Radiometric Performance of Digital Image Data Collection – A Comparison of ADS40, DMC, UltraCamD and Emerge DSS

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Contents

- Introduction
- Image radiometry
- Radiometry of digital photogrammetric cameras
- Empirical results
- Conclusions
Introduction

- Radiometry: Measurement of electromagnetic radiation in wavelength range 0.01-1000 μm
- Digital number (DN)
- Radiometric properties of CCD sensors: linearity, low noise level, stability, good resolution, multispectral data
- Application of digital photogrammetric images
  - Improved performance and automation potential of conventional applications
  - New applications, quantitative use: multispectral classification, monitoring, change detection, ...
- Rigorous radiometric processing new issue for photogrammetric processing lines -> efficient radiometric processing chains needed to process huge amounts of photogrammetric data
- Radiometric performance of photogrammetric sensors is evaluated from public literature and empirically

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Image radiometry

DMC orthophoto mosaic

- Factors influencing DN
  - Atmosphere
  - Illumination
  - Object
  - Sensor and system
Influence of atmosphere and illumination

Atmosphere
- Molecular and aerosol scattering
- Absorption by gases (water vapor, ozone...)

Major radiation components
- A Direct component
- B Skylight
- C Path scattered radiance

Influence of atmosphere and illumination

Atmosphere
- Molecular and aerosol scattering
- Absorption by gases (water vapor, ozone...)

Major radiation components
- A Direct component
- B Skylight
- C Path scattered radiance

Object properties
- Reflectance as the function of the wavelength
- BRDF – Bidirectional Reflectance Distribution Function: Object reflectance as the function of the illumination and observation angles

Reflectance spectra
- Dry grass
- Seawater (open)
- Melting snow
- Pine

Digital photogrammetric sensors
Sensor and system

- Sensor: construction, parameters, quality, calibration
- Sensor settings: exposure, aperture, ...
- Post processing

Camera model

\[
E^i_{\lambda}(x, y) = \frac{\pi r_0(\lambda)}{4N^2} L_{\lambda}(x, y)
\]

\[
s_b(x, y) = \int_{\lambda_{\min}}^{\lambda_{\max}} R_b(\lambda) E^i_{\lambda}(x, y) d\lambda
\]

\[
e_b(x, y) = \frac{\tau_{\max}{\beta_{\max}}}{\tau_{\min}{\beta_{\min}}} s_b(\alpha, \beta) PSF (x - \alpha, y - \beta) d\alpha d\beta
\]

Sensor parameters
- Optics transmittance
- F-number
- Spectral sensitivity
- CCD pixel size
- PSF
- A/D conversion
- Gain and offset
Sensor/system radiometric calibration

- **Parameters**
  - Relative pixel wise calibration: normalize output of all detectors to the similar level
    - sensitivity of each pixel, defect pixels, light falloff, dark current
  - Spectral response
  - Absolute calibration (radiometric response): relationship between the incoming radiance and DN
    \[
    \text{Radiance} = \text{cal\_gain} \times \text{DN} + \text{cal\_offset}
    \]
  - Quality evaluation (linearity, uniformity, radiometric accuracy, dynamic range, sensitivity, noise, stray light, MTF, polarization...)

- **Methods**
  - Laboratory calibration using Integrating spheres/flat fields, MacBeth color targets, mono-chromators, calibrated light sources
  - In-flight calibration using lamps and/or reflective panels
  - Vicarious test field system calibration using calibrated reflectance targets, atmospheric observations, ...

Radiometric calibration matrix

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Laboratory</th>
<th>(In-flight)</th>
<th>Test-field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel sensitivity</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Light falloff</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Dark current</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Spectral response</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiometric response</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Camera characterization</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>System characterization</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

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### Radiometric post processing

- Provide comparable DNs by eliminating effects by sensor/system, illumination, atmosphere, object anisotropy
- Image enhancement

<table>
<thead>
<tr>
<th></th>
<th>Visual</th>
<th>Classical remote sensing</th>
<th>BRDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>System correction -&gt;</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>uniform DN response to constant radiation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absolute radiometric correction -&gt; object reflectance</td>
<td>(x)</td>
<td>(x)</td>
<td>x</td>
</tr>
<tr>
<td>DN -&gt; Radiance transformation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atmospheric correction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-Physical</td>
<td>x</td>
<td>x</td>
<td>(x)</td>
</tr>
<tr>
<td>Physical</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Reflectance calibration</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>BRDF correction</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Relative radiometric correction -&gt; corrected DN</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Other: pan-sharpening, MTFC, noise removal, tonal adjustments (e.g. gamma correction), 16-&gt;8 bit transformations</td>
<td>x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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### Digital photogrammetric sensors

- **DMC**
  - Intergraph, 2007

- **UltraCam**
  - Microsoft, 2007

- **ADS40**
  - Leica Geosystems, 2007

- **DSS**
  - Applanix, 2007

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## Sensor parameters

<table>
<thead>
<tr>
<th></th>
<th>ADS40 1st/2nd</th>
<th>DMC</th>
<th>UltraCamD/ UltraCamX</th>
<th>DSS 301/322/349</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS-CCD size (k)</td>
<td>12</td>
<td>3x2</td>
<td>4x3/ 4.8x3.1</td>
<td>4x4/ 5.5x4 / 7.2x5.4</td>
</tr>
<tr>
<td>Pixel size (μm)</td>
<td>6.5</td>
<td>12</td>
<td>9 / 7.2</td>
<td>9/ 9/ 6.8</td>
</tr>
<tr>
<td>A/D conversion (bit)</td>
<td>14</td>
<td>12</td>
<td>14 /</td>
<td>12</td>
</tr>
<tr>
<td>N channels</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>FOV (Along/across)</td>
<td>64/14.2, 2</td>
<td>69/42</td>
<td>65/46</td>
<td></td>
</tr>
<tr>
<td>TDI</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Pan sharpening ratio</td>
<td>no</td>
<td>4.8</td>
<td>3.6 / 3</td>
<td>no</td>
</tr>
</tbody>
</table>

---

## Spectral response

### Spectral response graphs

- **ADS40**
  - PAN
  - R
  - G
  - B
  - NIR

- **DMC**
  - PAN
  - R
  - G
  - B
  - NIR

- **UltraCamD**
  - PAN
  - R
  - G
  - B
  - NIR

- **DSS**
  - PAN
  - R
  - G
  - B
  - NIR

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Radiometric calibration

- **ADS40**
  - flat field by NIST traceable Ulbricht sphere: relative calibration, radiometric response, DSNU, sensor characterization
  - NIST traceable spectral measurement unit: spectral response
  - In flight: DSNU

- **DMC**
  - flat field by Ulbricht sphere: relative calibration for each TDI, aperture, and temperature settings.
  - LUT generation for white balancing in post processing

- **UltraCamD**
  - by 60 flat field images using normal light lamps with known spectral illumination: relative calibration for each sensor and aperture setting

- **DSS**
  - MacBeth color targets, integrating spheres, and optimization software: pixel and column defects, dark signal, and pixel level gain corrections.

Radiometric post-processing

- **ADS40**: Chain for reflectance image generation
  - DN-> At-sensor radiance transformation using laboratory calibration data
  - Atmospheric correction: Modified dark pixel substraction method
  - Reflectance calibration
  - Semi empirical BRDF correction

- **DMC**
  - Application of laboratory calibration data
  - White balancing, 12 bit -> 8 bit conversions, pansharpening

- **UltraCamD**
  - Application of laboratory calibration data
  - 14 bit -> 8 bit conversions, pansharpening

- **DSS**
  - Application of laboratory calibration data
  - Image enhancements: image sharpening, color balance, 12 bit -> 8 bit conversions, Further processing by Inpho software
Reported problems

- ADS40
  - Limitations in dynamic range due to short integration times
  - Unrealistic colorimetric content due to separate spectral channels
  - Displacement of one of the MS-channels
- DMC
  - Color artifacts due to PAN-sharpening
  - Electronic TDI
- UltraCamD
  - Color artifacts due to PAN-sharpening
  - Color artifacts caused by the lens quality
  - Electronic TDI
- DSS
  - Reduced resolution and color artifacts due to mosaic filtering
  - Chromatic aberrations
  - Missing FMC of the DSS

Empirical tests at Sjökulla test field
Test flights

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Date</th>
<th>Flying height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UltraCamD</td>
<td>11.10.2004</td>
<td>450</td>
</tr>
<tr>
<td>UltraCamD</td>
<td>14-15.10.2004</td>
<td>450, 900, 2800, 5600</td>
</tr>
<tr>
<td>UltraCamD</td>
<td>14.5.2005</td>
<td>450</td>
</tr>
<tr>
<td>DSS 301</td>
<td>12.7.2005, 17.7.2005</td>
<td>1000, 3000</td>
</tr>
<tr>
<td>DMC + goniometer</td>
<td>31.8-2.9.2005</td>
<td>500, 800, 2500, 5000</td>
</tr>
<tr>
<td>ADS40</td>
<td>26-27.9.2005</td>
<td>1500, 2500</td>
</tr>
<tr>
<td>UltraCamD</td>
<td>1.7.2006, 5.7.2006</td>
<td>450, 900</td>
</tr>
<tr>
<td>Nikon D2X</td>
<td>1.7.2006</td>
<td>560</td>
</tr>
</tbody>
</table>

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Reflectance-based test field calibration

- At-sensor radiance calculation
  - Measure
    - reflectance of ground target,
    - atmospheric properties
  - Model atmosphere by using radiative transfer code.
  - Propagate the ground target radiance through the modelled atmosphere.
  - Calculate at-sensor radiance by applying sensor spectral response

- Empirical study
  - Reference target: Portable gray scale calibrated partially at laboratory
  - Atmospheric correction using MODTRAN default models
  - Spectral response from sensor manufacturer
  - Quality evaluation by comparing the at-sensor radiances and DNs
  - Measures: linearity, sensitivity, dynamic range, absolute calibration

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FGI portable grey scale

- 8 reference targets: 5 m x 5 m
- Nominal reflectance: 5% - 70%
- Reflectance measurements using ASD Field Spec Pro FR spectro radiometer at laboratory and at field

Grey scale BRDF

- Effect of wavelength
- Effect of observation angle

Reflectance difference at principal plane [%]

0 10 20 30 40 50 60 70 80 90
-40 -30 -20 -10 0 10 20 30 40

P05 P10 P20 P25 P30 P45 P50 P70
Results: DMC

- Excellent weather, experienced operator
- Raw DN
- Results
  - Linear
  - Over exposure and saturation at green channel
  - Dynamic range 12 bit for all channels
  - Green and NIR the most sensitive

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Absolute calibration, DMC

- Accuracy evaluation:
  - Calibration: 5% and 70% targets (5%, 50% for green channel) and accuracy evaluation using remaining 6 (5) targets
  - Relative accuracy better than < 5% (excluding green channel and 20% tarp)

<table>
<thead>
<tr>
<th>Band</th>
<th>param gain</th>
<th>offset</th>
<th>stddev gain</th>
<th>offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAN</td>
<td>2.54E-04</td>
<td>-</td>
<td>2.76E-06</td>
<td>-</td>
</tr>
<tr>
<td>R</td>
<td>2.09E-04</td>
<td>-</td>
<td>2.13E-06</td>
<td>-</td>
</tr>
<tr>
<td>G</td>
<td>1.55E-04</td>
<td>-</td>
<td>2.74E-06</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>2.36E-04</td>
<td>-</td>
<td>2.78E-06</td>
<td>-</td>
</tr>
<tr>
<td>NIR</td>
<td>2.16E-04</td>
<td>-4.69E-03</td>
<td>3.30E-06</td>
<td>8.41E-04</td>
</tr>
</tbody>
</table>

Nominal reflectance

Absolute values of radiances as % radiance

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Results: ADS40

- Acceptable weather and illumination conditions, unexperienced operator
- System corrected DN's
- "Photogrammetric" recording mode -> artifacts on 2-3 brightest taps
- Results:
  - Linear
  - Great sensitivity differences, dynamic range
    - PAN: 13 bit
    - R, G: 10 bit
    - B: 9 bit
    - NIR: 11 bit

At-sensor radiances

ADS40, GSD = 25 cm
Results: UltraCamD

- Acceptable weather and illumination conditions, regular geometric calibration flight of a mapping company
- Raw DNs, only 4 targets
- Results:
  - Linear
  - Dynamic range 12.6 bit
  - Blue channel the least sensitive
  - Red channel saturated in 800 m flight

Results: DSS 301 CIR mode

- Acceptable weather and illumination conditions, unexperienced operator
- Regular output from mapping company (8 bit/pixel/channel)
- Saturated at >20% reflectance
- Sensitivity?
Radiometric resolution, 30% reflectance target

<table>
<thead>
<tr>
<th>Sensor</th>
<th>GSD</th>
<th>Pan, sd (%)</th>
<th>Green, sd (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMC</td>
<td>5cm</td>
<td>5.1%</td>
<td></td>
</tr>
<tr>
<td>DMC</td>
<td>8cm</td>
<td>3.9%</td>
<td></td>
</tr>
<tr>
<td>DMC</td>
<td>25cm</td>
<td>3.4%</td>
<td></td>
</tr>
<tr>
<td>RC20</td>
<td>4cm</td>
<td>1.3%</td>
<td></td>
</tr>
<tr>
<td>DSS</td>
<td>3.5cm</td>
<td></td>
<td>Green</td>
</tr>
</tbody>
</table>

Radiometric resolution, 30% reflectance target

<table>
<thead>
<tr>
<th>Sensor</th>
<th>GSD</th>
<th>Pan, sd (%)</th>
<th>Green, sd (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADS40</td>
<td>25cm</td>
<td>2.4%</td>
<td>1.7%</td>
</tr>
<tr>
<td>DSS</td>
<td>16cm</td>
<td></td>
<td>1.7%</td>
</tr>
<tr>
<td>DMC</td>
<td>25cm</td>
<td>3.4%</td>
<td>3.4%</td>
</tr>
<tr>
<td>UltraCamD</td>
<td>25cm</td>
<td>2.3%</td>
<td>2.8%</td>
</tr>
<tr>
<td>RC25</td>
<td>25cm</td>
<td></td>
<td>2.8%</td>
</tr>
</tbody>
</table>

Blue, sd=2.3%  GSD=50 cm  
Green, sd=1.7%

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Sensor improvement

- **UltraCamD->UltraCamX**
  - Pansharpening ratio ->3
  - Pixel size 9 -> 7.2 μm
  - New lens
- **ADS40 2nd generation**
  - Perfect co-registration of all multi-spectral bands by the new Tetrachroid beamsplitter
  - 4 times increased sensitivity compared to 1st generation sensors

Conclusions

- **Radiometry of digital photogrammetric sensors**
  - Large dynamic range (12-14 bit)
  - Linearity
  - Similar, high radiometric resolution over entire dynamic range
  - Low noise level
  - Multi-spectral data
  - Multi-angular data
- **Problems:**
  - DMC, UltraCamD: saturation
  - ADS40: low sensitivity of MS-channels
- **Applications**
  - Conventional metric and interpretative applications
  - Quantitative remote sensing, BRDF
  - Change detection
  - Historical data archives
Needed

- Fluent radiometric processing chains for various applications (visual, classification, BRDF)
- Recovering raw DNs from the processed values (storing transformations or raw data)
- Radiometric concepts for photogrammetric production lines
- Information from sensor manufacturers concerning
  - Sensor parameters, radiometric stability, radiometric quality
  - Radiometric calibration
  - DN processing chains
- Sensor absolute radiometric calibration at laboratory
- Radiometric system calibration using test fields

Thank you!

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