Calibration Protocol
DMC III

Camera Calibration Certificate
No: DMC III 27553

For

Aerial Survey Office, Forestry Bureau Taiwan

No.100, Sec 2, Heping W.Rd, Zhongzheng Dist
Taipei City 10070

Taiwan

This calibration certificate complies with DIN 18740-4

Camera:	DMC III
Manufacturer:	Leica Geosystems Technologies, D-73430 Aalen, Germany
Reference:	PAN
Serial Number:	00129134 (PAN Head)
Date of Calibration:	22. November 2023
Date of Report:	22. November 2023
Number of Pages:	48

This camera system is certified by Leica Geosystems Technologies and is fully functional within its specifications and tolerances.

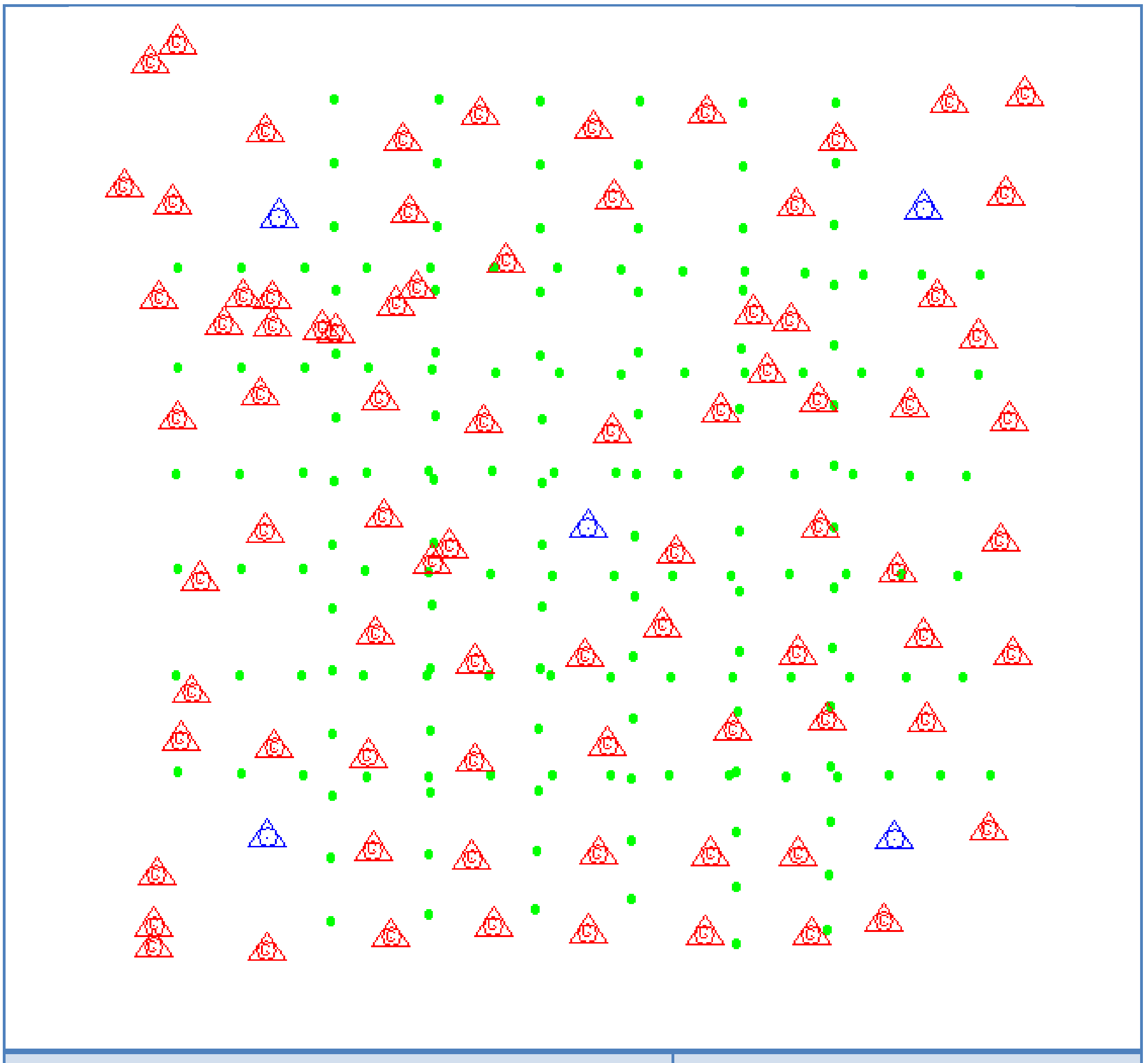
Date of Calibration: November 2023	Date of Certification: November 2023
Riedl Bernhard	Gerald Kapoun
Bernhard Riedl, Head of Production	Dipl.Ing. Gerald Kapoun, Technical Consultant

Camera Serial Numbers and Calibration flight

Camera Head	Serial Number	Calib. Date
PAN (reference)	00129134	22.11.2023
MS1 (NIR)	00128794	22.11.2023
MS2 (Blue)	00128818	22.11.2023
MS3 (Red)	00128795	22.11.2023
MS4 (Green)	00128819	22.11.2023

Calibration flight performed: 16. November 2023

Flight parameters of 5cm Calibration Flight



Parameter	Burn-in flight
GSD [cm]	5
End-lap [%]	75
Side-lap [%]	75
Number of Exposures	171
Number of Flight Lines	6
Number of Cross Flight Lines	6
Number of Control Points	5
Number of Check Points	81
GPS/INS	YES

Application

Parameter	Burn-in flight
Weighting for manual measured image points	1.0
Weighting for automatic measured image points	1.0
Weighting for Control Points	2.8 / 2.8 / 1.6
Weighting for GPS	1.6 / 1.6 / 1.6
Weighting for INS	0.4 / 0.4 / 0.2
Modeling of GPS systematic residuals	NO
Bore Sight Alignment (YES/NO)	NO
Camera Self Calibration (YES/NO)	NO

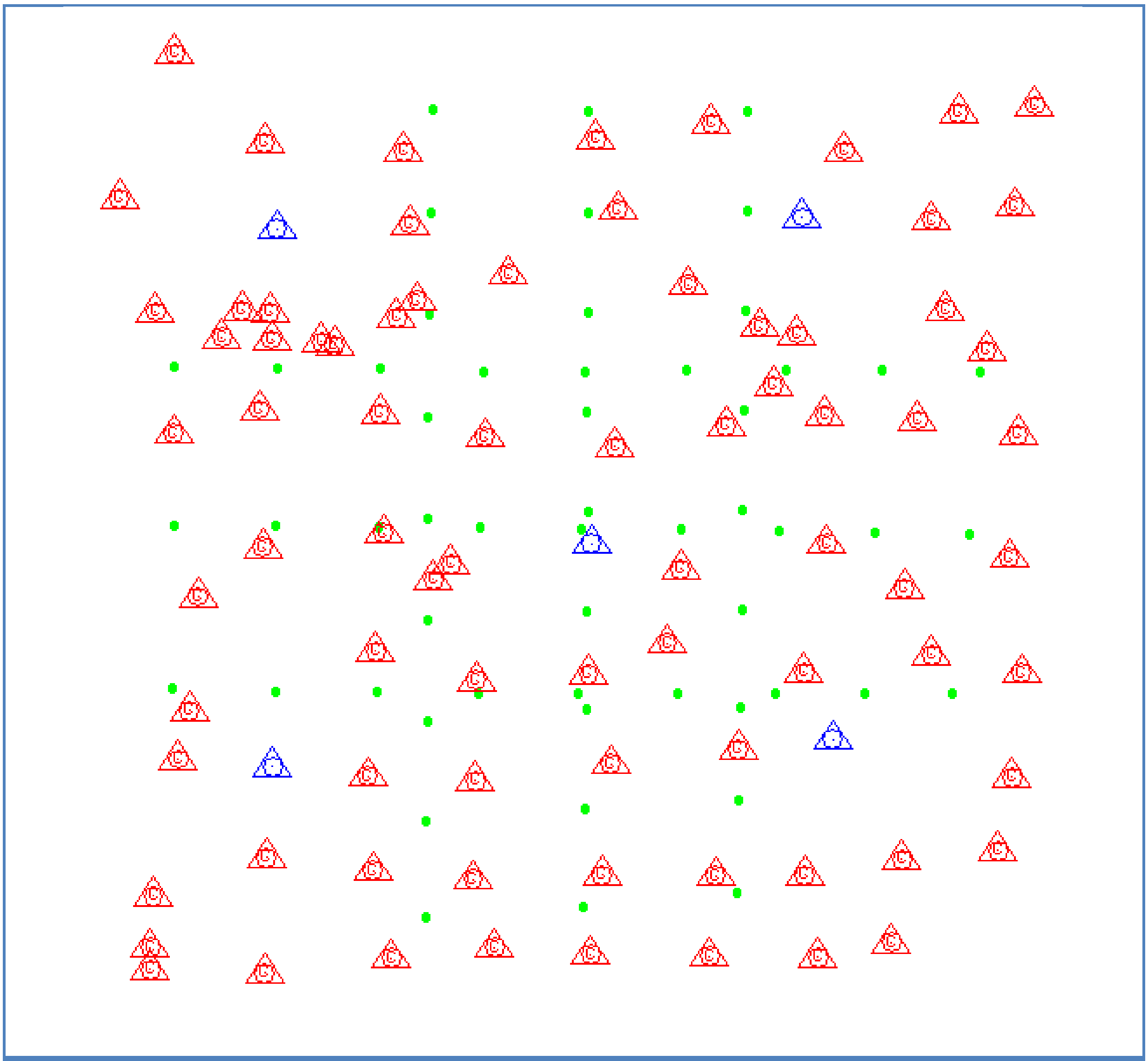
Statistics – Bundleblockadjustment

Parameter	Burn-in flight
Sigma0 [µm]	0.649
Mean Std Dev Photo Position [cm]	0.6 / 0.6 / 0.2
Mean Std Dev Photo Attitude [mdeg]	0.2 / 0.3 / 0.1
Mean Std Dev Control Points [cm]	0.3 / 0.2 / 0.5
Mean Std Dev Check Points [cm]	0.3 / 0.3 / 0.8
RMS Photo Position [cm]	1.3 / 0.9 / 1.2
RMS Photo Attitude [mdeg]	1.5 / 1.7 / 2.2

Statistics – Results

Parameter	Burn-in flight
RMS of Control Points – horizontal [cm]	1.2 / 1.3
Max Ground Residual of Control Points – horizontal [cm]	1.8 / 1.9
RMS of Control Points – vertical [cm]	0.9
Max Ground Residual of Control Points – vertical [cm]	1.3
RMS of Check Points – horizontal [cm]	2.4 / 2.4
Max Ground Residual of Check Points – horizontal [cm]	5.8 / 6.4
RMS of Check Points – vertical [cm]	2.0
Max Ground Residual of Check Points – vertical [cm]	5.0

Flight parameters of independent 8cm Reference Block



Parameter	Burn-in flight
GSD [cm]	8
End-lap [%]	70
Side-lap [%]	60
Number of Exposures	54
Number of Flight Lines	3
Number of Cross Flight Lines	3
Number of Control Points	5
Number of Check Points	79
GPS/INS	YES

Application

Parameter	Burn-in flight
Weighting for manual measured image points	1.0
Weighting for automatic measured image points	1.0
Weighting for Control Points	7.1 / 7.1 / 4.0
Weighting for GPS	4.0 / 4.0 / 4.0
Weighting for INS	0.4 / 0.4 / 0.2
Modeling of GPS systematic residuals	NO
Bore Sight Alignment (YES/NO)	NO
Camera Self Calibration (YES/NO)	NO

Statistics – Bundleblockadjustment

Parameter	Burn-in flight
Sigma0 [µm]	0.653
Mean Std Dev Photo Position [cm]	0.7 / 0.7 / 0.3
Mean Std Dev Photo Attitude [mdeg]	0.2 / 0.2 / 0.2
Mean Std Dev Control Points [cm]	0.4 / 0.4 / 0.7
Mean Std Dev Check Points [cm]	0.6 / 0.6 / 1.5
RMS Photo Position [cm]	1.0 / 0.9 / 1.0
RMS Photo Attitude [mdeg]	1.2 / 1.5 / 1.9

Statistics – Results from independent Referenceblock

Parameter	Burn-in flight
RMS of Control Points – horizontal [cm]	1.1 / 1.1
Max Ground Residual of Control Points – horizontal [cm]	1.6 / 2.0
RMS of Control Points – vertical [cm]	1.4
Max Ground Residual of Control Points – vertical [cm]	2.6
RMS of Check Points – horizontal [cm]	2.9 / 1.9
Max Ground Residual of Check Points – horizontal [cm]	6.8 / 4.8
RMS of Check Points – vertical [cm]	3.0
Max Ground Residual of Check Points – vertical [cm]	6.6

The results of aerial triangulation were generated with ImageStation Orientations (2022) by Hexagon Geospatial.
The maximum RMS in check points is ≤ 0.5 GSD in x,y and ≤ 0.7 GSD in z.

Aerial Triangulation performed by Gerald Kapoun

Dipl. Ing. Gerald Kapoun

22.11.2023
Date

Geometric Calibration

The output image geometry is based on the Pan Camera head (reference head = master camera). All other camera heads are registered and aligned to this head. Aerial triangulation checks overall system performance based on.

Output image

Reference Camera	PAN	
Serial Number	00129134	
Number of rows/columns [pixels]	25728 x 14592	
Pixel Size [µm]	3.900 x 3.900	
Image Size [mm]	100.3392 x 56.9088	
Focal Length [mm]	92.0000 mm	+ /- 0.001 mm
Principal Point [mm]	X= 0.0000 mm, Y= 0.0000 mm	+ /- 0.001 mm

The "SYNTHETIC" geometric calibration is based on a simulated mathematical lens distortion calculation based on the detailed optical design data of the lens.

It is equivalent to the DMC II collimator calibration procedure, projecting 800 "light targets" on 28 lines that are distributed diagonally on the focal plane.

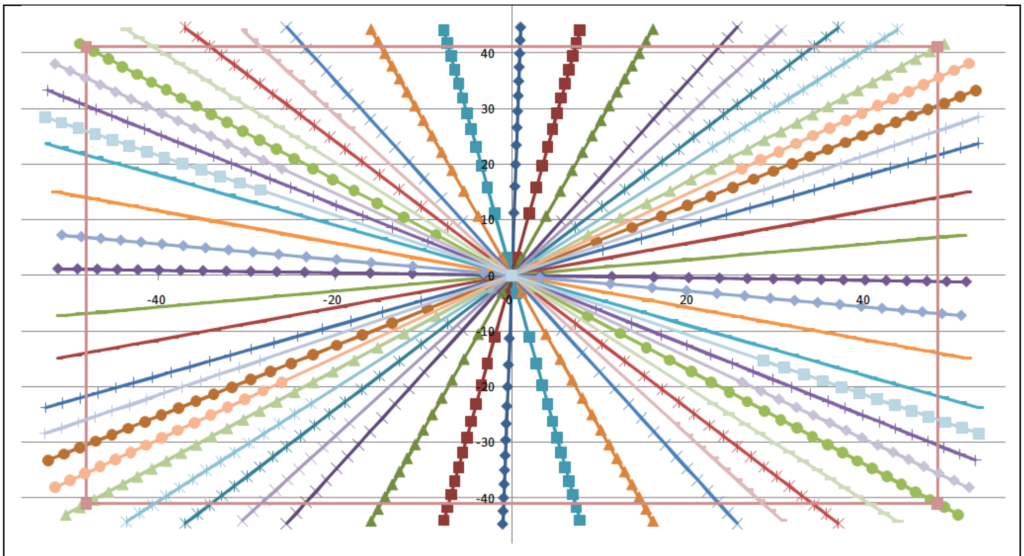


Figure 1: SYNTHETIC Light Target Simulation

Geometric Calibration

Image Residuals

Figure 2 shows the image residuals, split in radial and tangential directions after the calibration adjustment. The maximum residuals are less than or equal to 1.0 microns and the RMSE values are below 0.5 microns.

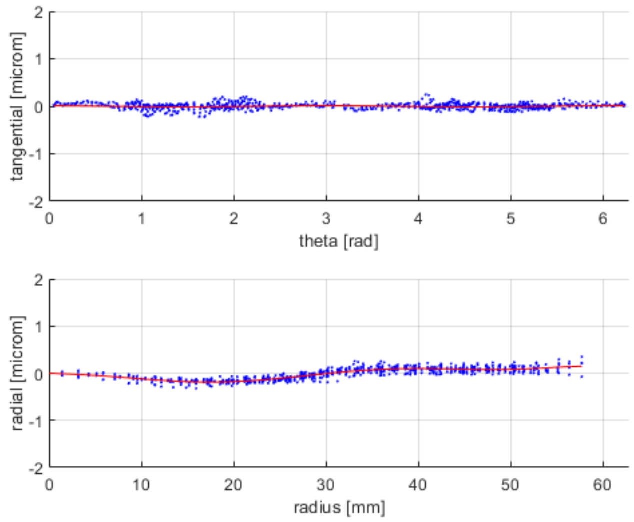


Figure 2: Tangential/Radial Distortion Residuals

Figure 3 shows the 2-D plot of the image residuals in mm.

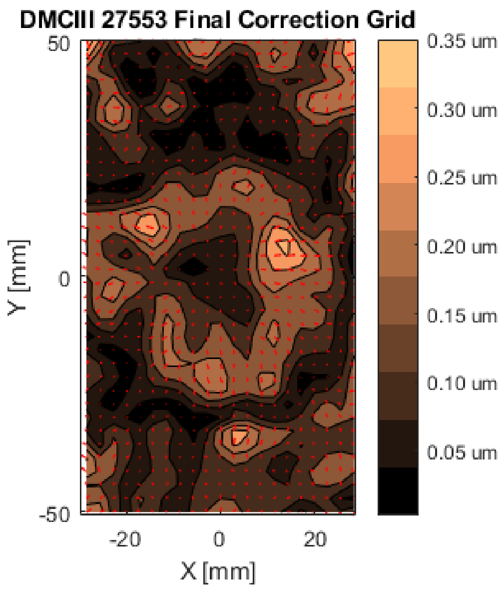


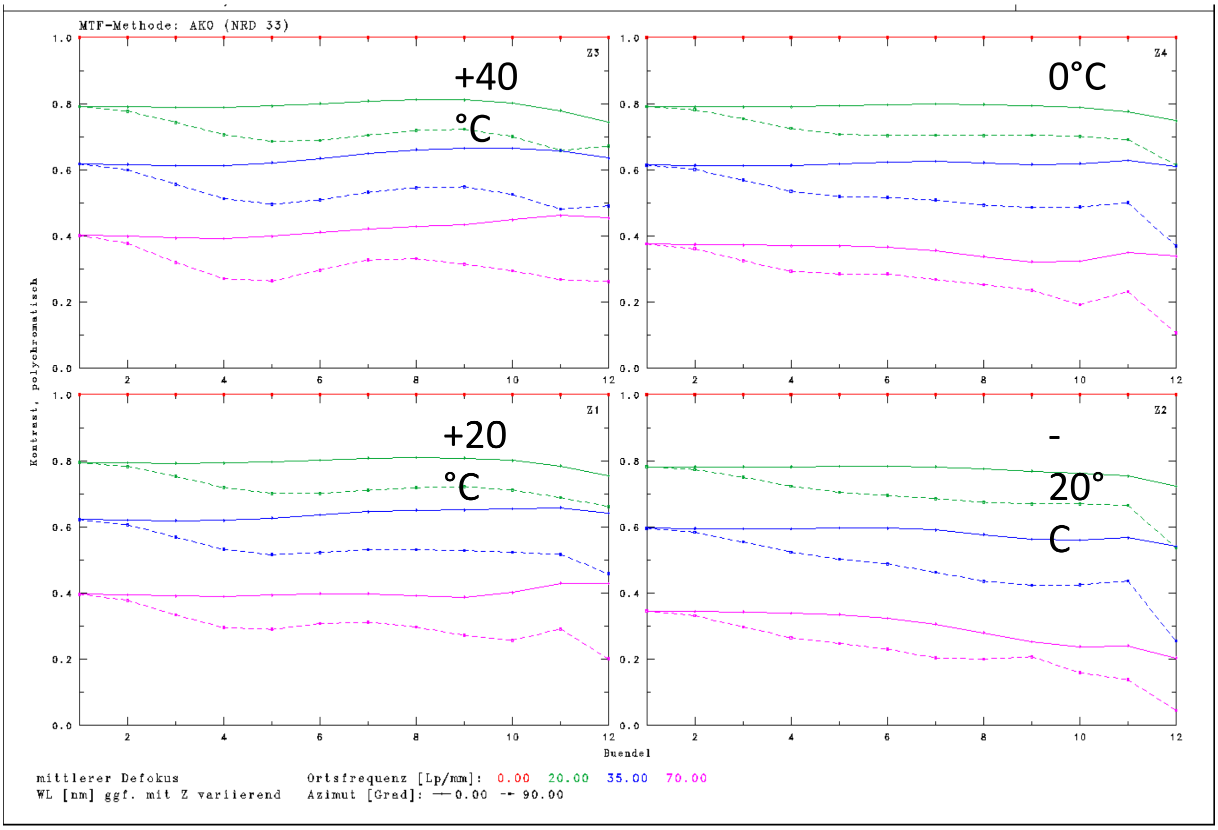
Figure 3: 2-D Image Residuals.

Mean RMS ≤ 0.1 um (maximum 0.4 microns)

Optical System

Modulation Transfer Function, MTF of PAN Camera (Reference)

DMC III PAN – MTF Polychromatic F/5.6 ; 92 mm – Temperature Stability

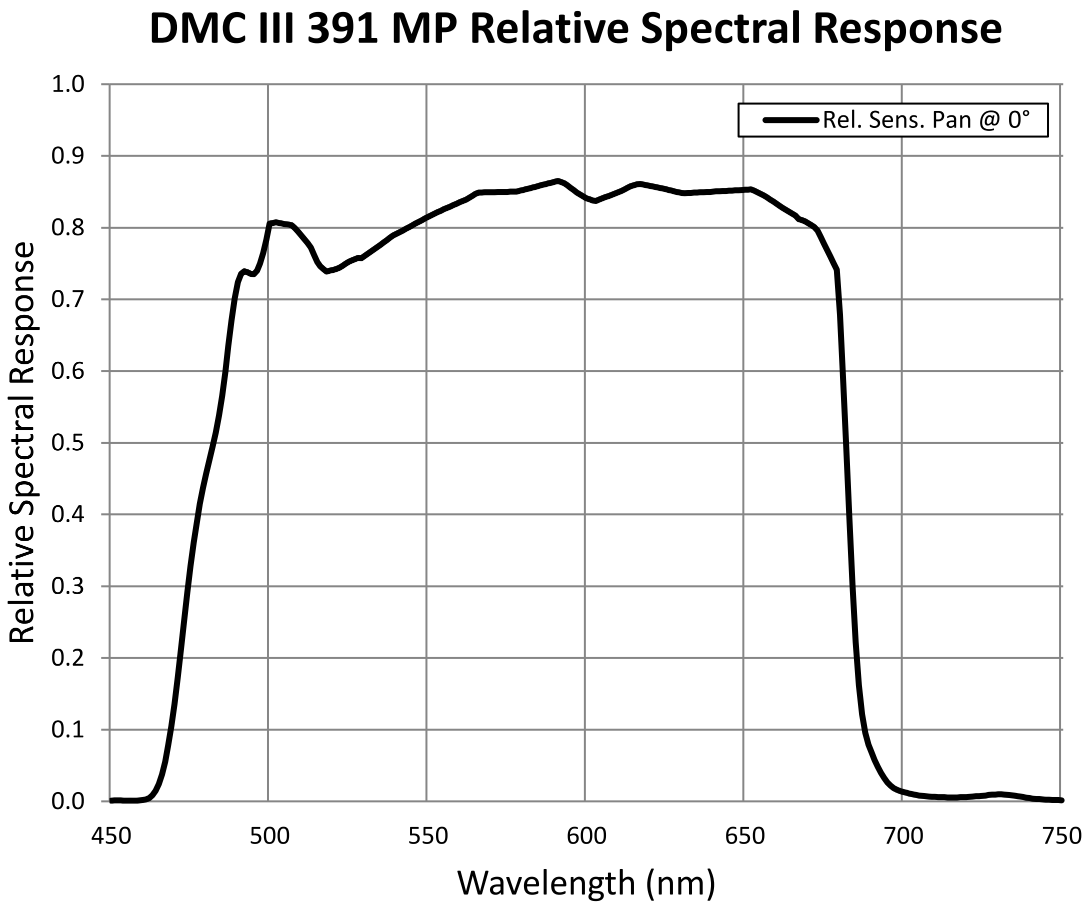


The MTF measurement is camera type specific and shows variation of the MTF within the specified temperature range.

This is a camera type specific measurement.

Radiometric Calibration

Sensitivity of PAN camera (Reference)

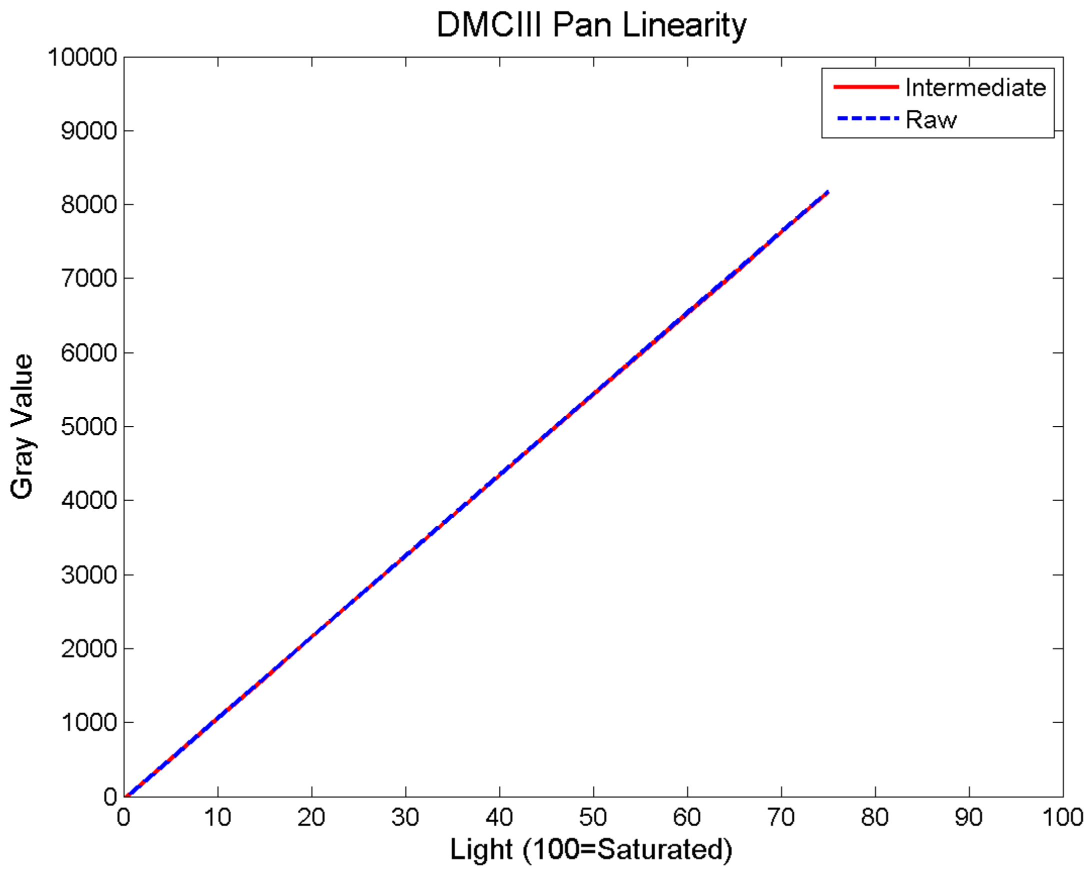


The sensitivity shows the spectral response curve of the single camera head including the optical system (optics, filter) and the sensor response. The DMC III is calibrated with a NIST traceable spectroradiometer and an integrating sphere. This allows computing pixel radiance values from pixels digital numbers and is a camera type specific calibration.

This is a camera type specific measurement.

Sensor Linearity (Reference)

The sensor linearity is measured in the Lab with calibrated spectrometer.
This is a camera type specific calibration.
Below figure shows the linearity of the raw sensor and after flat fielding:



Senor Linearity

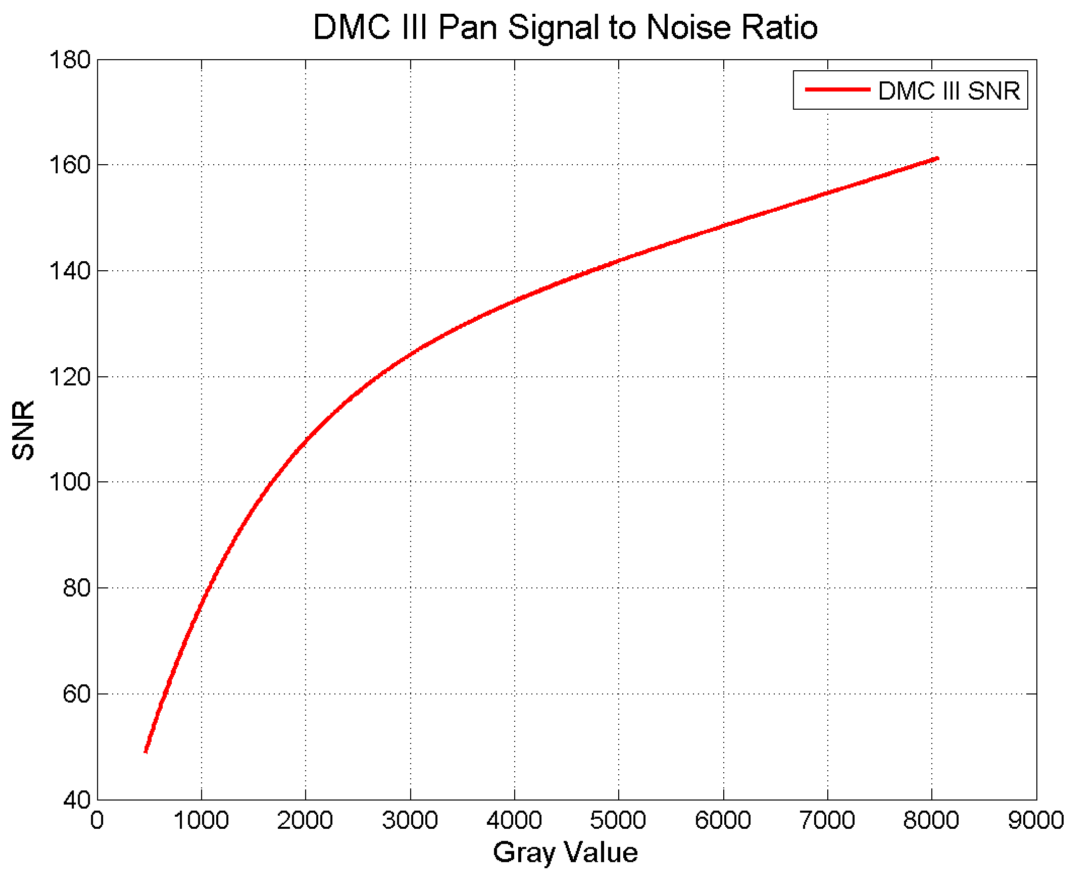
The deviation from the linearity is below 1%.

This is a camera type specific measurement.

Radiometric Calibration

Sensor Noise (Reference)

Sensor noise shows image noise with respect to the image center measured at an aperture of 16 with exposure time of 16msec.



Sensor Signal to Noise Ratio

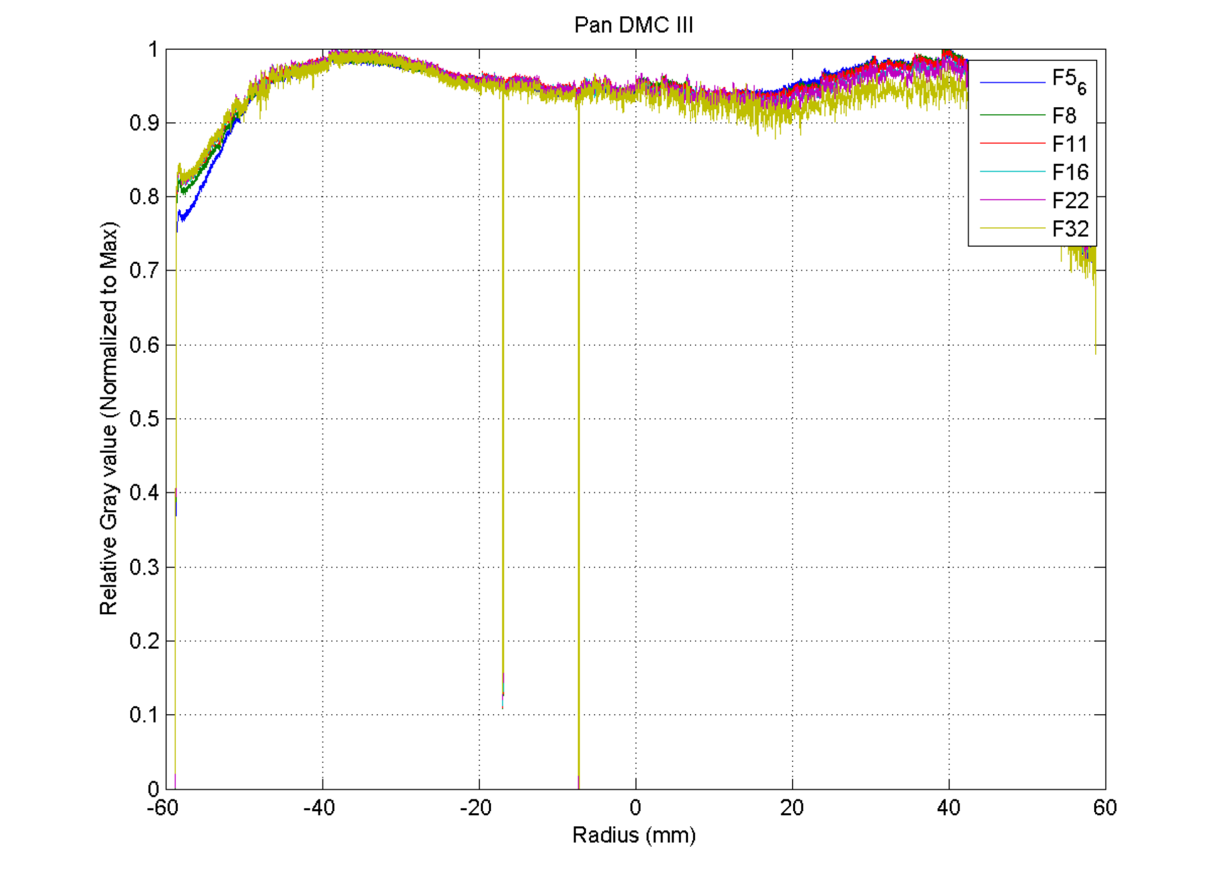
This is from a camera type specific calibration.

Radiometric Calibration

Aperture Correction (Reference)

Camera PAN (00129134)

The light fall off to the border due the influence of the optics depends on the aperture used. Therefore this calibration approach delivers individual calibration images for each aperture (Full F-Stop). In general the light fall off is a function of the image height (radial distance from center). The figure below shows the profile from the upper left corner to the lower right corner of the calibration images. Compensation of the light fall off can be measured after normalization and is within ± 2.5% of the dynamic range.



Light fall off and correction after normalization (blue) for PAN sensor

This is from a camera type specific calibration.

Radiometric Calibration

Defect Pixel

Camera PAN (00129134)

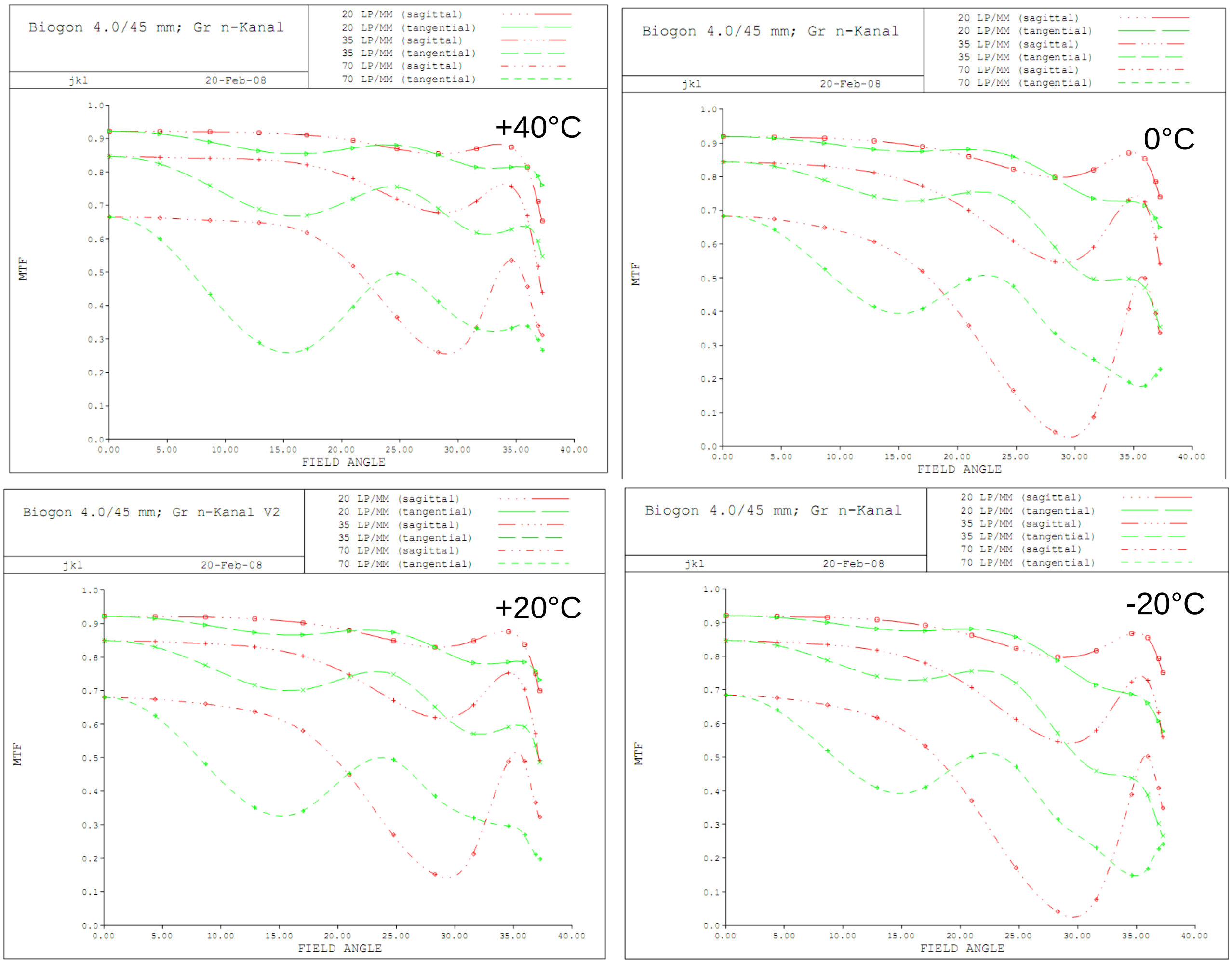
Defect pixels are detected during radiometric calibration and will be corrected during radiometric processing of the images.

The quantity and cumulative percentage and specification of defects are described in Appendix “Defect Pixel Recognition” at page 46.

Optical System

Modulation Transfer Function, MTF of Green camera

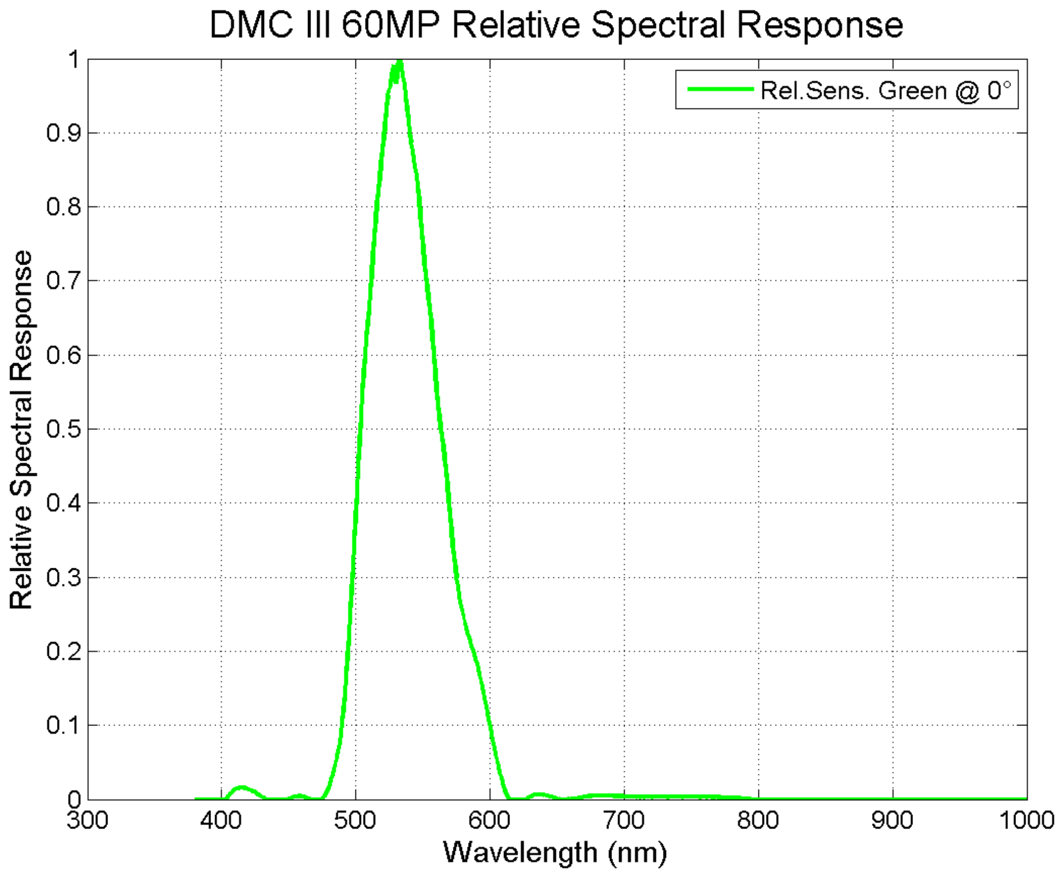
DMC III MS Green – MTF F/4.0 ; 45 mm– Temperature Stability



Radiometric Calibration

Sensitivity of Green camera

Spectral response curve of the single camera head.

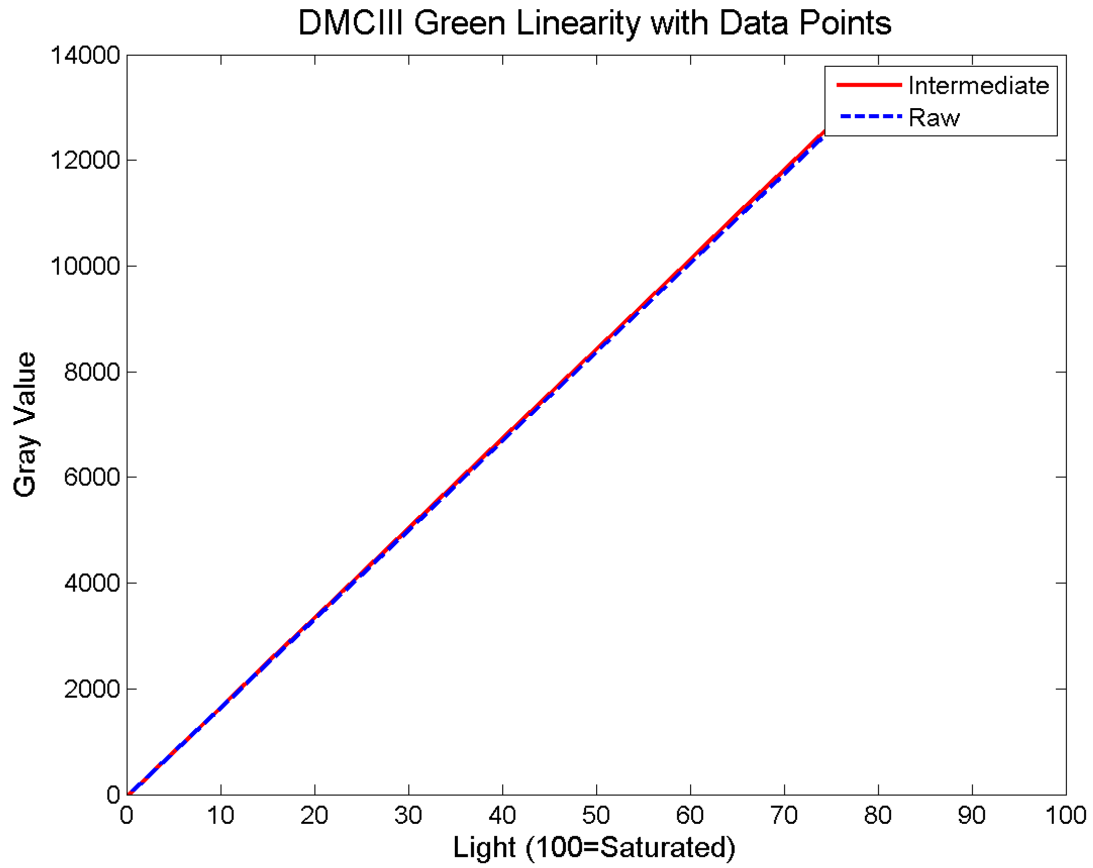


The sensitivity shows the spectral response curve of the single camera head including the optical system (optics, filter) and the sensor response. The DMC III is calibrated with respect to the absolute spectrometer. This allows computing pixel radiance values from pixels digital numbers and is a camera type specific calibration.

Radiometric Calibration

Sensor Linearity (Reference)

The sensor linearity is measured in the Lab with calibrated spectrometer.
This is a camera type specific calibration.
Below figure shows the linearity of the raw sensor and after flat fielding:



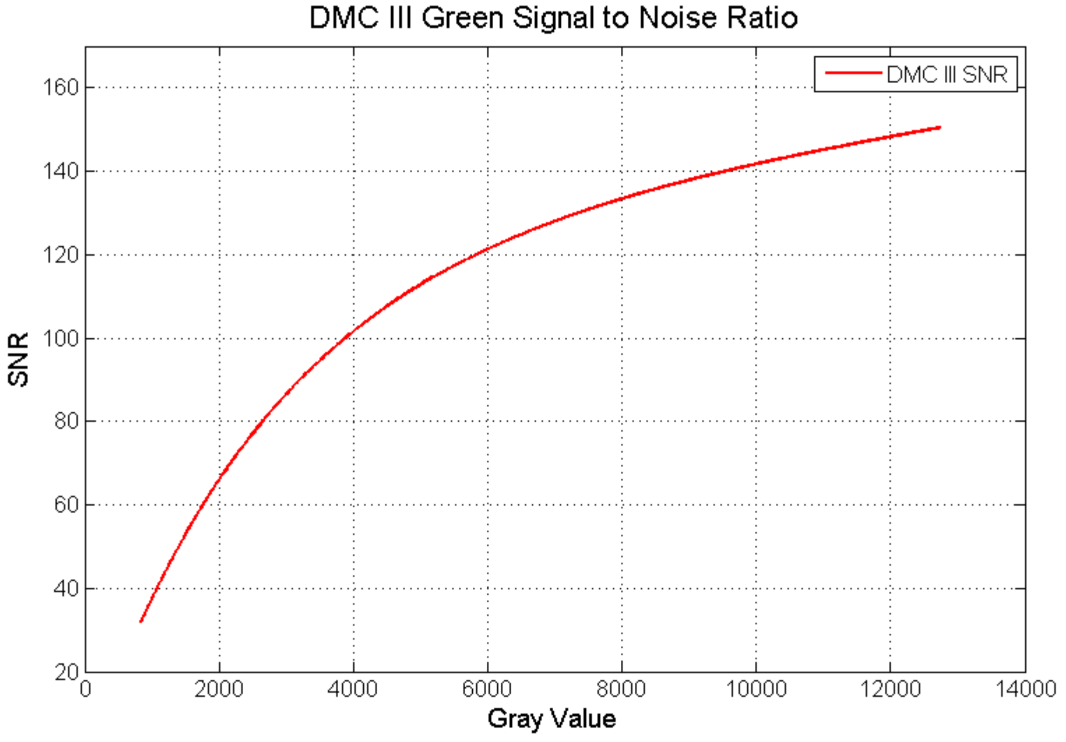
Senor Linearity from Light Level 0 (dark) to (100 % = Saturation)

The deviation from the linearity is below 1%.

Radiometric Calibration

Sensor Noise (Reference)

Sensor noise shows image noise with respect to the image center measured at an aperture of 5.6 with exposure time of 10msec.



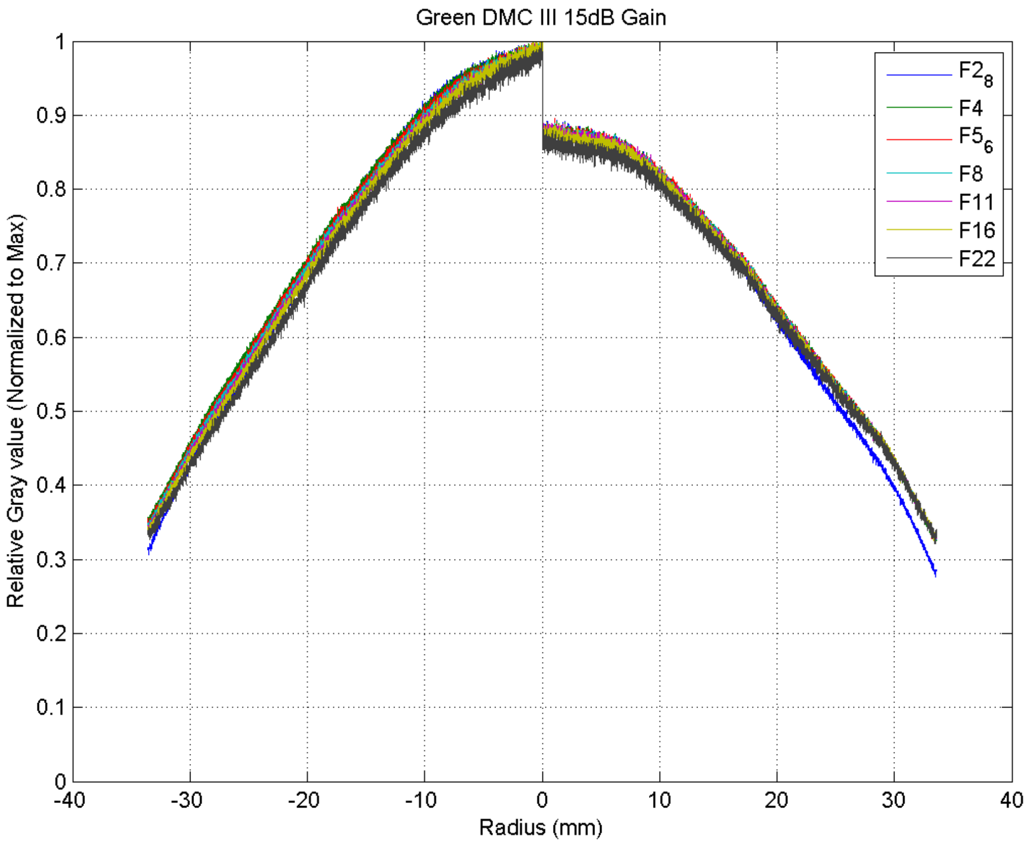
Sensor Signal to Noise Ratio

Radiometric Calibration

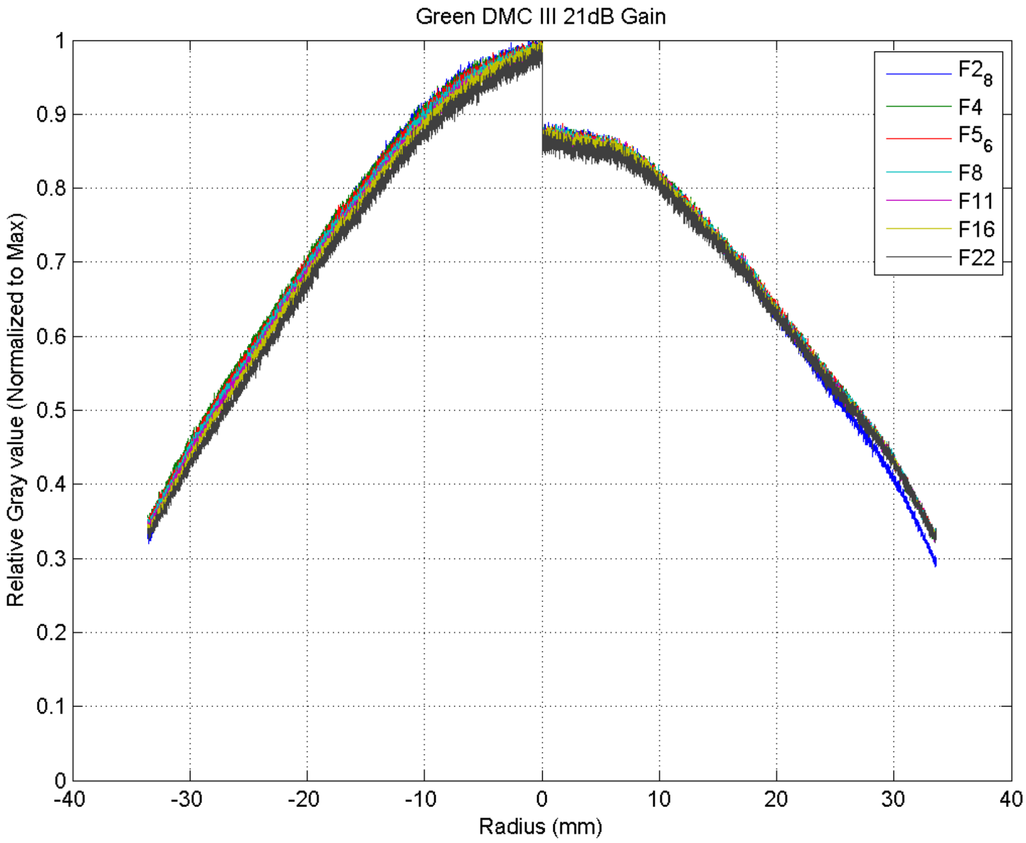
Aperture Correction

Green (00128819)

The light fall off to the border due the influence of the optics depends on the aperture used. Therefore this calibration approach delivers individual calibration images for each aperture (Full F-Stop). In general the light fall off is a function of the image height (radial distance from center). The figure below shows the profile from the upper left corner to the lower right corner of the calibration images.



Green 15 dB



Green 21 dB

This is a camera type specific calibration.

Radiometric Calibration

Defect Pixel

Green (00128819)

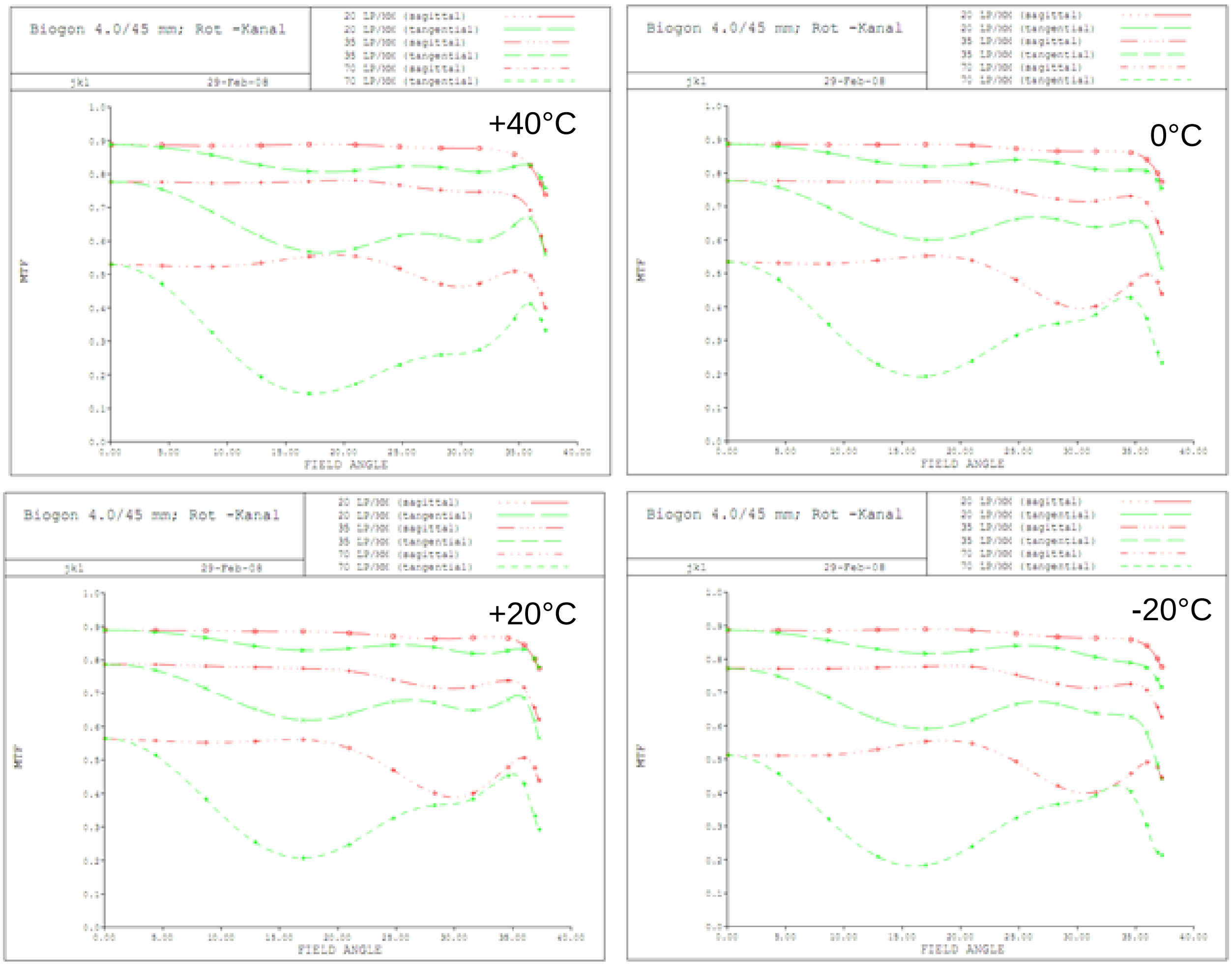
Defect pixels are detected during radiometric calibration and will be corrected during radiometric processing of the images.

The quantity and cumulative percentage and specification of defects are described in Appendix “Defect Pixel Recognition” at page 46.

Optical System

Modulation Transfer Function, MTF of Red camera

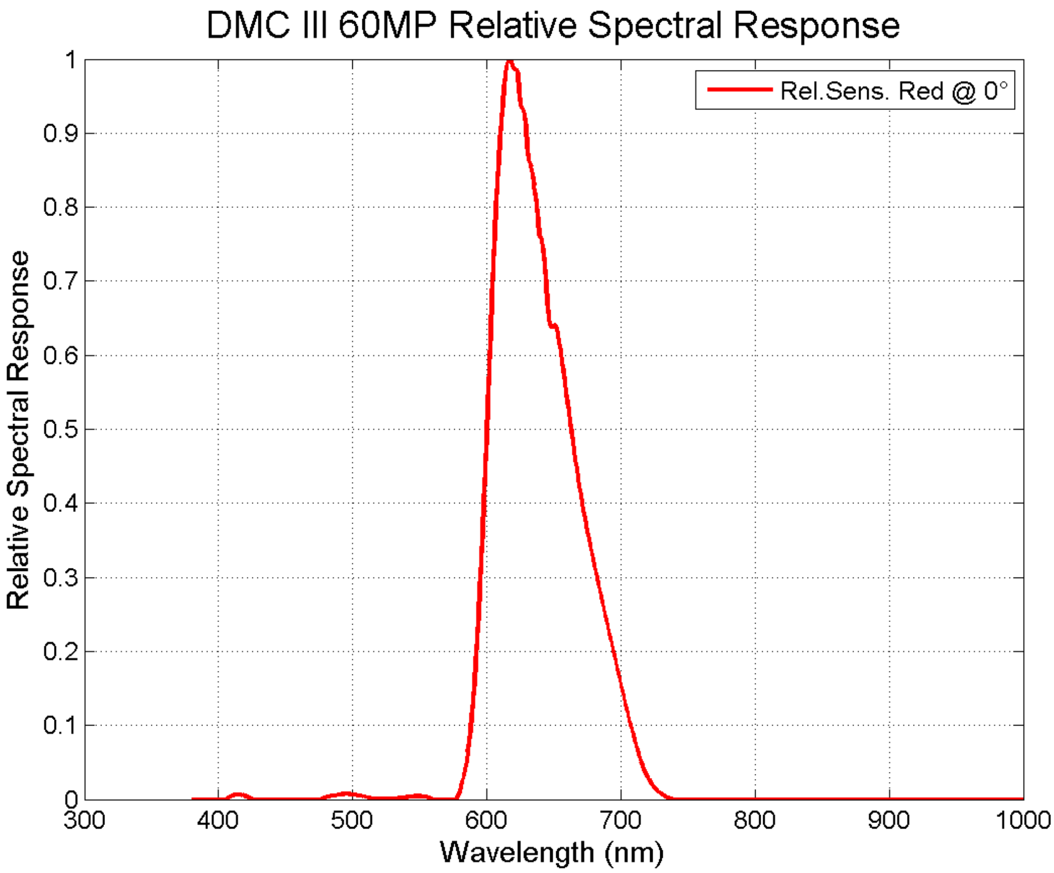
DMC III MS Red – MTF F/4.0 ; 45 mm– Temperature Stability



Radiometric Calibration

Sensitivity of Red camera

Spectral Response Curves of the single camera head.

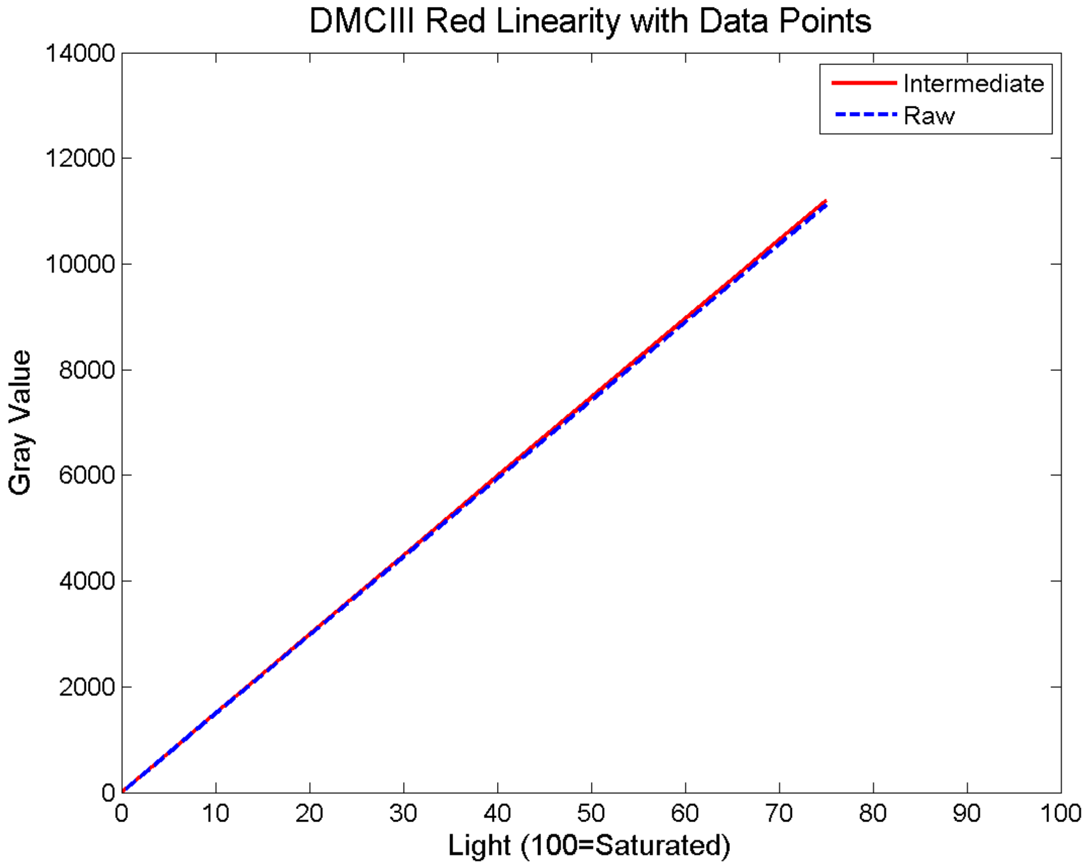


The sensitivity shows the spectral response curve of the single camera head including the optical system (optics, filter) and the sensor response. The DMC III is calibrated with respect to the absolute spectrometer. This allows computing pixel radiance values from pixels digital numbers and is a camera type specific calibration.

Radiometric Calibration

Sensor Linearity (Reference)

The sensor linearity is measured in the Lab with calibrated spectrometer.
This is a camera type specific calibration.
Below figure shows the linearity of the raw sensor and after flat fielding:



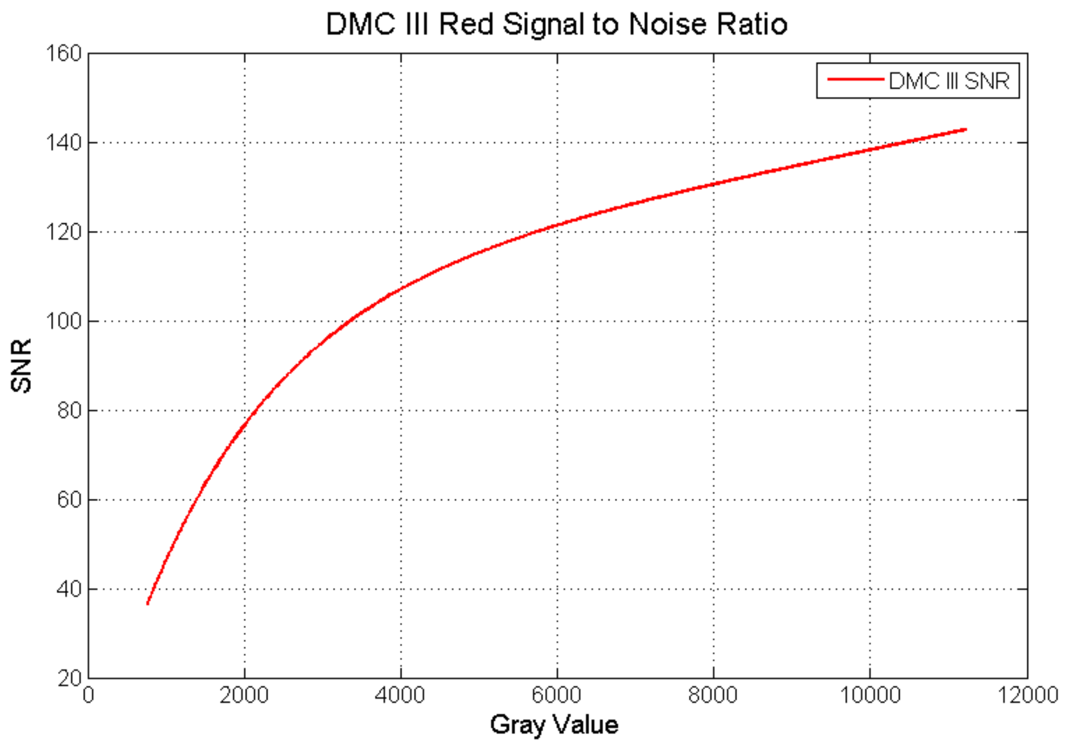
Senor Linearity from Light Level 0 (dark) to (100 % = Saturation)

The deviation from the linearity is below 1%.

Radiometric Calibration

Sensor Noise (Reference)

Sensor noise shows image noise with respect to the image center measured at an aperture of 5.6 with exposure time of 10msec.



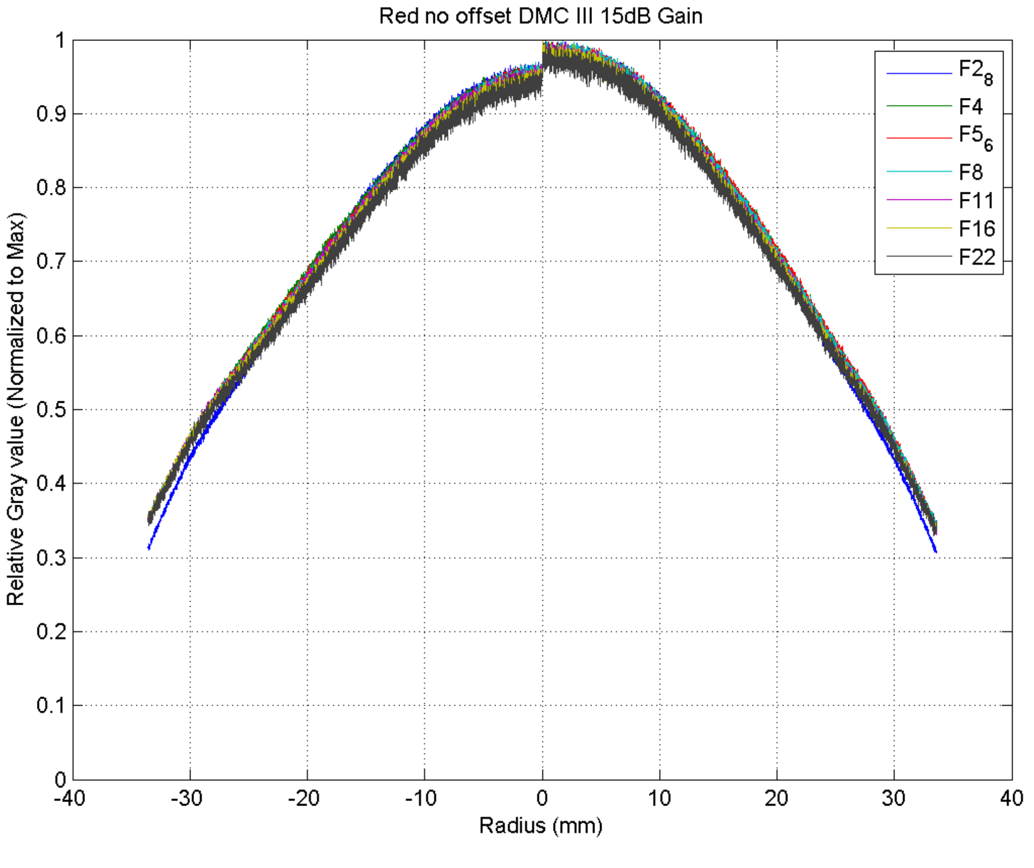
Sensor Signal to Noise Ratio

Radiometric Calibration

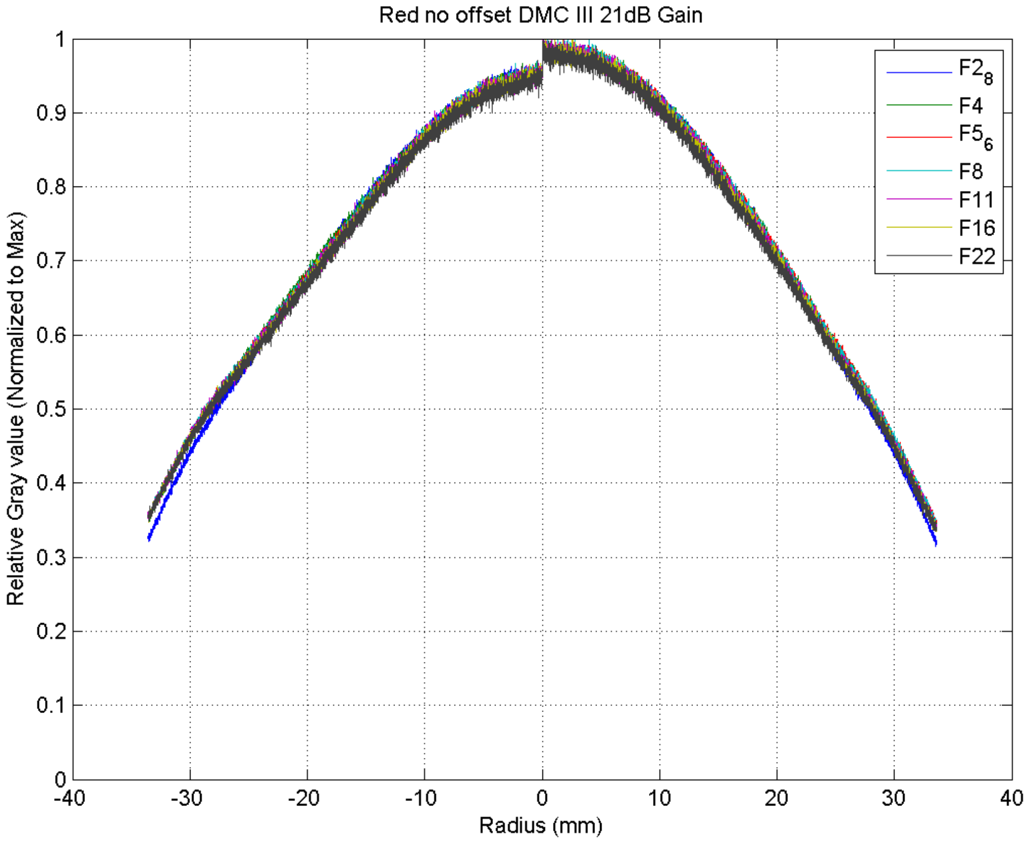
Aperture Correction

Red (00128795)

The light fall off to the border due the influence of the optics depends on the used aperture. Therefore this calibration approach has for each aperture (Full F-Stop) its own calibration image. In general the light fall off is a function of the image radius. In this calibration approach instead of function the real measured values in the image is used. The figure below shows the profile from the upper left corner to the lower right corner of each of this calibration images to give a feeling on the amount of correction.



Red 15 dB



Red 21 dB

This is a camera type specific calibration.

Radiometric Calibration

Defect Pixel

Red (00128795)

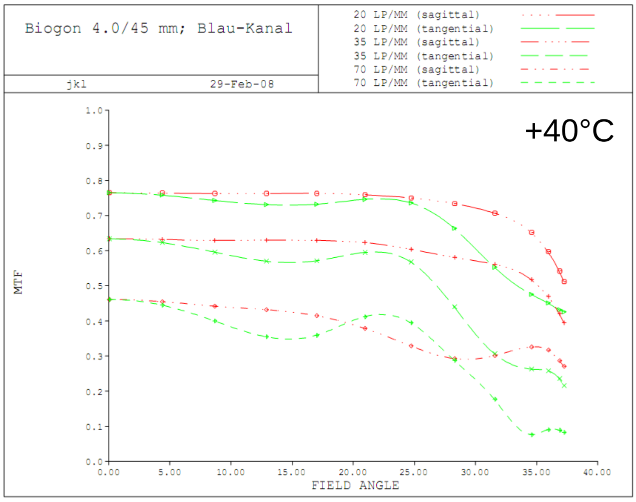
Defect pixels are detected during radiometric calibration and will be corrected during radiometric processing of the images.

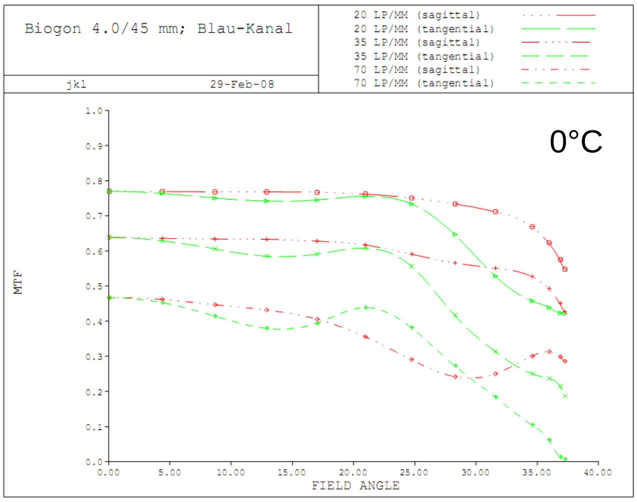
The quantity and cumulative percentage and specification of defects are described in Appendix “Defect Pixel Recognition” at page 46.

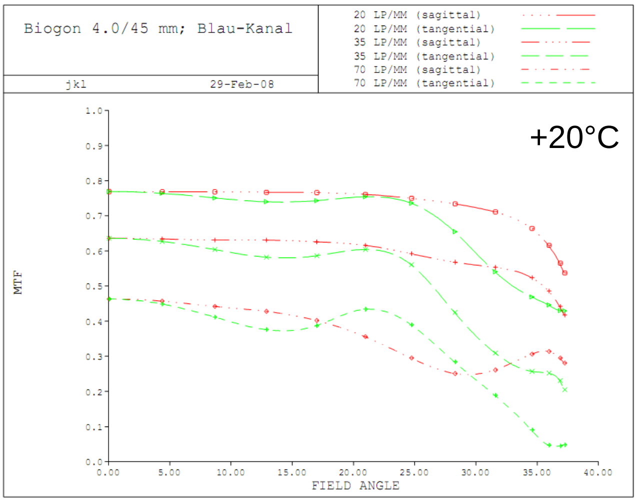
Optical System

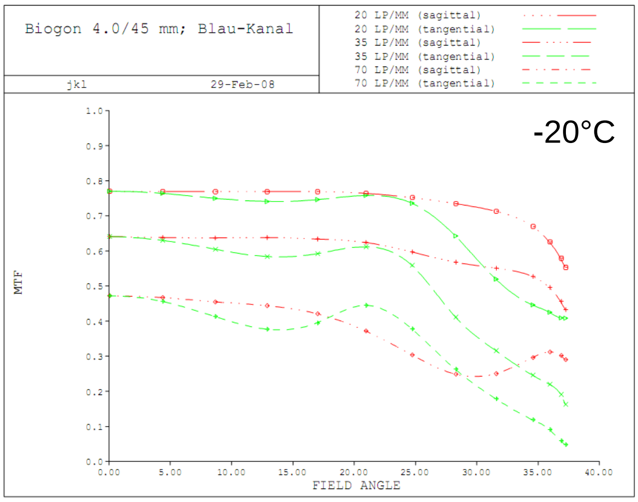
Modulation Transfer Function, MTF of Blue camera

DMC III MS Blue – MTF F/4.0 ; 45 mm– Temperature Stability





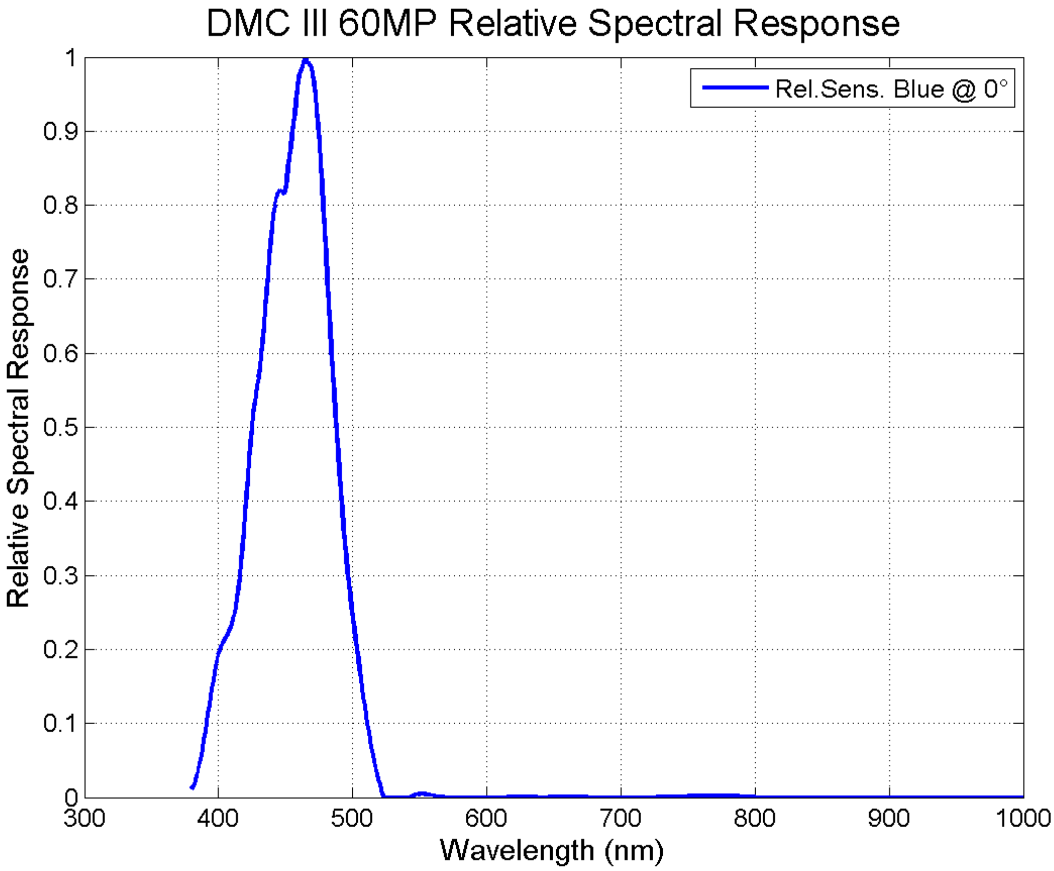




Radiometric Calibration

Sensitivity of Blue camera

Spectral Response Curves of the single camera head.

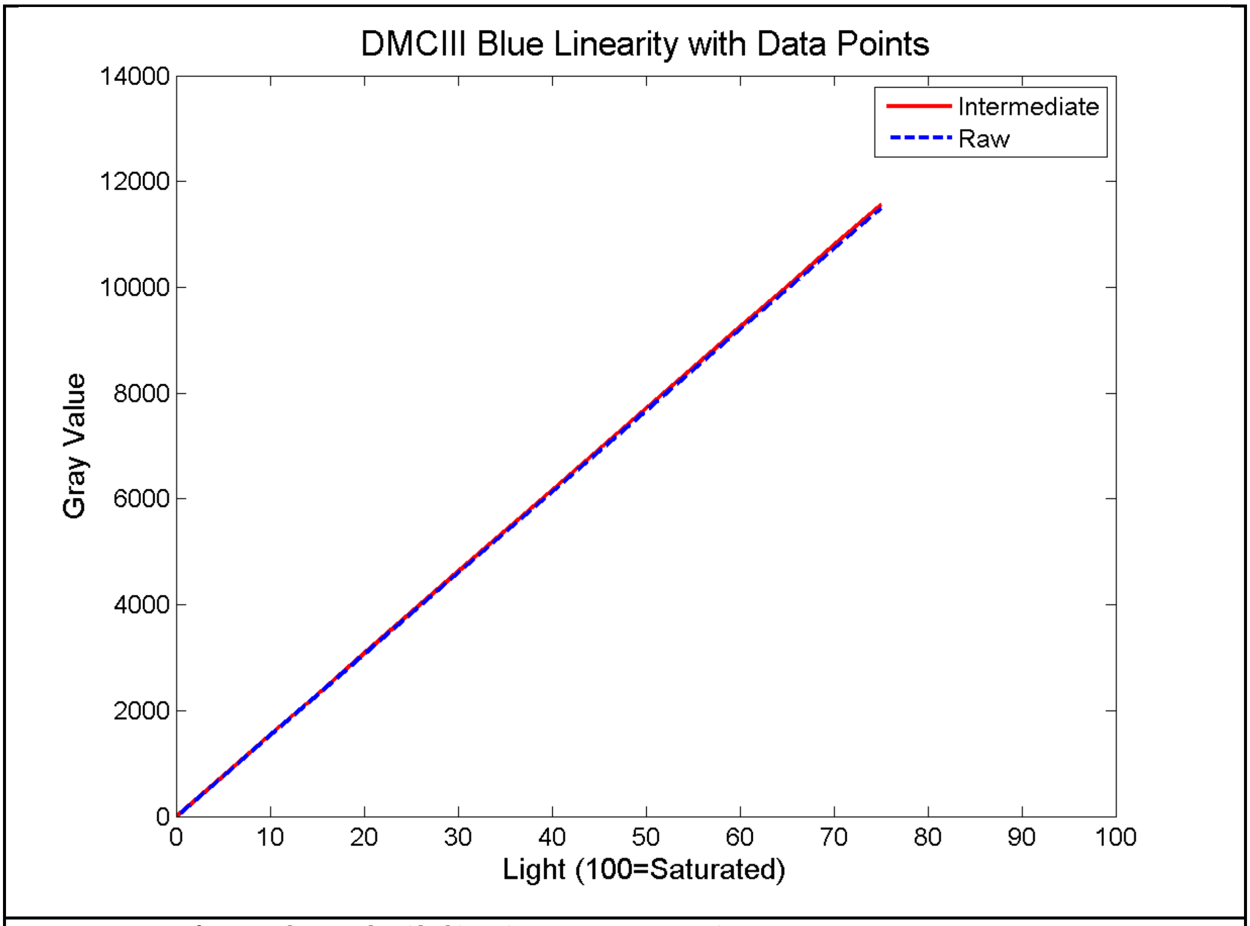


The sensitivity shows the spectral response curve of the single camera head including the optical system (optics, filter) and the sensor response. The DMC III is calibrated with respect to the absolute spectrometer. This allows computing pixel radiance values from pixels digital numbers and is a camera type specific calibration.

Radiometric Calibration

Sensor Linearity (Reference)

The sensor linearity is measured in the Lab with calibrated spectrometer.
This is a camera type specific calibration.
Below figure shows the linearity of the raw sensor and after flat fielding:



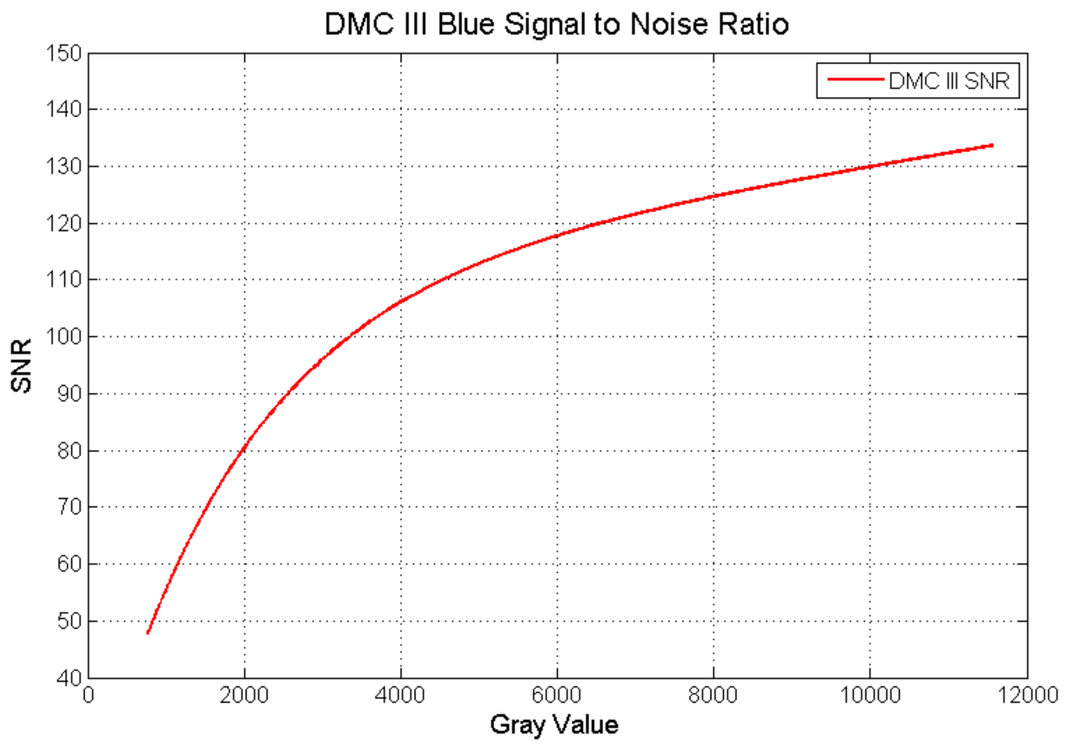
Senor Linearity from Light Level 0 (dark) to (100 % = Saturation)

The deviation from the linearity is below 1%.

Radiometric Calibration

Sensor Noise (Reference)

Sensor noise shows image noise with respect to the image center measured at an aperture of 5.6 with exposure time of 10msec.



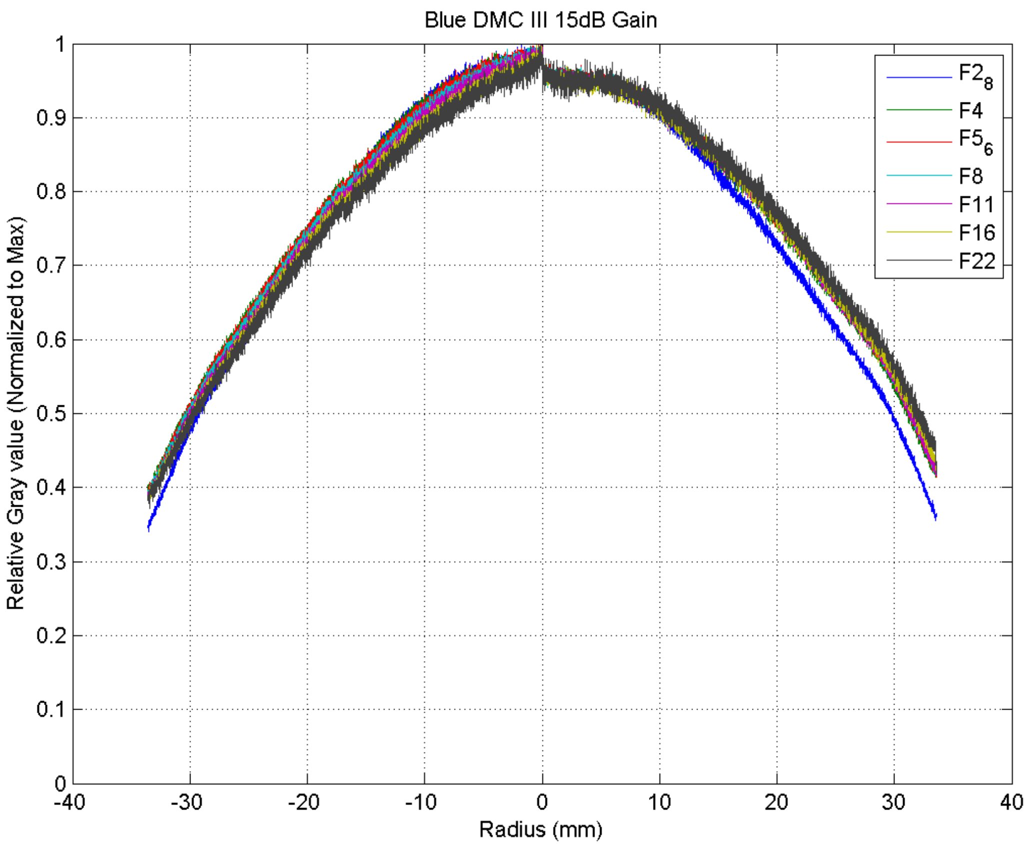
Sensor Signal to Noise Ratio

Radiometric Calibration

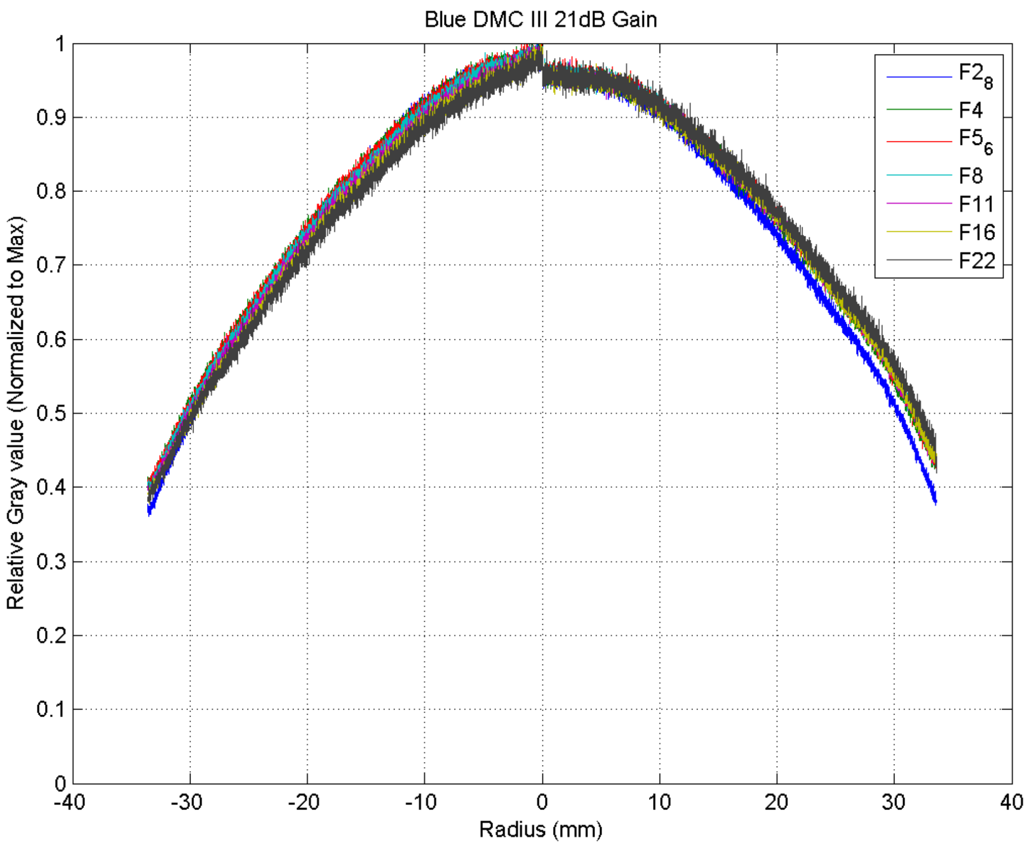
Aperture Correction

Blue (00128818)

The light fall off to the border due the influence of the optics depends on the used aperture. Therefore this calibration approach has for each aperture (Full F-Stop) its own calibration image. In general the light fall off is a function of the image radius. In this calibration approach instead of function the real measured values in the image is used. The figure below shows the profile from the upper left corner to the lower right corner of each of this calibration images to give a feeling on the amount of correction.



Blue 15 dB



Blue 21 dB

This is a camera type specific calibration.

Radiometric Calibration

Defect Pixel

Blue (00128818)

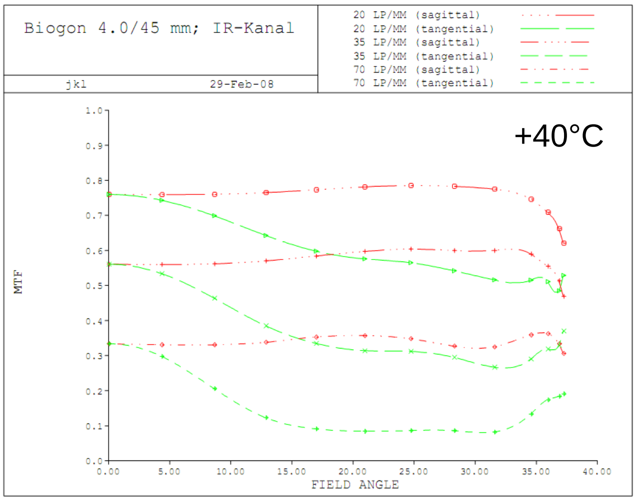
Defect pixels are detected during radiometric calibration and will be corrected during radiometric processing of the images.

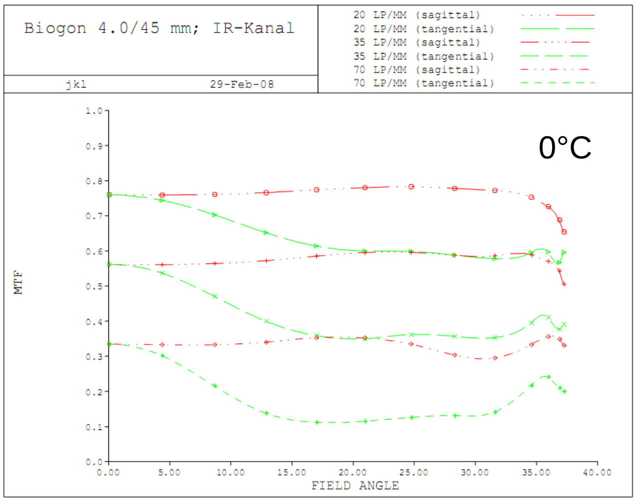
The quantity and cumulative percentage and specification of defects are described in Appendix “Defect Pixel Recognition” at page 46.

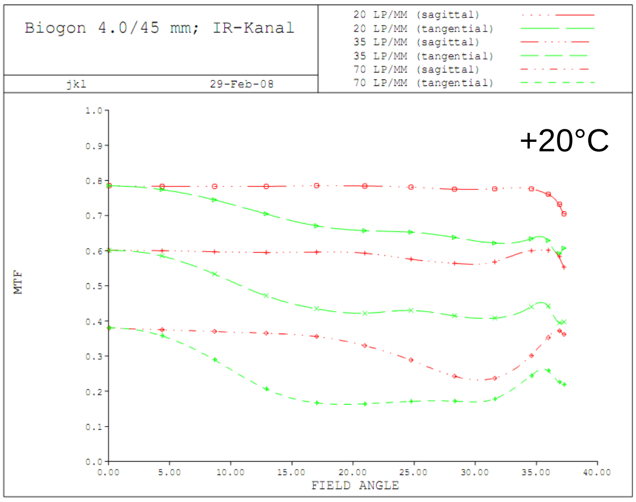
Optical System

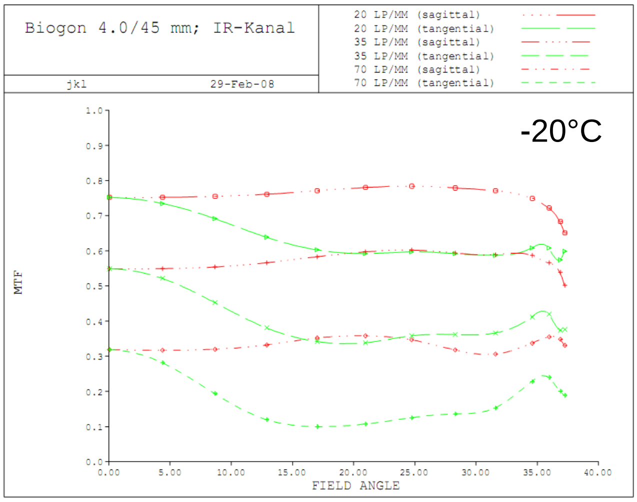
Modulation Transfer Function, MTF of IR camera

DMC III MS IR – MTF F/4.0 ; 45 mm– Temperature Stability





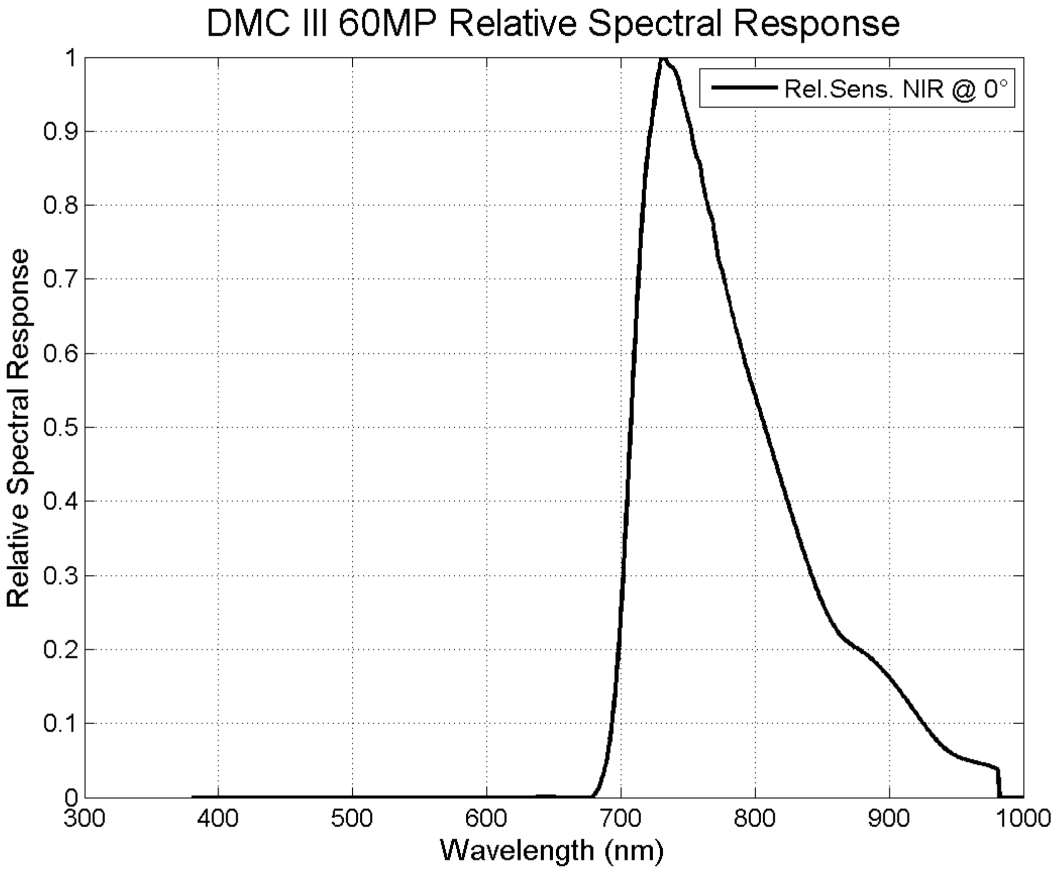




Radiometric Calibration

Sensitivity of NIR camera

Spectral Response Curves of the single camera head.

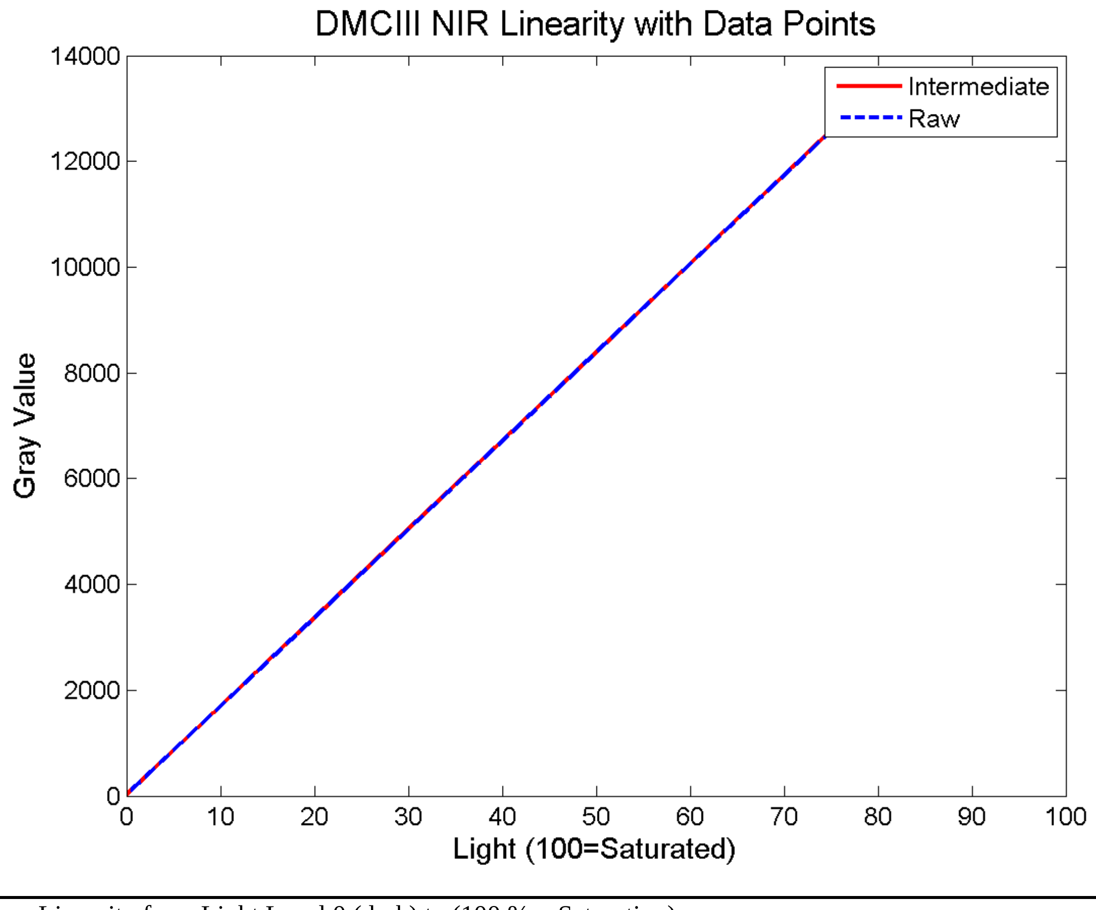


The sensitivity shows the spectral response curve of the single camera head including the optical system (optics, filter) and the sensor response. The DMC III is calibrated with respect to the absolute spectrometer. This allows computing pixel radiance values from pixels digital numbers and is a camera type specific calibration.

Radiometric Calibration

Sensor Linearity (Reference)

The sensor linearity is measured in the Lab with calibrated spectrometer.
This is a camera type specific calibration.
Below figure shows the linearity of the raw sensor and after flat fielding:



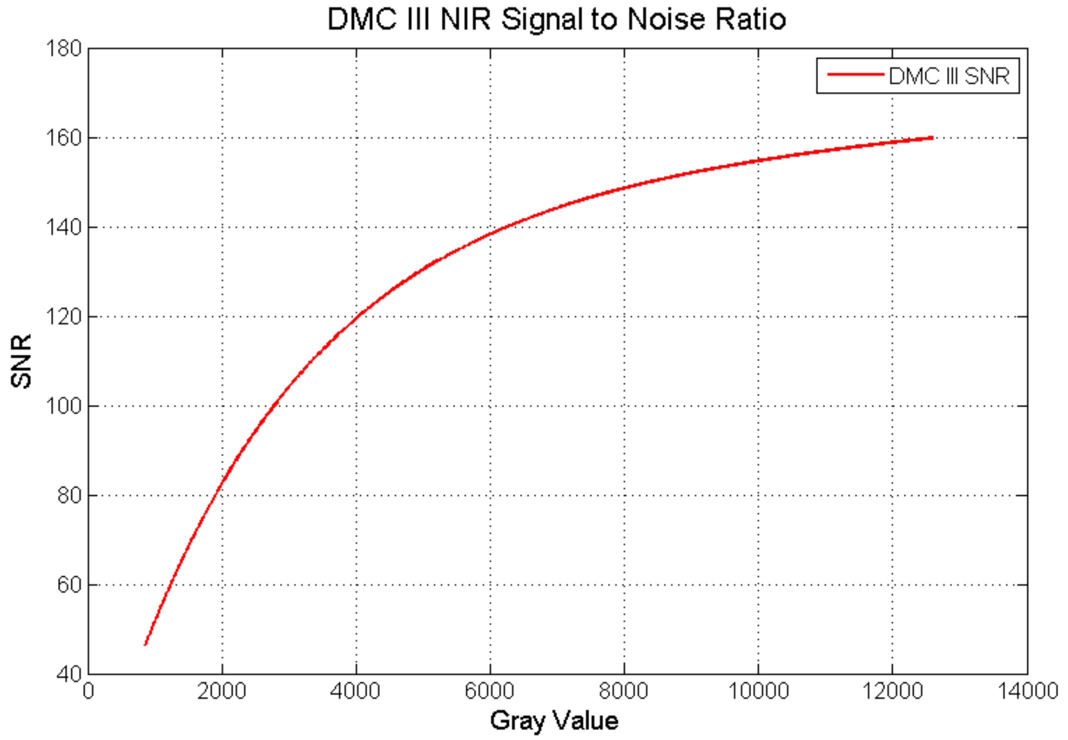
Senor Linearity from Light Level 0 (dark) to (100 % = Saturation)

The deviation from the linearity is below 1%.

Radiometric Calibration

Sensor Noise (Reference)

Sensor noise shows image noise with respect to the image center measured at an aperture of 5.6 with exposure time of 10msec.



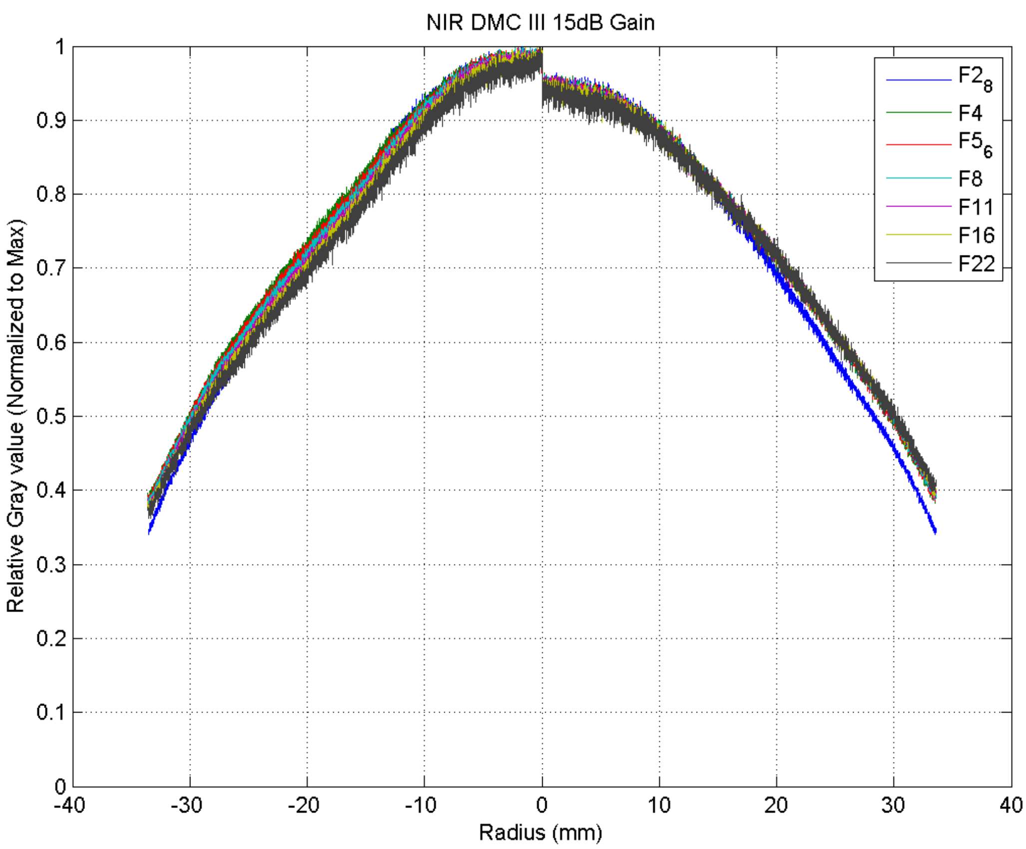
Sensor Signal to Noise Ratio

Radiometric Calibration

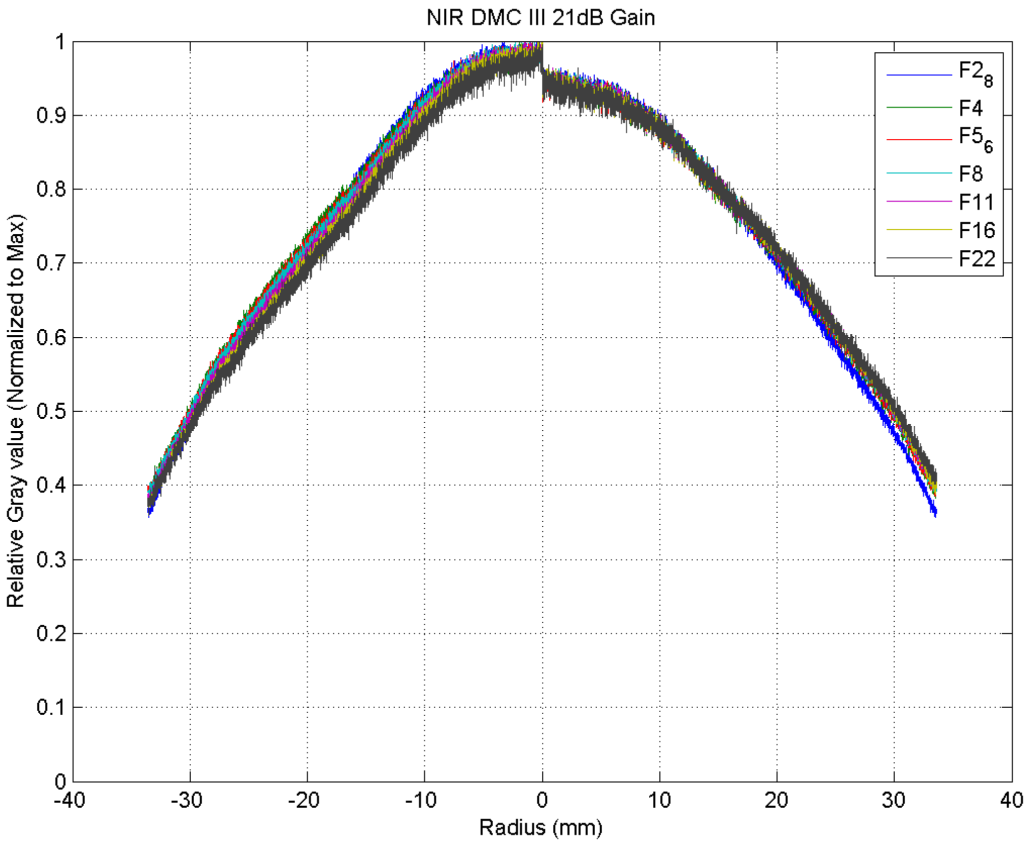
Aperture Correction

NIR (0012879400128774)

The light fall off to the border due the influence of the optics depends on the used aperture. Therefore this calibration approach has for each aperture (Full F-Stop) its own calibration image. In general the light fall off is a function of the image radius. In this calibration approach instead of function the real measured values in the image is used. The figure below shows the profile from the upper left corner to the lower right corner of each of this calibration images to give a feeling on the amount of correction.



NIR 15 dB



NIR 21 dB

This is a camera type specific calibration.

Radiometric Calibration

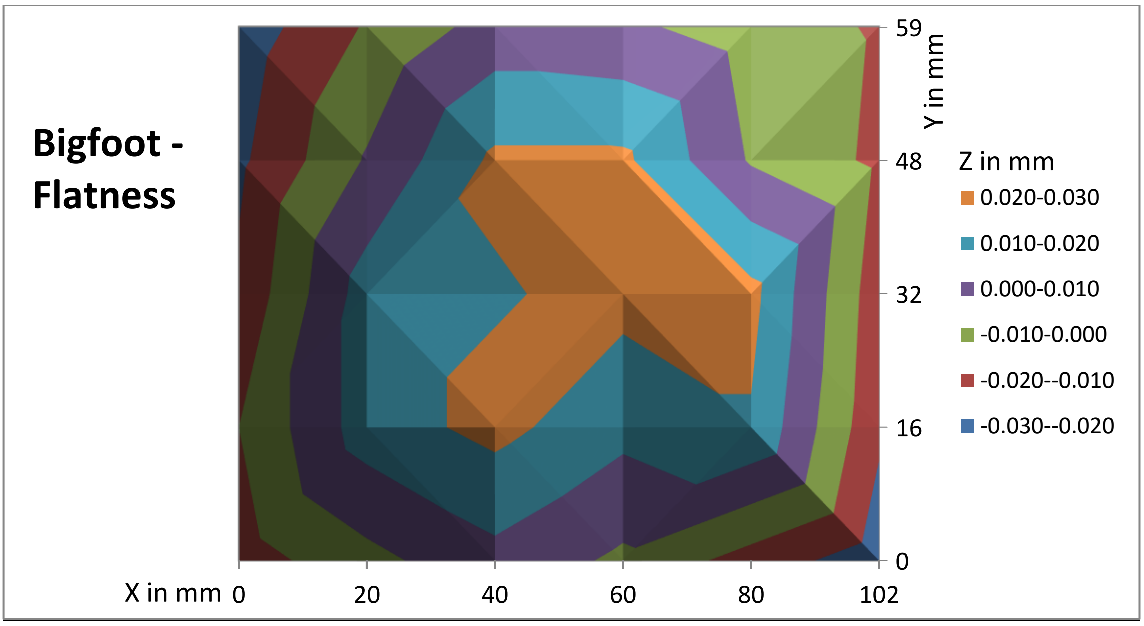
Defect Pixel

NIR (00128794)

Defect pixels are detected during radiometric calibration and will be corrected during radiometric processing of the images.

The quantity and cumulative percentage and specification of defects are described in Appendix “Defect Pixel Recognition” at page 46.

Sensor Geometry



Radiometric Reference Camera Calibration

The DMC III absolute radiometric calibration uses a reference camera to produce consistent DN and radiance values from all cameras systems. The application of the reference camera values occurs within PPS, when color balancing output is selected. Then, a single set of calibration coefficients, along with the current acquisition F# and exposure time, may be used to convert the color balanced (radiometric corrected) DN values to radiance.

A single, reference camera absolute radiometric calibration coefficient is provided for each camera band. For the multispectral cameras, which have variable gains, the calibration is provided at a single reference gain. Theses calibration coefficients are applied to image DN values that have been corrected within PPS to match the reference camera. In PPS, the uncorrected, raw DN values are dark image subtracted and flat fielded using the current camera's calibration files. Then the DN values are scaled to the reference camera maximum DN value for the current acquisition F-stop, and if appropriate, scaled to account for differences in gain. Once these corrections have occurred, the DN values are representative of the reference camera. Then, the corrected DN values can be converted to radiance using the following equation:

$$\mathrm{L} = \mathrm{C}_{ref} \cdot \mathrm{DN}' \frac{\mathrm{F\#}^2}{\tau}$$

Where: **C_{ref}** -- calibration coefficient (in µW ms / (cm2·sr·nm))
F# -- current aperture or f-number
τ -- current exposure time (in ms)
$\mathbf{DN}'$ – radiometric corrected DN value output from PPS

Defect Pixel Recognition

The table below shows the maximal allowed physical defects on the CMOS and CCD Sensors and its definitions.

	Description	CMOS/CCD Spec s/n	PAN 00129134 meet spec	GREEN 00128819 meet spec	RED 00128795 meet spec	BLUE 00128818 meet spec	NIR 00128794 meet spec
Pixel	Bright image	Pixel whose signal, at nominal light (illumination at 50% of the linear range), deviates more than ±30% from its neighboring pixels.					
	Dark image	Pixel whose signal, in dark, deviates more than 6mV from its neighboring pixels (about 1% of nominal light).					
	Max Count	PAN ≤ 15000	yes	---	---	---	---
		MS ≤ 500	---	yes	yes	yes	yes

	Description	CMOS/CCD Spec s/n	PAN 00129134 meet spec	GREEN 00128819 meet spec	RED 00128795 meet spec	BLUE 00128818 meet spec	NIR 00128794 meet spec
Column/Row	Definition	A column which has more than 8 pixel defects in one 1x12 kernel Column defects must be horizontally separated by 5 columns for single line defects and 10 for double line defects					
	Recognition (bright and dark)	Same as defect pixel recognition					
	Max Single Column	PAN ≤ 140	yes	---	---	---	---
		MS ≤ 20	---	yes	yes	yes	yes
	Max double Column	PAN ≤ 40	yes	---	---	---	---
		MS ≤ 6	---	yes	yes	yes	yes
	Max Single Row	PAN ≤ 140	yes	---	---	---	---
	Max double Row	PAN ≤ 40	yes	---	---	---	---

The Post-Processing-Software is correcting following pixel and columns:

	PPS Correction
Pixel	Pixel whose gray value in a 16 x16 kernel differs from the median more than 30%

	PPS Correction
Column	Pixel whose gray value in a 16 x16 kernel differs from the median more than 5% and more than 15 defects in one column

	PPS Correction
Row	Pixel whose gray value in a 16 x16 kernel differs from the median more than 5% and more than 15 defects in one row

Bibliography

Brown D. C. Close-Range Camera Calibration, Photogrammetric Engineering 37(8) 1971

Dörstel C., Jacobsen K., Stallmann D. (2003): DMC – Photogrammetric accuracy – Calibration aspects and Generation of synthetic DMC images, Eds. M. Baltsavias / A.Grün, Optical 3D Sensor Workshop, Zürich

Fraser C., Digital Camera sel-f calibration. ISPRS Journal of Photogrammetry and Remote Sensing, (997, 5284): 149-159

Zeitler W., Dörstel C., Jacobsen K. (2002): Geometric calibration of the DMC: Method and Results, Proceedings ASPRS, Denver, USA.

Ryan R., Pagnutti M. (2009): Enhanced Absolute and Relative Radiometric Calibration for Digital Aerial Cameras, in: Fritsch D. (Ed.), Photogrammetric Week 2009, Wichmann-Verlag, pp. 81-90.

Doering D., Hildebrand J., Diete N. (2009): Advantages of customized optical design for aerial survey cameras, in: Fritsch D. (Ed.), Photogrammetric Week 2009, Wichmann-Verlag, pp. 69-80.

Stoldt, H. (2010): DALSA Ultra large CCD technology Customized for Aerial Photogrammetry. At: ASPRS 2010, San Diego, USA, p. 15.