that construction of permanent test fields was feasible.

This investigation concerned first generation large-format digital photogrammetric airborne imaging systems. The same methodology can be used for the calibration of other systems as well. The recommendation is that, for the time being at least, those properties of digital airborne imaging systems that are quantitatively used should be calibrated in a test field.

The developed prototype calibration method gives a certain level of accuracy for. As soon as sufficient understanding of the parameters that are needed is available, the calibration accuracy can be improved by fine-tuning the reference targets, calibration block structures, and measurement methods.

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