Publication I


© 2008 American Society for Photogrammetry and Remote Sensing (ASPRS)

Reprinted with permission from the American Society for Photogrammetry and Remote Sensing.
Radiometric Calibration and Characterization of Large-format Digital Photogrammetric Sensors in a Test Field

Lauri Markelin, Eija Honkavaara, Jouni Peltoniemi, Eero Ahokas, Risto Kuittinen, Juha Hyvölä, Juha Suomalainen, and Antero Kukko

Abstract

Test field calibration is an attractive approach to calibrating and characterizing the radiometry of airborne imaging instruments. In this study, a method for radiometric test field calibration for digital photogrammetric instruments is developed, and it is used to evaluate the radiometric performance of large-format photogrammetric sensors the ADS40, the DMC, and the UltraCam. In the study, linearity, dynamic range, sensitivity, and absolute calibration were evaluated. The results demonstrated the high radiometric quality of the sensors tested. All the sensors were linear in response. The DMC used the 12-bit dynamic range entirely, while the ADS40 and the UltraCam indicated close to the 13-bit dynamic range. The sensors performed quite differently with respect to sensitivity. Because the sensors were linear in response, they could be absolutely calibrated using linear models.

Introduction

Digital sensors are replacing analog sensors in photogrammetric production. One of the most attractive features of digital sensors compared with analog sensors is the radiometric properties. There are significant improvements, such as lower noise level (i.e., no granularity), linearity, better resolution, larger dynamic range, and better stability (Sandau et al., 2000; Heier, 2001; Graham and Koh, 2002; Perko et al., 2004; Leberl and Gruber, 2005; Markelin et al., 2005; Paparoditis et al., 2006). These properties improve the automation potential of the image measurement tasks and create new prospects for the use of photogrammetric images in interpretation applications. The radiometric properties and calibration issues of digital photogrammetric sensors and images should be carefully studied in order to optimize their processing for various tasks and to also maximize the value of the collected images for future use as historical data sets.

Photogrammetric sensors are carefully calibrated and laboratory tested by the system manufacturers. However, there is increasing interest in test field calibration, which takes all the system components and the airborne operational environment into account. If functional test fields are available, field calibration can be performed efficiently, and it seems that test field system calibration will be a fundamental part of future photogrammetric production lines (Pagnutti et al., 2002; Cramer, 2006; Honkavaara et al., 2008). Radiometric test field calibration is a new issue in the case of photogrammetric sensors.

Calibration is defined as a process of quantitatively defining the systems’ responses to known, controlled signal inputs (Morain and Zanoni, 2004). Radiometric calibration involves determining the functional relationship between the incoming radiation and the instrument output (digital number, i.e., DN). Calibration approaches can be divided into absolute and relative (Dianguirard and Slater, 1999). Absolute calibration is performed by determining the relation of the DN output from a sensor with the value of an accurately known, uniform radiance field at its entrance pupil. In relative calibration, the outputs of the detectors are normalized to a given, often average, output from all the detectors in the band. As a result of the normalization, all the detectors give the same output when the focal plane of the sensor is irradiated with a uniform-radiance field. Relative calibration can also be used for interband calibration and multitemporal calibration. Accurate radiometric calibration becomes a necessity if images from different dates and sensors are used for the change detection and interpretation, which is one of the main advantages of digital photogrammetric sensors.

Functional approaches have been developed for the radiometric calibration of spaceborne and airborne remote sensing instruments. With spaceborne sensors radiometric calibration is a three-phase process consisting of preflight calibration, on-board calibration, and vicarious calibration (Dianguirard and Slater, 1999). Preflight calibration is performed in the laboratory using large integrating spheres or hemispheres, and collimators. On-board calibrators are either artificial (typically lamps) or natural (the Sun) light sources and they are used to obtain checks of sensor calibration in flight. The problems with these devices are that they are subject to degradation, which has generated a need for in-flight (vicarious) calibration methods. Vicarious methods determine the absolute calibration utilizing accurately determined at-sensor radiance information and corresponding DNs. The calibration of airborne instruments is simpler than that of spaceborne instruments, because the laboratory calibration can be repeated if necessary. With airborne video systems and spectrometers, laboratory and
vicarious calibration methods are used (Vane et al., 1993; Pellikka, 1998; Moran et al., 2001; Pagnutti et al., 2002; Edirisinghe et al., 2004).

In the case of digital photogrammetric systems, radiometric calibration is a part of the laboratory calibration processing performed by the sensor manufacturers. Generally, only relative calibration is performed; typical parameters include the corrections for the sensitivity of each CCD element, defect pixels, aperture, and vignetting (Schuster and Braunecker, 2000; Diener et al., 2000; Beisl, 2006; Hefele, 2006). In the case of the ADS40, the absolute calibration approach has also been established (Beisl, 2006). For airborne test field calibration of radiometry, reflectance-based vicarious calibration methods utilizing artificial or natural reflectance reference targets are appropriate (e.g., Moran et al., 2001; Pagnutti et al., 2002; Honkavaara et al., 2008).

The Sjökulla test field (Figure 1) of the Finnish Geodetic Institute (FGI) has been used operationally for the calibration and testing of photogrammetric systems since 1994 (Kuittinen et al., 1994; Ahokas et al., 2000; Honkavaara et al., 2007). It contains targets for the calibration of geometry, radiometry, and spatial resolution. Experiments with digital systems were begun in 2004 (Honkavaara et al., 2005, 2006a, 2006b, and 2006c; Markelin et al., 2005 and 2006a). The first radiometric calibration experiments are summarized in this article.

Currently, there does not exist recommendations for the radiometric test field calibration of digital photogrammetric sensors. Furthermore, no empirical quantitative results of sensor radiometric performance studies have been reported in the literature. The objective of this article is to develop a method for test field calibration of radiometry for airborne instruments and to investigate the radiometric performance of three first-generation large format photogrammetric systems. Image radiometry, radiometric properties of digital photogrammetric sensors, and the test field based vicarious calibration method are discussed in the next section. The materials and methods used in the empirical study are then described followed by the results and discussion.

Radiometric Calibration of Digital Photogrammetric Sensors

Image Radiometry

Many factors affect the properties of airborne images. These include the camera, camera settings, system, flight, atmosphere, object, and data post-processing (Hakkarainen, 1991; Read and Graham, 2002; Honkavaara et al., 2008). With regard to image radiometry, the essential issues are the radiance entering the sensor (at-sensor radiance [W/(m² sr nm)], how the sensor quantifies this radiance, and data post-processing.

The radiance entering the sensor is composed of several components: the three most important ones are sunlight reflected from the surface, diffuse skylight reflected from the surface, and sunlight scattered by the atmosphere to the sensor (Schowengerdt, 1997). Additionally, the adjacency components scattering from surrounding objects and multiple atmospheric scattering have an influence on the radiance obtained.

The sensor optics and spectral filters transfer the radiance entering the sensor to the detector focal plane where the image is formed. The electronic signal in a certain band is amplified electronically using appropriate gain and offset values and filtered by the electronic point spread function. Finally, the amplified and filtered signal is sampled and quantized to DNs. In the case of CCD sensors, this process can be modeled using linear functions (Schowengerdt, 1997):

\[ DN_{pb} = K_b L_{pb} + \text{offset}_b, \]

where \( DN_{pb} \) is the gray value, and \( L_{pb} \) is the radiance at pixel \( p \) on band \( b \); \( K_b \) is the linear calibration factor, and \( \text{offset}_b \) is the offset term on band \( b \).

Figure 1. (a) Sjökulla test field, and (b) Portable gray scale in field (Photo by Harri Kaartinen (FGI)). A color version of this figure is available at the ASPRS website: www.asprs.org.
The radiometric properties are manipulated in the post-processing phase. It is important to apply the laboratory calibration data. For applications relying on numerical radiometric and spectral information, the data can be absolutely calibrated. For visual applications gamma corrections and other tonal adjustments are made. Many sensors provide data in 16-bit format, which is often transformed to 8-bit format. If the system collects high-resolution panchromatic data and low-resolution multi-spectral data, the color fusion or pansharpening is a common operation to improve the resolution of multi-spectral data. Finally, the image data is typically also corrected for atmospheric and bidirectional reflectance effects.

Radiometric Laboratory Calibration of Digital Photogrammetric Cameras

Currently, there are three digital large-format sensors available on the photogrammetric market, the multi-head systems Intergraph DMC and Vexcel UltraCam®, and the Leica Geosystems ADS40 pushbroom sensor. The radiometric properties of these sensors are briefly described in the following sections; more details are given in Table 1 and in referenced literature.

**ADS40**

The ADS40 is a single-lens pushbroom sensor with three-line panchromatic stereo and red (R), green (G), blue (B), and near infrared (NIR) multispectral CCD-lines, all installed on the same focal plane (Sandau et al., 2000). Similar CCD arrays with 12,000 pixels are used for the panchromatic and multispectral channels, thus the spatial resolution of the panchromatic and multispectral data is the same. The spectral sensitivities of the ADS40 channels are shown in Figure 2a (nominal values based on box filters and available filter width information). The dynamic range of the ADS40 is at least 12 bits and the A/D-conversion is made using 14 bits. The design principle of the ADS40 has been that it should be suitable both for traditional photogrammetric and remote sensing applications. The radiometric/spectral quality is based on specially designed, narrow, box-shaped, and accurate interference filters, a trichroid beam splitter ensuring that radiation for the three separated color channels will geometrically coincide, temperature stabilization of the focal plate to 20°C, telecentric lens ensuring that radiation reaches the focal plane at right angles, and on accurate radiometric calibration.

The laboratory calibration of radiometry involves the radiometric and spectral parts (Schuster and Braunecker, 2000; Beisl, 2006). Spectral calibration is performed using a spectral measurement unit consisting of a light source and a goniometer; the CCD-line response to a monochromatic light is measured step by step over the whole spectrum. The calibration model for ADS40 is thus:

\[ L = c \cdot DN/t, \]  

where \( t \) is the integration time.

**DMC**

The Intergraph DMC is a multi-head system with eight independent cameras (Hinz et al., 2000). The large-format panchromatic image is composed of four medium-format CCD images collected using four slightly convergent cameras. Four multispectral channels (R, G, B, NIR) are collected using individual nadir-viewing medium-format cameras. The spectral sensitivities of the DMC channels are shown in Figure 2b. The radiometric resolution of CCDs is 12 bits. Final color images are provided either at a low color resolution or high panchromatic resolution. The post-processing is highly automated; the user can only affect the radiometric transformation parameters (LUT generation).

The radiometric calibration of the DMC has two stages: the manufacturing calibration in a laboratory and the LUT generation for each image flight (Diener et al., 2000; Hefele, 2006). The laboratory calibration is carried out using an Ulbricht sphere, and it involves determination of defect pixels, individual sensitivity of each pixel, vignetting, and the influence of aperture and filter. To utilize the calibration data, information on operational conditions (TDI, temperature, aperture, etc.) are stored during the image exposures. The radiometric calibration is applied to the images during the image post-processing phase. The LUT generation can be performed for each photo flight by using an object having similar reflectivity in each band, e.g., asphalt. In the case of panchromatic channels, differences in brightness of the overlapping images are eliminated. Absolute calibration is not discussed in the calibration documentation of the DMC.

### Table 1. Properties of Digital Photogrammetric Sensors

<table>
<thead>
<tr>
<th>Sensor</th>
<th>ADS40</th>
<th>DMC</th>
<th>UltraCam®</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Pushbroom, single-head</td>
<td>Customized</td>
<td>Multi-head</td>
</tr>
<tr>
<td>Array size</td>
<td>PAN: 2 × 12000 (staggered) MS: 12000</td>
<td>PAN: 7168 × 4096</td>
<td>PAN: 4008 × 2672</td>
</tr>
<tr>
<td>Pixel size (µm)</td>
<td>6.5</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>Dynamic range (bit)</td>
<td>&gt;12</td>
<td>12</td>
<td>&gt;12</td>
</tr>
<tr>
<td>Image size (pixels)</td>
<td>PAN: 2 × 12000 (staggered) MS: 12000</td>
<td>PAN: 13824 × 7680</td>
<td>PAN: 11500 × 7500</td>
</tr>
<tr>
<td>f (mm)</td>
<td>62.5</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>FOM</td>
<td>–</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Frame rate (Hz)</td>
<td>200 to 800 (line rate)</td>
<td>0.5</td>
<td>1.3</td>
</tr>
<tr>
<td>TDI</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

PHOTOGRAMMETRIC ENGINEERING & REMOTE SENSING December 2008 1489
UltraCamD (Leberl and Gruber, 2003) consists of four optical cones for high-resolution panchromatic channels and four cones for multi-spectral (R, G, B, and NIR) channels. The panchromatic large-format image is produced from nine individual CCDs. Each multispectral cone is equipped with medium-format CCDs. The spectral sensitivities of the channels are shown in Figure 2c. The radiometric resolution of CCDs is 12 bits or more, analog-to-digital conversion is made with 14 bits and images are stored in a 16-bit format. As in the case of DMC, the color images are provided either in high panchromatic resolution or low color resolution.

User interaction is limited to the final phases of post-processing when some radiometric parameters (gamma settings, cut out of the darkest/lightest DN, 16- or 8-bit radiometric resolution, pansharpening) can be given.

The radiometric laboratory calibration is performed at each sensor for five different aperture settings using a series of 60 flat-field images (ULTRACAMD, 2004). Two normal light lamps with known spectral illumination curves illuminate the flat field. These images are used to calculate the specific sensitivity of each pixel to compensate for local and global variations in sensitivity. The results of this process are sensitivity tables for each sensor and aperture setting and reports of outlier pixels. Radiometric corrections are applied during the post-processing phase. This calibration provides a uniform response for all the pixels in each band, thus it can be regarded as relative calibration. The calibration documentation does not discuss absolute radiometric calibration.

Test Field-based Vicarious Calibration Method

For airborne sensors, a feasible vicarious calibration approach is reflectance-based test field calibration. In this method, the at-sensor radiance is predicted by measuring the reflectance of a ground target, modeling the atmosphere using a radiative transfer code and measured atmospheric properties, and then propagating the ground-target radiance through the modeled atmosphere (Dianguirard and Slater, 1999; Pagnutti et al., 2002; Pagnutti et al., 2003; Biggar et al., 2003; Edirisinghe et al., 2004; USGS, 2004).

A procedure for the photogrammetric sensor test field calibration is shown in Figure 3; details of this process are discussed below.

Accurate reference reflectance targets are the prerequisite for radiometric calibration. The targets should be calibrated, and they should have uniform reflectivity with respect to viewing direction and wavelength (Pagnutti et al., 2002). In the spaceborne case, typical reference reflectance targets include test fields, stable deserts, clouds, glitter, and lunar observations (Dianguirard and Slater, 1999; Biggar et al., 2003). For the airborne systems,
The inputs for radiometry analysis are the DN statistics and analysis of radiometric properties, which is discussed in the following section.

In order to eliminate atmospheric effects and to take illumination conditions into account, the test site should possess the ability to measure the reflectance of the reference targets and properties of the atmosphere between the target and the sensor at the time the scene is imaged.

After image collection, the image orientations are determined using standard either direct or indirect photogrammetric methods.

The reference reflectance values are transformed to at-sensor radiances using radiative transfer codes, such as MODTRAN (Berk et al., 2003).

The measurement process of the reflectance targets includes their identification and the calculation of image statistics and necessary angular data. The location accuracy of one pixel is usually obtained if the target locations are measured using GPS techniques and image orientations are determined with standard methods; further enhancement is obtained using automatic or interactive measurement methods. For the at-sensor radiance calculation, necessary observation angles are the solar zenith angle, the observer azimuth, and the respective azimuths, which are determined from target location, sensor orientation, and illumination information. Key statistics to be measured from the images are averages, standard deviations, medians, minimums and maximums of DNs in appropriate image windows.

The last phase of the calibration method is analysis of radiometric properties, which is discussed in the following section.

**Analysis of Radiometric Properties**

The inputs for radiometry analysis are the DN statistics and the at-sensor radiance data of the reflectance reference targets. The field calibration process should include system characterization in addition to calculation of the absolute calibration coefficients. The key properties to be analyzed include linearity, dynamic range, noise, uniformity, channel sensitivities, and the stability of the system.

Absolute calibration parameters are calculated using an appropriate model, which in the case of linear sensors, such as CCD-sensors, is the linear model (Equation 1). With reflectance targets it is normally feasible to use average values of radiance and image measurements on a larger than one-pixel area, thus the calibration model to transform the DNs to radiances is:

\[ L_{tb} = \text{cal\_gain}_b \cdot D_{b,t} + \text{cal\_offset}_b, \]

where \( \text{cal\_gain}_b \) and \( \text{cal\_offset}_b \) are the parameters of the linear calibration model for band \( b \). \( L_{tb} \) is the average at-sensor radiance value, and \( D_{b,t} \) is the average DN calculated in an appropriate image window for target \( t \) for band \( b \).

The sensor linearity can be evaluated by presenting the measured DNs as the function of the reference at-sensor radiances or reflectances, and by analyzing the fit of the linear model. Inaccuracies of sensor and many image-processing steps, e.g., gamma correction, can result in non-linear change of the DNs.

The dynamic range (DR) of the sensor is determined by the logarithm of the ratio of the saturation and noise levels: \( DR = 20 \log(V_{sat}/V_{noise}(RANS)) \) (Graham and Koh, 2002). With the field calibration it is appropriate to evaluate how large an object reflectance range the sensor can measure without saturation. The reference targets should preferably cover a large reflectance range, at least 5 to 70 percent.

The reflectance-range analysis can be supplemented by a histogram analysis of the entire image content.

The noise-level can be evaluated, and channel sensitivity is assessed by comparing DN responses of various channels to certain at-sensor radiances.

To assess stability, calibration time-series over one day and over a longer period of time should be evaluated.

**Materials and Methods**

**Test Flights**

Extensive test flights with digital photogrammetric cameras the UltraCam, the DMC, and the ADS40 were carried out at the FGI Sjökulla test-field in 2005 to 2006 (Figure 1). The test flights were designed to enable complete system calibration of geometry, spatial resolution, and radiometry (Honkavaara et al., 2008). The radiometric properties of each system are analyzed in this article. The image data is briefly described below and more details are given by Honkavaara et al. (2006a, 2006b, and 2006c) and in Table 2.

The DMC mission was performed early September 2005. In this study, data from test flights at 500 m and 800 m flying altitudes are used. Data from flights at two altitudes were collected consecutively at midday. The objective of the mission was to evaluate the operational aspects and accuracy of the DMC, and it was performed with a rented camera and an experienced operator. Images were processed using DMC Post Processing Software, v. 4.4.

The ADS40 mission took place at the end of September 2005 at midday. The objective of the campaign was to test the new digital camera system of the Estonian Land Board. Flying altitudes were 1,500 m and 2,500 m. In this particular system, the color lines are 16° off-nadir, the NIR line is 2° off-nadir, and the panchromatic lines are 0°, 14.2°, and 28.4° off-nadir. A photogrammetric recording mode was used, which means that small batches of collected data are transformed to the 8-bits DN range and then JPEG-compressed; the data is recovered afterwards. During the study it became apparent that this mode was not optimal for radiometric evaluation; this issue is further discussed in the results section.

Image blocks with 480 m and 940 m flying altitudes were collected by the UltraCam, in July 2006. Flights were performed on different days at midday. The images were post-processed using UltraCam, Office Processing Center software (version 2.2.0). The flight was part of an operational system calibration flight for a mapping company.

The DMC and ADS40 were installed in the Rockwell 690A Turbo Commander (OH-ACN) belonging to the National Land Survey of Finland, and the UltraCam was installed in the...
The reflectance properties of the test targets were measured in the laboratory and in the field using an automatic field goniospectrometer FIGIFIGO (Finnish Geodetic Institute’s Field Gonio-spectrometer; Suomalainen, 2006). It consists of an ASD Field Spec Pro FR spectrometer with a spectral range of 350 to 2,500 nm, a motor-driven zenith arm with a length of 250 cm tilting ±70° from zenith, a 360° rotating azimuth ring for laboratory use, a GPS and electronic compass for field use, and a control computer. The sensor footprint diameter was about 10 cm at nadir. In the laboratory, the targets were illuminated using an Oriel QTH light source of 800 W. The measurements were normalized against a Labsphere Spectralon white reference standard. Some degradation, footprints, folds, unevenness, and other disturbances were visible, but a clean and flat spot was selected for measurement. For error analysis, a subset of measurements was taken at different places of targets. The instrumental accuracy is estimated to be about 1 to 3 percent. Another error (2 to 10 percent) may be caused by illumination: outside by varying atmosphere, and inside by a slightly non-ideal light spot. The illumination was monitored using an external pyranometer and re-measuring the Spectralon after each measurement set of about two minutes, with an acceptance threshold of 5 percent.

The reflectances measured at nadir with an illumination angle of 56° from the vertical and integrated for DMC spectral sensitivities are shown in Figure 4. These values are relatively close to the designed values. The targets have a slight dependence on the wavelength (Figure 5). The study showed a fairly strong dependence on the viewing direction. Especially in the forward direction each target brightens clearly, but if one can limit observations to a maximum of about 15° forward, 30° backward or sideways, the effect remains at under 10 percent. The effects of the inaccuracies of the targets (manufacturing inaccuracies, effects of dirt and use) are evaluated to be less than 10 percent of the reflectance value based on the measurements performed in different parts of the targets. A limitation of the targets is that when they are spread over rugged terrain they are not quite flat. If the radiometric and spatial resolution of the sensor is good enough, this appears in the images as dark and bright areas (Figure 6). The topographic variations are apparent on the images standard deviations caused by the topography were 2 to 5 percent of the DN. An experiment was conducted to compensate for the topographic effects by using a low pass filter.
filtering approach, but they could not be eliminated with this procedure. The estimated absolute error of the reflectance reference values is 5 to 20 percent; the relative error is 5 to 10 percent. For future use, it is necessary to calibrate the gray scale carefully. More details on the gray scale analysis are given by Markelin et al. (2006b).

In this study, the limitations of the reflectance reference targets were taken into account in the analysis. To avoid problems with directional behavior, only the images where the targets were close to the nadir were used. To compensate for the effects of non-uniformity and topographic variations, average values calculated in image windows corresponding an area of 2 m × 2 m in object space (from 6 × 6 to 80 × 80 pixels in the image) were used instead of individual pixels.

**At-sensor Radiance Calculation**

MODTRAN4 radiative transfer code (Version 3.1; Berk et al., 2003) and MODO (Version 3.0.6; Schläpfer and Nieke, 2005), which is a graphical front-end to the MODTRAN4, were used to calculate the at-sensor radiances. The closest weather stations were located at a distance of 20 km and sounding information was measured at a distance of 100 km from the test field. Because of the long distance, in this study the default atmospheric models of MODTRAN4 were applied. The at-sensor radiances were calculated for the target spectral profile at nadir (Figure 5), the rural mid-latitude summer atmospheric model with the available visibility information (Table 2) and the spectral sensitivity model of the sensor (Figure 2).

**Radiometric Calibration Method**

The method established in the previous section was used in the radiometric analysis. Reference targets (gray scale) are described in the Reference Reflectance Targets subsection, and the details of the test imagery are given in the Test Flights subsection. At-sensor radiances were calculated as described in the previous subsection.

The radiometric analysis procedure was previously described. In the absolute calibration, the entire linear model was used (Equation 3); the significant parameters were selected using the t-test with 95 percent confidence level. The linearity was studied by evaluating the linear fit between the target DNs and at-sensor radiances. The dynamic

---

**Figure 4. Reflectance of the targets measured at the laboratory (nadir observations, illumination angle 56° from nadir).**

**Figure 5. Reflectance spectra at nadir with illumination angle of 56° from nadir for eight reference reflectance targets.**

**Figure 6. 30 percent reflectance target on PAN-images: (a) DMC, GSD = 5 cm (mean_DN = 1517, stdev_DN = 77); (b) DMC, GSD = 8 cm (mean_DN = 1343, stdev_DN = 51); (c) DMC, GSD = 25 cm (mean_DN = 1640, stdev_DN = 55); and (d) RC20, GSD = 4 cm (mean_DN = 3873, stdev_DN = 52 (12-bit scanning)). Images are radiometrically adjusted for visualization.**
range was considered by evaluating the sensors response to the gray scale and by analyzing the statistics of the image histograms (minimums, maximums, averages, standard deviations). The differences in sensitivity at various bands were analyzed by comparing the sensor response to the calculated target at-sensor radiance. The results of the linearity and dynamic range evaluation can be considered reliable, while the results of the sensitivity analysis and absolute calibration should be considered as indicative due to the approximate atmospheric modeling. Noise, stability, and uniformity evaluation were not possible due to insufficient accuracy and calibration of reference targets and insufficient atmospheric modeling.

Results

At-sensor Radiances

Examples of the calculated at-sensor radiances as the function of the target reflectances are shown for the DMC (Figure 7a) and ADS40 (Figure 7b). The at-sensor radiance was calculated for both systems at a flying altitude of 1,520 m using similar atmospheric model (mid-latitude summer, rural area, with horizontal visibility of 26 km). The total radiance is composed of several elements as discussed in the Image Radiometry subsection. Because of this, various channels have considerably different at-sensor radiance values, even though the target reflectance is fairly uniform. The at-sensor radiance is clearly lower for the NIR channel, which is caused by the decreasing effect of atmospheric scattering at the longer wavelengths (less "blue scattering"). Differences in at-sensor radiances for ADS40 and DMC are caused by different spectral sensitivities; the differences were greatest for the panchromatic and blue channels.

Linearity

The linearity of the sensors can be evaluated from the DN-plots (Figure 8, Figure 9, Figure 10) and the absolute calibration results (Table 4, Table 5).

The DMC results show that the linearity of all the channels was good (Figure 8, Table 4). The curvature of the green channel was caused by saturation of the brightest target. The R² of the line fit was approximately 0.99. The results for 500 and 800 m flying altitudes were similar, because the forward motion compensation ensured that sufficient exposure times could be used.

For the ADS40, only the five darkest targets were included in the evaluation, because the photogrammetric recording mode (16-bit to 8-bit transformation and JPEG compression of small image patches) did not provide reasonable image quality if the image patch had large differences in contrast (at Sjökulla background: 5 percent and target: ~45 percent). This appeared as a striping effect and deteriorated radiometric resolution as shown in Figure 11a. The results (Figure 9, Table 5) show that the linearity of all the channels was good. The R² of the line fit was approximately 0.94 to 0.99. With regard to the linearity aspects, the two flying altitudes gave similar results.

For the UltraCam, only four targets were available (5 percent, 25 percent, 45 percent, and 70 percent). The...
Figure 9. ADS40: raw DNs as a function of the at-sensor radiance: (a) PAN and MS GSD = 15 cm, and (b) PAN and MS GSD = 25 cm (Reflectance targets 5 to 30 percent, except 5 to 70 percent for NIR).

Figure 10. UltraCamD: raw DNs as a function of the at-sensor radiances: (a) PAN GSD = 4 cm, MS GSD = 12 cm, and (b) PAN GSD = 8 cm, MS GSD = 24 cm (Reflectance targets 5 percent, 25 percent, 45 percent and 70 percent).

<table>
<thead>
<tr>
<th>Table 3. Image Histogram Statistics: DN Average, Standard Deviation, Minimum, Maximum and Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>PAN</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Red</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Green</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Blue</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>NIR</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
results (Figure 10) indicated good linearity. In the case of u4_g8-data the curvature of the PAN and red channels at the brightest tarps was caused by saturation. Two flying altitudes were collected in different days on different conditions causing differences in behavior.

For the DMC and the ADS40, when the full set of targets was used, similar nonlinearities at the darkest tarp values appeared. These were caused by inaccuracies in the reference target measurements. Empirical evaluation indicated 10 percent relative error for the 20 percent tarp.

**Dynamic Range**

The dynamic range was evaluated from two directions: using the gray scale with 5 to 70 percent reflectance range and by measuring the histograms of the entire images. Comparison of the image histogram data (Table 3) and the reference target statistics (Figure 8, Figure 9, and Figure 10) showed that there were lower and higher DNs in the scene than in the gray scale for most of the sensors and channels. The tarps had the brightest DNs only when the tarps were saturated (DMC: green channel, UltraCamD, u4_g8-block: red and PAN channels). Minimum DNs always appeared on the scene. Visual evaluation of the data showed that the darkest values were located in shadows and water areas, while the brightest values were located on roofs of buildings. In the case of NIR-images, vegetation also gave very bright values. The image histogram evaluation (Table 3) for the DMC showed that at each channel the 12-bit dynamic range was used entirely (DN minimums < 70, maximums 4095). Despite this, the images were not seriously saturated.

In the case of ADS40, the analysis of the image histograms (Table 3) showed that the dynamic range of images was 10 bits for the red and green channels, 9 bits for the blue channel, close to 11 bits for the NIR channel and almost 13 bits for the PAN channel. The results for the PAN-channel indicated that the dynamic range of the sensor was more than 12 bits, as expected, but due to the sensor sensitivity properties and other mission conditions, this range could not be reached for multi-spectral channels (see also the next section).

For the UltraCam, the image histogram evaluation together with the gray-scale analysis indicated dynamic range of up to 12.7 bits.

**Sensitivity**

For the DMC, the sensitivity of the PAN, red, and blue channels appeared to be similar, while the green and NIR-channels appeared to be clearly more sensitive than these three channels (Figure 8). For instance, the sensitivity of the green channel was 1.5 times greater than that of other color channels (this value should not be taken as an absolute value because of the limitations in atmospheric modeling). The sensitivity of the green channel was a problem, because the data was saturated with greater than 50 percent-object reflectance. Two flying altitudes performed in a similar way.

In the case of ADS40, the sensitivity of the multispectral channels was clearly lower than the sensitivity of the panchromatic channels (Figure 9). For instance, the sensitivity of the PAN channel was 7 times greater than that of RGB-channels. The reason for this is that narrower filters are used for the multi-spectral channels. The NIR-channel was

---

**Table 4. DMC Absolute Calibration Results (Parameters, Standard-Deviations, R², and \( \hat{a}_0 \): Standard Error of Unit Weight (in Radiance [W/(m² sr nm)]))**

<table>
<thead>
<tr>
<th>Height</th>
<th>Band</th>
<th>cal_gain</th>
<th>cal_offset</th>
<th>( \hat{a}<em>{cal</em>{gain}} )</th>
<th>( \hat{a}<em>{cal</em>{offset}} )</th>
<th>R²</th>
<th>( \hat{a}_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>H = 500 m</td>
<td>PAN</td>
<td>2.5E-04</td>
<td></td>
<td>2.8E-06</td>
<td></td>
<td>0.997</td>
<td>2.4E-03</td>
</tr>
<tr>
<td></td>
<td>Red</td>
<td>2.1E-04</td>
<td></td>
<td>2.1E-06</td>
<td></td>
<td>0.998</td>
<td>2.3E-03</td>
</tr>
<tr>
<td></td>
<td>Green</td>
<td>1.6E-04</td>
<td></td>
<td>2.7E-06</td>
<td></td>
<td>0.999</td>
<td>3.5E-03</td>
</tr>
<tr>
<td></td>
<td>Blue</td>
<td>2.4E-04</td>
<td></td>
<td>2.8E-06</td>
<td></td>
<td>0.996</td>
<td>3.3E-03</td>
</tr>
<tr>
<td></td>
<td>NIR</td>
<td>2.2E-04</td>
<td>-4.7E-03</td>
<td>3.3E-06</td>
<td>8.4E-04</td>
<td>0.999</td>
<td>1.2E-04</td>
</tr>
<tr>
<td>H = 800 m</td>
<td>PAN</td>
<td>2.8E-04</td>
<td>-4.8E-03</td>
<td>6.0E-06</td>
<td>1.7E-03</td>
<td>0.997</td>
<td>2.5E-03</td>
</tr>
<tr>
<td></td>
<td>Red</td>
<td>1.9E-04</td>
<td></td>
<td>1.8E-06</td>
<td></td>
<td>0.998</td>
<td>2.1E-03</td>
</tr>
<tr>
<td></td>
<td>Green</td>
<td>1.4E-04</td>
<td></td>
<td>2.2E-06</td>
<td></td>
<td>0.994</td>
<td>3.2E-03</td>
</tr>
<tr>
<td></td>
<td>Blue</td>
<td>2.0E-04</td>
<td></td>
<td>2.2E-06</td>
<td></td>
<td>0.997</td>
<td>3.0E-03</td>
</tr>
<tr>
<td></td>
<td>NIR</td>
<td>1.9E-04</td>
<td>-8.8E-03</td>
<td>2.5E-06</td>
<td>8.1E-04</td>
<td>0.999</td>
<td>1.1E-03</td>
</tr>
</tbody>
</table>

**Table 5. ADS40 Absolute Calibration Results (Parameters, Standard-Deviations, R², and \( \hat{a}_0 \): Standard Error of Unit Weight (in Radiance [W/(m² sr nm)]))**

<table>
<thead>
<tr>
<th>Height</th>
<th>Band</th>
<th>cal_gain</th>
<th>cal_offset</th>
<th>( \hat{a}<em>{cal</em>{gain}} )</th>
<th>( \hat{a}<em>{cal</em>{offset}} )</th>
<th>R²</th>
<th>( \hat{a}_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>H = 1500 m</td>
<td>PAN00</td>
<td>7.3E-05</td>
<td>-9.4E-03</td>
<td>3.4E-06</td>
<td>2.6E-03</td>
<td>0.994</td>
<td>1.8E-03</td>
</tr>
<tr>
<td></td>
<td>Red</td>
<td>3.6E-04</td>
<td>-6.7E-03</td>
<td>1.7E-05</td>
<td>2.0E-03</td>
<td>0.994</td>
<td>1.5E-03</td>
</tr>
<tr>
<td></td>
<td>Green</td>
<td>3.7E-04</td>
<td></td>
<td>9.9E-06</td>
<td></td>
<td>0.982</td>
<td>2.6E-03</td>
</tr>
<tr>
<td></td>
<td>Blue</td>
<td>4.7E-04</td>
<td></td>
<td>1.7E-05</td>
<td></td>
<td>0.960</td>
<td>3.0E-03</td>
</tr>
<tr>
<td></td>
<td>NIR</td>
<td>2.4E-04</td>
<td>-0.2E-02</td>
<td>7.7E-06</td>
<td>1.0E-03</td>
<td>0.997</td>
<td>6.4E-04</td>
</tr>
<tr>
<td>H = 2500 m</td>
<td>PAN00</td>
<td>7.7E-05</td>
<td>-1.1E-02</td>
<td>3.6E-06</td>
<td>2.7E-03</td>
<td>0.994</td>
<td>1.8E-03</td>
</tr>
<tr>
<td></td>
<td>Red</td>
<td>4.0E-04</td>
<td>-8.1E-03</td>
<td>1.9E-05</td>
<td>2.2E-03</td>
<td>0.993</td>
<td>1.6E-03</td>
</tr>
<tr>
<td></td>
<td>Green</td>
<td>4.5E-04</td>
<td></td>
<td>8.1E-03</td>
<td></td>
<td>0.963</td>
<td>4.6E-03</td>
</tr>
<tr>
<td></td>
<td>Blue</td>
<td>4.8E-04</td>
<td></td>
<td>9.4E-03</td>
<td></td>
<td>0.994</td>
<td>1.5E-03</td>
</tr>
<tr>
<td></td>
<td>NIR</td>
<td>2.5E-04</td>
<td>-1.3E-02</td>
<td>8.8E-06</td>
<td>1.2E-03</td>
<td>0.996</td>
<td>6.9E-04</td>
</tr>
</tbody>
</table>
more sensitive than the red, green, and blue channels, probably due to the fact that the radiation for the color channels is provided by a trichroid filter, which splits the beam into three parts, while the data for the NIR-channel is provided by its own filter. The sensitivity of the 15 cm GSD imagery was lower than the sensitivity of the 25 cm GSD imagery. This was caused by a shorter integration time; decreasing the flying speed enough was not possible for the aircraft used.

For the UltraCam, the sensitivity of the red and NIR-channels appeared to be fairly similar, while the green channel was slightly less sensitive. The blue channel was clearly the least sensitive and the panchromatic channel was the most sensitive; the PAN-channel was 2.5 times more sensitive than the blue channel. The system appeared to be clearly more sensitive at an altitude of 940 m and also saturation appeared, which suggest that the camera settings were probably less than optimal.

**Absolute Calibration**
The absolute calibration results for the DMC are given in Table 4. Generally, only the linear term was significant; the offset term was only significant for the NIR-channel at both altitudes and for PAN channel at 800 m altitude. The differences between the linear terms at altitudes of 500 m and 800 m were 6 to 16 percent. One possible reason for these small differences between the two flying altitudes is errors in the atmospheric modeling.

The calibration coefficients for the ADS40 are given in Table 5. It appeared that for most of the channels, the full linear model with offset and linear terms was required. The expectation for the ADS40 was that only the linear term is needed (Beisl, 2006), thus the result contradicts expectations. Possible explanations for this behavior are errors in the atmospheric modeling or the difference between the laboratory and system calibration. For the two flying altitudes, differences between the significant gain parameters were less than 10 percent and for offset parameters less than 20 percent. Again, the one feasible explanation for the small difference between two flying heights is inappropriate atmospheric modeling.

**Discussion**

**Radiometric Properties of Digital Sensors**
The presented results show that the digital photogrammetric cameras tested had a high radiometric performance. A very convenient feature of the systems is the linearity, which makes it possible to transform the DNs to reflectance by relatively simple means. It is sufficient to use two accurate reference targets to calibrate the two-parameter linear model. The high radiometric resolution throughout the dynamic...
range, which improves image interpretability and measurability, is another attractive feature (Figure 6 and Figure 11).

In most cases, the systems managed to measure the 5 to 70 percent reflectance range of the gray scale; the brightest tarps were saturated in only some cases. The DMC utilized the entire 12-bit dynamic range, while the ADS40 and the UltraCam, appeared to have close to a 13-bit dynamic range. Especially in the cases of the DMC and the UltraCam, a risk of saturation at bright values appeared, while for the ADS40 the maximum dynamic range could not be reached for all the channels due to problems with sensitivity.

Sensitivity and differences in sensitivity among various channels are one potential source of problems in digital systems. Sensitivity differences cause problems, especially if tuning the sensitivity of various channels is impossible, as in single-lens systems or in Beyer filter-based systems. In some cases, too low sensitivity also reduces the image quality. All the systems had some differences in channel sensitivities. The ratios of the most and least sensitive channels were 1.5 for the DMC, 7 for the ADS40, and 2.5 for the UltraCam. the ratio obtained in this study should not be taken as absolute values because of the inappropriate atmospheric modeling.

In many test flights, analog images were collected simultaneously. The radiometric performance of the digital systems clearly outperformed those of the analog systems. Analysis of the analog sensor response showed the expected logarithmic behavior, thus to absolutely calibrate analog sensors, more reference targets are needed to model the logarithmic curve accurately. The analog system gave the best radiometric resolution with object reflectance lower than 25 percent; with higher reflectance values mainly sensor noise was detected (Figure 6 and Figure 11a). All the analysis was disturbed by the noise caused by granularity. Markelin et al. (2005 and2006a) give more results of studies with analog sensors.

In the evaluations, probably the most serious limitation was the low sensitivity of the ADS40 multispectral channels, which was partially caused by small pixel size, narrow interference filters, and beam splitters. Obviously, the optimum performance for this system is obtained in good illumination conditions using the lowest speed aircraft possible, which is not possible in normal photogrammetric applications. The optimum performance cannot be reached.

In this study only the sensor properties were analyzed. Further topics of research are the analysis of various end products after the image post-processing, which are important issues for the users of the sensors.

Many types of sensors are available on the airborne imaging markets. Some of these sensors are specially designed for radiometric calibration. For these systems the test fields can be used for system characterization and the development of appropriate processing models.

Conclusions

In this article, a method for radiometric calibration of digital photogrammetric systems in a test field was described and the radiometric properties of a digital large format sensors the Leica Geosystems ADS40, the Intergraph DMC, and the Vexcel UltraCam, were studied. The analysis included evaluation of linearity, dynamic range, sensitivity, and absolute calibration.

The results proved that the radiometric properties of the tested sensors were in accordance with expectations. All the sensors had linear response if not saturated and the dynamic range was 12 to 13 bits at best. The sensitivity appeared to be the most serious problem of the tested systems; in the case of the ADS40 the sensitivity of the color
channels appeared to be too low, while with the DMC and the UltraCam, too high sensitivity was detected in some cases. The linear model either with slope or slope and offset terms was appropriate for absolute calibration for all tested systems.

Radiometric test field calibration and characterization provides important information on sensor performance for sensor users even if the test site does not fulfill the strictest requirements. In the fully equipped test site, the accurate absolute radiometric calibration factors can be determined and the sensor can reliably characterized. The advantages of field calibration are that when the appropriate infrastructure has been established, the calibration and characterization can be performed with little effort, without the need for unmounting of the camera and shipping it to the laboratory of the system manufacturers. In the test field the calibration is performed in the same conditions as the operational image data collection. Furthermore, all the systems, even the small format ones, can be calibrated using similar methodology. International standardization is needed to make the test field calibration processes widely accepted and used. However, the test field calibration is only supplementary calibration method; the most accurate pixel wise and spectral calibration has to be performed in laboratory.

Better radiometry improves the use of remote sensing methods with aerial images. Typical processes developed for spaceborne data cannot be implemented with very-high-resolution aerial images. However, in order to be able to develop practical solutions improved radiometric calibrations are needed.

Acknowledgments

The financial support of the Ministry of Agriculture and Forestry of Finland is gratefully acknowledged. Authors are thankful to Blom ASA, the Estonian Land Board, and the Aerial Image Center of National Land Survey of Finland for participating in the sensor testing campaigns and providing image materials for the study. The entire Department of Remote Sensing and Photogrammetry of the Finnish Geodetic Institute is acknowledged for the assistance in the fieldwork.

References

Beisl, U., 2006. Absolute spectroradiometric calibration of the ADS40 sensor, International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 36(B1), unpaginated CD-ROM.


(Received 29 November 2006; accepted 05 March 2007; revised 14 May 2007)