xiSpec

hyperspectral imaging camera series

Technical Documentation

Version 1.01, Aug 2019

1. Introduction

1.1. About This Manual

Dear customer,

Thank you for purchasing a hyperspectral imaging product from XIMEA.

We hope that this technical manual, together with the manuals for the xiQ- and xiX-camera series, can answer your questions, but should you have any further questions or if you wish to claim a service or warranty case, please contact your local dealer or refer to the XIMEA Support on our website: www.ximea.com/support

This document is subject to change without notice.

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1.2. Helpful Links

- XIMEAHomepage http://www.ximea.com/
- xiSpec hyperspectral cameras https://www.ximea.com/en/usb3-vision-camera/hyperspectral-usb3-cameras-mini
- USB3 Vision Camera Zone http://www.ximea.com/usb3zone
- XIMEA API / SDK description https://www.ximea.com/support/wiki/apis/APIs
- xiAPI stable versions download https://www.ximea.com/support/documents/4
- xiAPI beta versions download https://www.ximea.com/support/documents/14
- Frequently Asked Questions https://www.ximea.com/support/wiki/standard-cameras/FAQ_Hyperspectral_cameras
- Knowledge Base http://www.ximea.com/support/wiki/allprod/Knowledge_Base
- XIMEA Registration http://www.ximea.com/en/products/register
- XIMEA General Terms & Conditions http://www.ximea.com/en/corporate/generaltc

1.2.1. Table of Contents

2. xiSpec Camera Series

2.1. What is xiSpec

xiSpec is an ultra-compact Industrial hyperspectral imaging (HSI) camera family with outstanding facts and features:

Facts

- Cameras with 4, 16, 25, 100 & 150 spectral bands
- 170 fps with USB3 interface, 340 fps with PCIe
- Snapshot and line scan versions
- Smallest and lightest hyperspectral cameras available
- Low power consumption
- Rugged, without moving parts

Features

- Small - fast - flexible
- Snapshot with global shutter
  - 4x4 for 16 bands in the visible 470-630 nm range
  - 4x4 for 16 bands in the red / NIR 600-860 nm range
  - 5x5 for 25 bands in the NIR 600-975 nm (Gen 1) or 665-975 nm (Gen 2) range
- Multi-line scan with global shutter
  - 100 spectral bands 600-975 nm range
  - 150 spectral bands 470-900 nm range
- Snapshot RGB-NIR with global shutter
  - 4 spectral bands 400-900 nm range
- Starter kit available for rapid development
- Flexible and programmable GPIO options

2.2. Model Nomenclature

Order numbers name conventions for the different models:

Based on xiQ USB3.0 camera series:

MQ022HG-IM-<Layout>-<Wavelength>

MQ: xiQ family name

<Layout>: Layout of the Interference filter

OPT = SMnXn snapshot mosaic layout, n=4 | 5

OPT = LSm line scan layout, m= 100 | 150

2.3. Models Overview, sensor and models

The sensor technology used in XIMEA's xiSpec HSI-cameras (HSI = Hyperspectral imaging) is based on standard CMOS area sensors with a native resolution of 2048*1088 pixels (AMS/CMOSIS CMV2000 mono).

The HSI sensors are integrated in the standard USB3-Vision camera series xiQ with up to 170 frames per second.

The technical manual for the xiQ camera series is available at:

http://www.ximea.com/downloads/usb3/manuals/xiq_technical_manual.pdf

The xiSpec cameras are based on the camera model MQ022MG-CM, but of course use other sensors and special filter glasses to optimally support the HSI sensors and calibration data specially adapted for the xiSpec cameras. All standard camera parameters (structure, dimensions, interface, IO system, ...) can be found in the xiQ manual.

Basic information about the camera used

Value	Description
Sensor	AMS / CMOSIS CMV2000 mono
Resolution	2048 x 1088, 2.2 Mpix
Pix. size [µm]	5.5
ADC [bits]	10, 8
Sensor size / diagonal [mm]	11.3 x 6.0
Optical size	2/3 "
Fps	170 (USB3.0), 340 (PCIe X2G2)
Power typ. [W]	1.5

table 2-1, basic camera specs

Note: Maximum frame rate measured at 8 bits per pixel

Model	Bands	Spectral range [nm]
MQ022HG-IM-LS100-NIR	100+	600 – 975
MQ022HG-IM-LS150-VISNIR	150+	470 – 900
MQ022HG-IM-SM4X4-VIS	16	475 – 640 / 450 - 650
MQ022HG-IM-SM4X4-REDNIR	16	600 - 860
MQ022HG-IM-SM5X5-NIR Gen 1	25	600 – 975
MQ022HG-IM-SM5X5-NIR Gen 2	25	665 – 975

table 2-2, models overview

3. General Overview

3.1. Spectral filters and filter response

Hyper spectral filters are added at wafer-level on top of the pixel structure of the sensor.

The spectral filters are Fabry-Perot interference filters. The thickness L of a cavity between two highly reflective surfaces and the refractive index n of the material in the cavity defines the main central wavelength λ of the filter.

$$k\lambda = 2nL\cos\theta$$

The response depends on

- The angle θ inside the cavity / between the light and perpendicular to the sensor surface
- The harmonics k of the interference

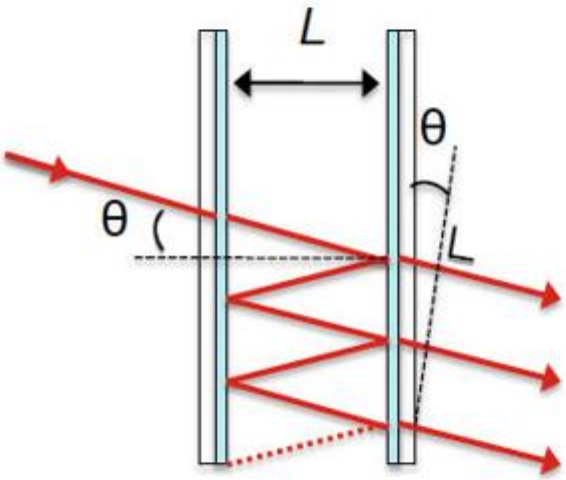


Figure 3-1, Fabry-Perot interference filter - schematics

These filters are added to any of the pixels of the sensor individually (2048 * 1088 pixels with a size of 5.5 µm each).

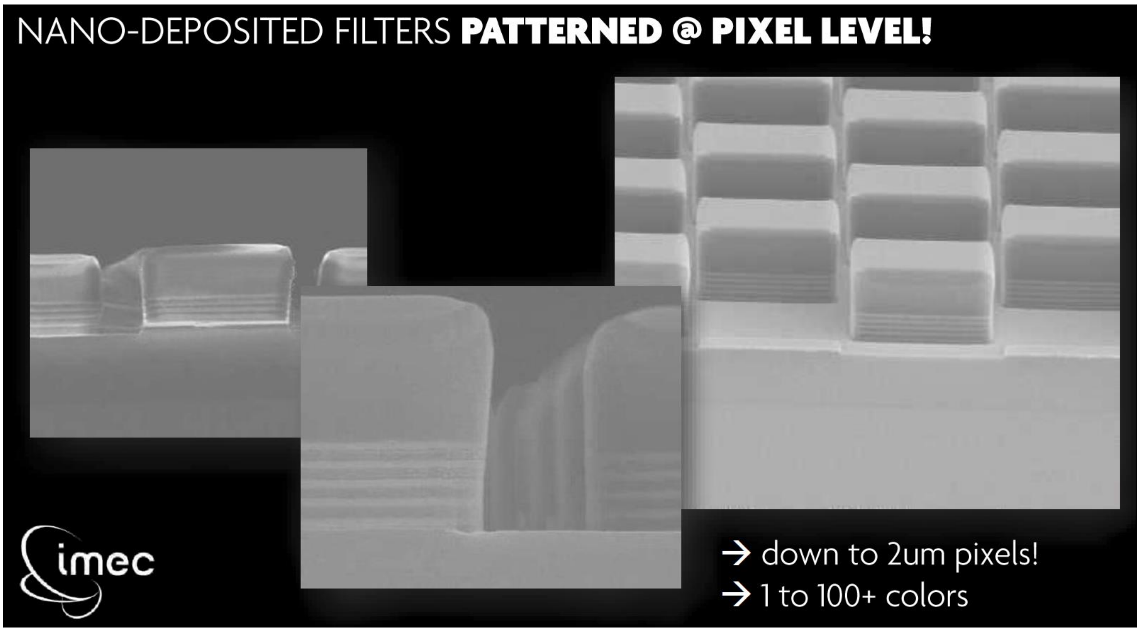


Figure 3-2, Microscope image at wafer level

The response of an ideal interference filter has narrow peaks around the harmonic central wavelength. The intensity distribution is a Gaussian distribution with a given FWHM (Full Width at Half Maximum).

Different cavity heights used on a sensor result in different central wavelength which can be differentiated.

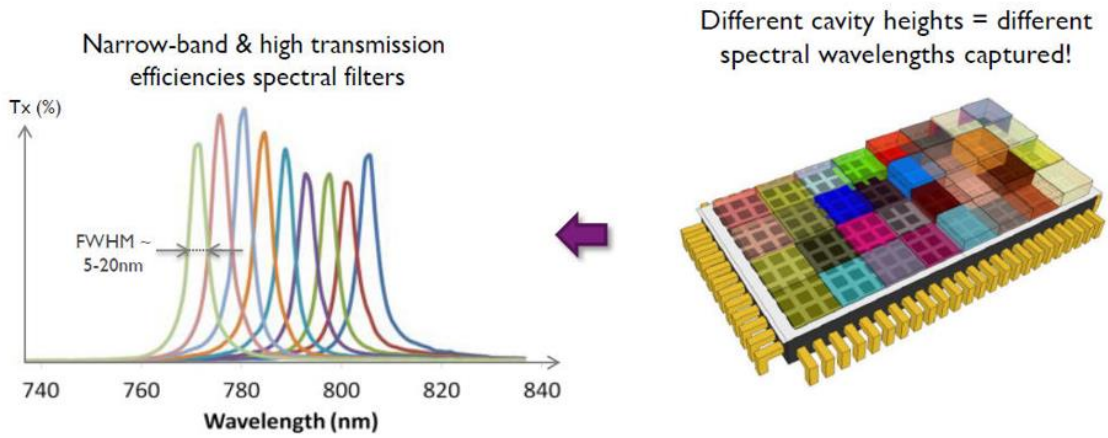


Figure 3-3, example: position of the Fabry-Perot filters and their ideal filter response

The sensors are defined to be used in a camera model with a defined spectral range, or the active (wavelength) range.

The sensor behavior is not defined outside of this range (due to spectral leakage).

Cross talks happen when the signal of one pixel influences the signal on another (neighboring) pixel. This effect causes unwanted response outside the expected peaks of the influenced pixels.

Some filters have two sensitivity peaks (first and second order response) in the active range of the sensor.

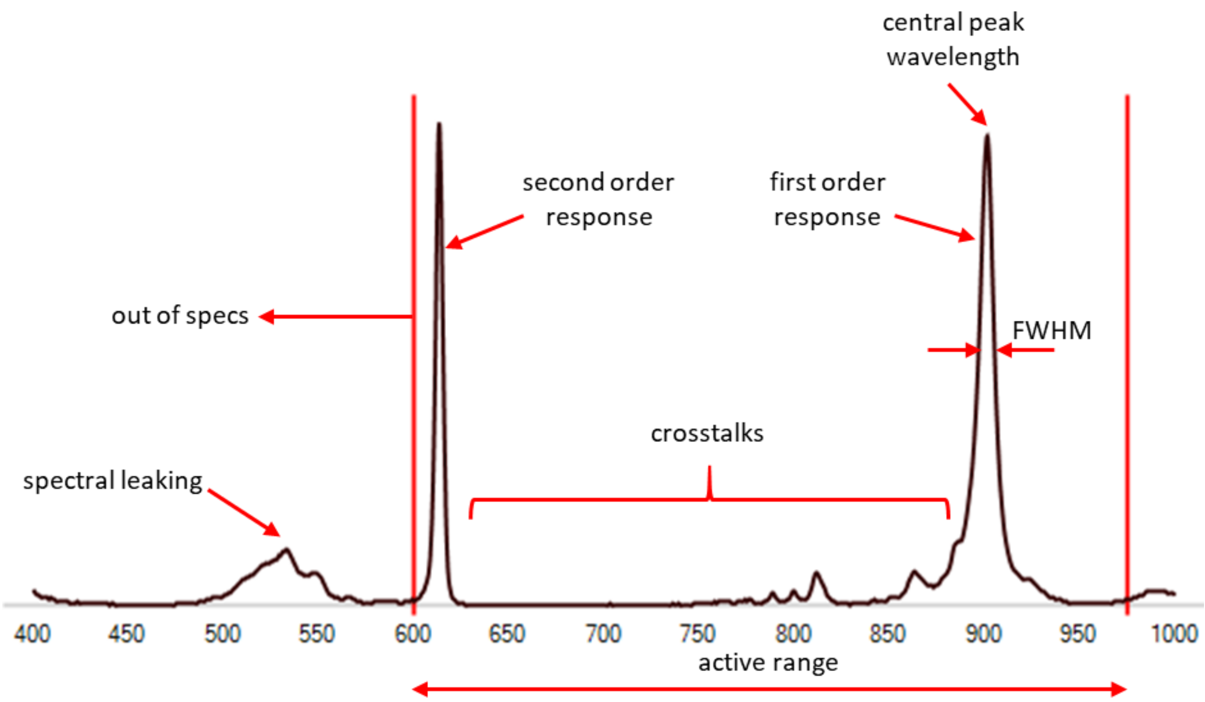


Figure 3-4, example response curve with explanations (from a SM5X5 sensor)

3.2. Camera filter glasses

In xiSpec cameras customized bandpass filters are used, which limit the wavelength range of the light reaching the active area of the sensor.

This glass is placed on a layer of silicone, but not glued. Do not use compressed air to clean the camera as this could push dust into the camera. Distance from the flange to sensor is designed so the optical distance is 17.526mm – 0.2mm.

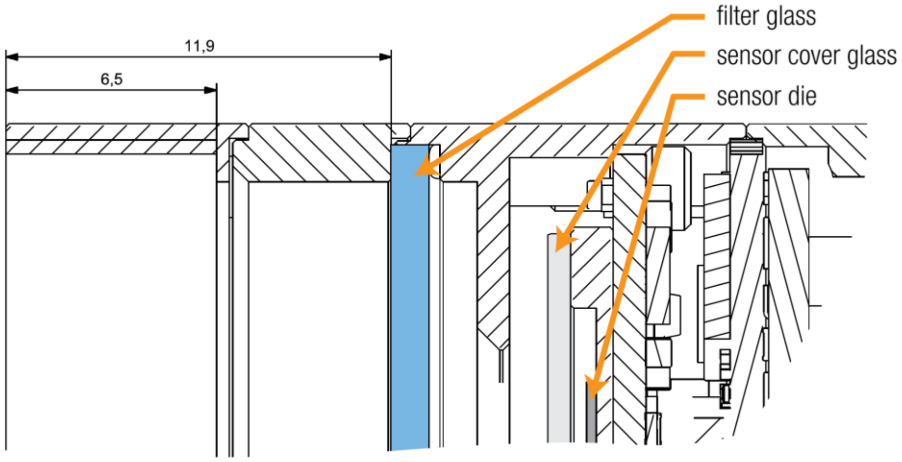


Figure 3-5, position of the customized camera filter glass

3.2.1. Additional filter glasses

With the SM5X5, it is recommended to use additional filters to retain only one of the two interference harmonics.

3.3. Sensor calibration

All sensors have been calibrated / measured at the wafer level. The camera specific calibration file is part of the scope of delivery.

3.4. Hyperspectral data storage and handling format

Basically, the structure is a three dimensional (x, y, λ) hyperspectral data cube, where x and y represent two spatial dimensions and λ represents the spectral dimension.

Usually, such data is stored in ENVI file format (XIMEA use the HDR/BSQ format variant).

Info about the spatial and spectral resolution, the data format and the peak wavelength (width of the spectral bands as an option) are stored in the *.hdr file. Usually, the bands in the cube are sorted by their peak wavelength.

Example of an HDR file:

```
ENVI
description = { XIMEA xiSpec MQ022HG-IM-SM5X5-NIR, SerNr 09580554, Sensor-SN
5.3.3.6
date/time 20180205151004 }
sensor type = IMEC SSM5x5-NIR
file type = ENVI Standard
header offset = 0
samples = 409
lines = 215
bands = 25
data type = 12
interleave = bsq
byte order = 0
```

```
wavelength = {
 693.748, 708.233, 732.38, 746.423, 758.481,
 772.009, 783.529, 797.016, 808.578, 820.679,
 839.837, 851.527, 861.345, 872.504, 882.33,
 891.786, 900.398, 908.869, 926.54, 934.909,
 943.368, 948.619, 955.604, 962.88, 968.93}
```

Further information can be found e.g. here: http://www.exelisvis.com/docs/enviimagefiles.html

3.5. Cubes created by XIMEAs tools xiSpec01 (beta)

Non-spectrally corrected data cubes are always stored with the number of peak wavelengths corresponding to the number of pixels in the HSI pattern, e. g. 16 for SM4x4 and 25 for SM5x5 sensors.

For information: In some cases, the peak wavelengths are very close, the response curves overlap almost completely. This effect is not considered when saving the uncorrected data.

4. Filter layouts / camera models

xiSpec cameras use HSI sensors with different filter layouts. These layouts differ in the basic arrangement of the different filters on the sensor surface.

Basically, we support

- Snapshot mosaic sensors
- Line scan sensors

4.1. Snapshot mosaic sensors

Three different snapshot-mosaic sensors are available. 4x4 or 5x5 mosaic patterns are repeated continuously on the sensor surface:

- 4x4-Filter-array, 16 HSI-bands between 470 -630 nm (camera model MQ022HG-IM-SM4X4-VIS)
- 4x4-Filter-array, 16 HSI-bands between 600 -860 nm (camera model MQ022HG-IM-SM4X4-REDNIR)
- 5x5-Filter-array, 25 HSI-bands between 600 -975 nm (camera model MQ022HG-IM-SM5X5-NIR)

The spatial resolution is approx. 512x272 pixels (4x4 pattern) or 409x217 pixels (5x5 pattern). The original sensor resolution can be interpolated.

These cameras can be used for real time applications. Each image can be interpreted as hyperspectral imaging cube immediately.

4.1.1. Camera MQ022HG-IM-SM4X4-VIS

Wavelength range	470 – 630 nm
# bands	16
Calibration file names	CMV2K-SSM4x4-470_620-x.x.x.x.xml

table 4-1, basic sensor specs, SM4X4-VIS

The CMV2K-SSM4x4 VIS sensor is a CMOSIS CMV2K sensor with 16 filters in a snapshot mosaic layout, active in the visible light. The filter layout is organized in patterns of 4 rows and 4 columns. The 0-based index for the position of the band in the pattern, numbered from left to right, top to bottom. Index positions:

0	1	2	3
4	5	6	7
8	9	10	11
12	13	14	15

Figure 4-1, filter index positions, SM4X4-VIS

A custom made 450-650 nm band pass filter is built into the XIMEA xiSpec camera:

- 450 – 650 nm (cameras produced in 2015 or 2016)
- 475 – 640 nm (cameras produced from 2017)

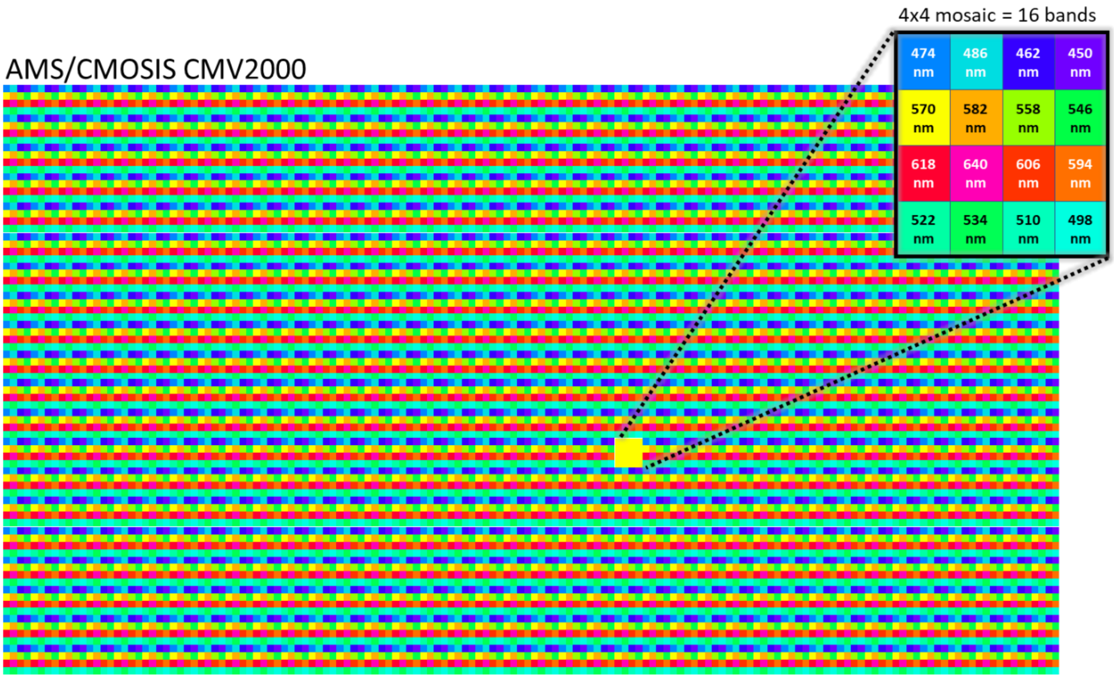


Figure 4-2, filter arrangement at sensor SM4X4-VIS (peak wavelength only exemplary)

Example filter response of the SM4x4 VIS Sensor (470-630 nm):

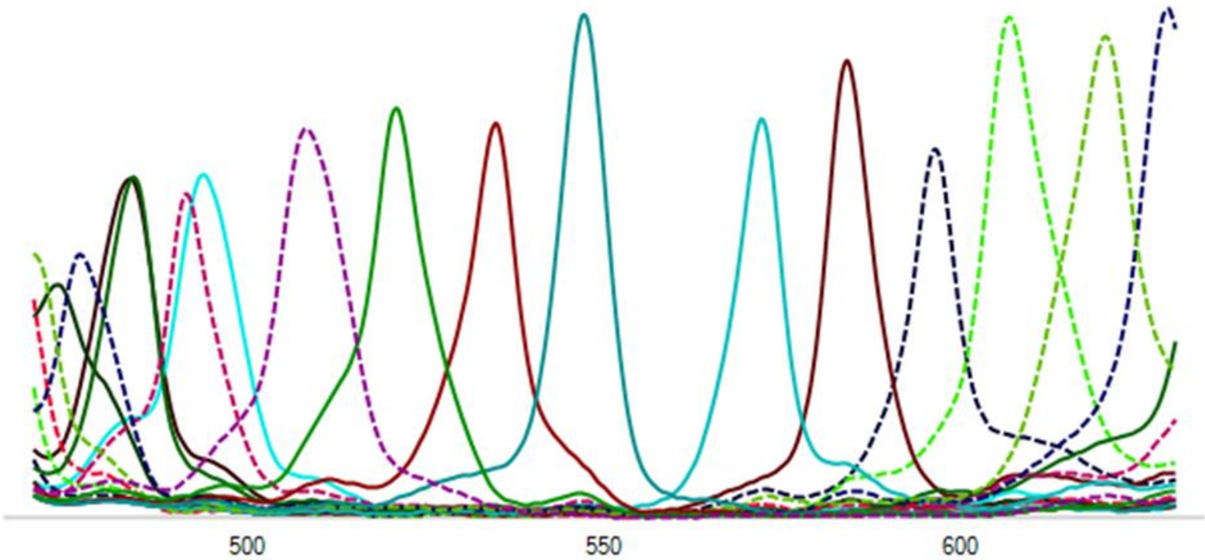


Figure 4-3, example filter response of the SM4X4-VIS Sensor

4.1.2. Camera MQ022HG-IM-SM4X4-REDNIR

Wavelength range	600 – 860 nm
# bands	16
Calibration file names	CMV2K-SSM4x4-600_850-x.x.x.x.xml

table 4-2, basic sensor specs, SM4X4-REDNIR

The CMV2K-SSM4x4 REDNIR sensor is a CMOSIS CMV2K sensor with 16 filters in a snapshot mosaic layout, active in red and near infrared. The filter layout is organized in patterns of 4 rows and 4 columns. The 0-based index for the position of the band in the pattern, numbered from left to right, top to bottom. Index positions:

0	1	2	3
4	5	6	7
8	9	10	11
12	13	14	15

Figure 4-4, filter index positions, SM4X4-REDNIR

A BK7 filter glass, antireflection coated on both sides is installed in the camera, which has no bandpass filter properties. Additional filters for limiting the wavelength range must be used.

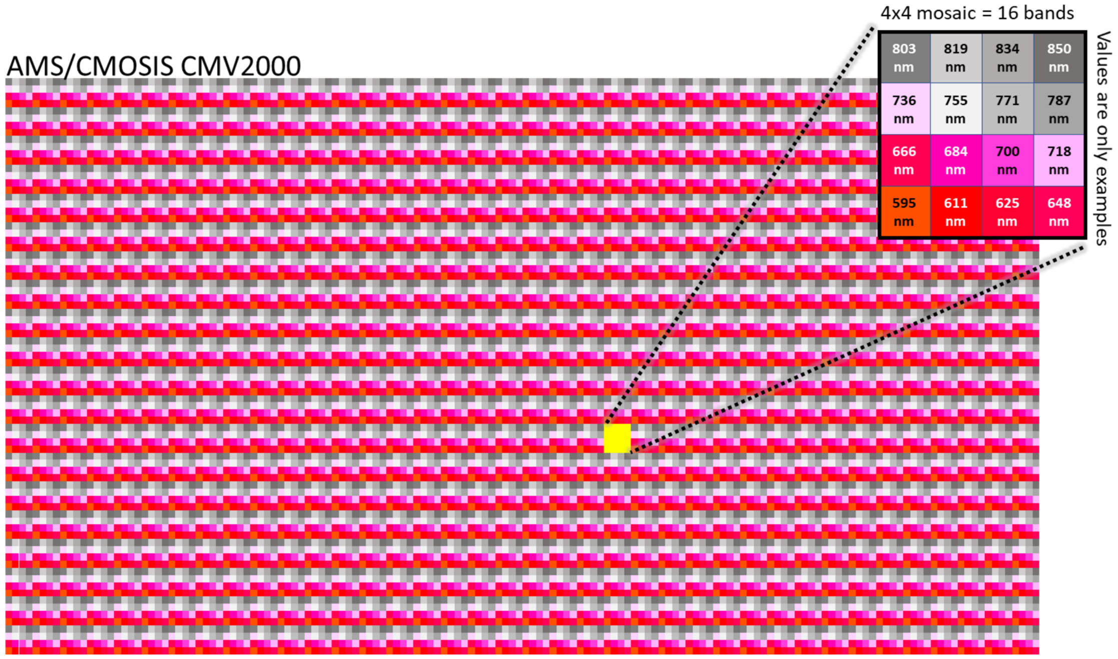


Figure 4-5, filter arrangement at sensor SM4X4-REDNIR (peak wavelength only exemplary)

Example filter response of the SM4x4 REDNIR Sensor (600-860 nm):

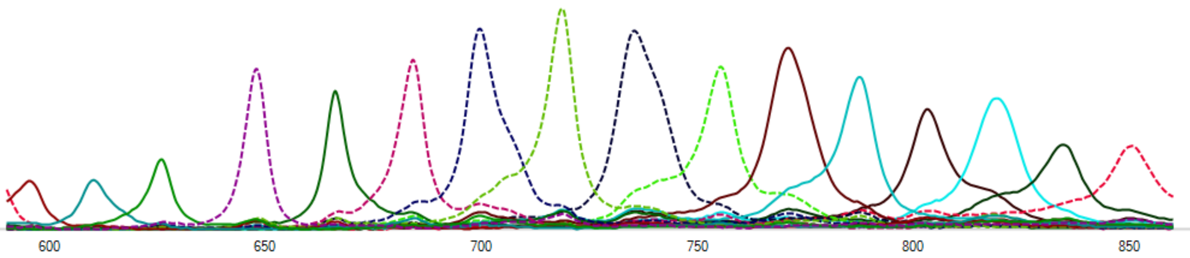


Figure 4-6, example filter response of the SM4X4-REDNIR Sensor

In the following figure the influence of using a 590nm long-pass and a 875nm short-pass filter is visualized. All 16 bands are represented in the effective spectrum.

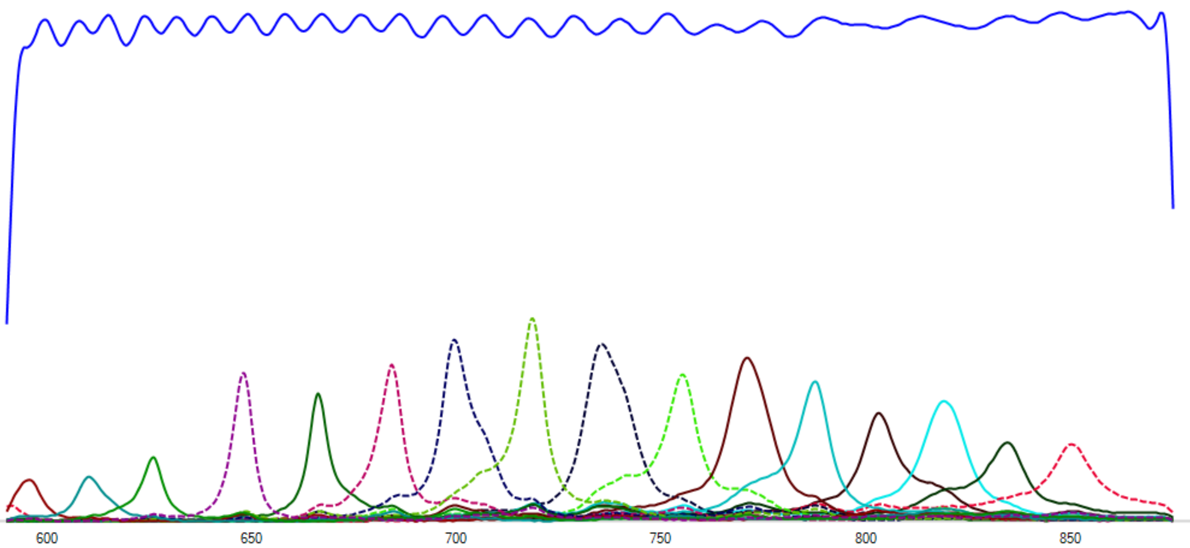


Figure 4-7, effective response curve SM4X4-REDNIR, with filters 590-875nm

Both filters are included in the XIMEA starter kit.

4.1.2.1. Requirements:

It is recommended to use a filter set to limit the light to the recommended wavelength range:

- 590nm long pass (only wavelengths above 590nm will pass)
- 875nm short pass (only wavelengths below 875nm will pass).

The camera requires a broadband coated lens designed for wavelengths ranges of visible light and near infrared up to 875 nm.

4.1.3. Camera MQ022HG-IM-SM5X5 NIR (1st Generation)

Wavelength range	600 – 975 nm (with filters: 600 – 875 nm or 675 – 975 nm)
# bands	25
Calibration file names	CMV2K-SSM5x5-600_1000-x.x.x.x.xml

table 4-3, basic sensor specs, SM5X5-NIR, Gen 1

The CMV2K-SSM5x5 NIR sensor is a CMOSIS CMV2K sensor with 25 filters in a snapshot mosaic layout, active in the near infrared. The filter layout is organized in patterns of 5 rows and 5 columns. The 0-based index for the position of the band in the pattern, numbered from left to right, top to bottom. Index positions:

0	1	2	3	4
5	6	7	8	9
10	11	12	13	14
15	16	17	18	19
20	21	22	23	24

Figure 4-8, filter index positions, SM5X5-NIR

A custom made 600-975 nm band pass filter is built into the XIMEA xiSpec camera.

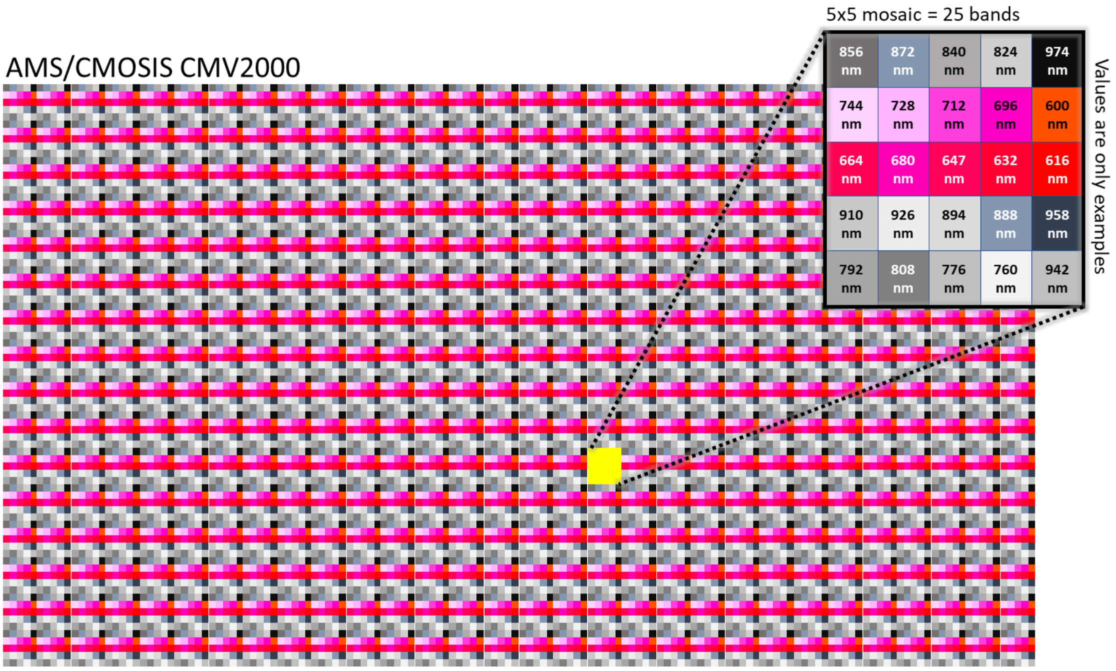


table 4-4 filter arrangement at sensor SM5X5-NIR (peak wavelength only exemplary)

Example filter response of the SM5x5 NIR Sensor (600-975 nm):

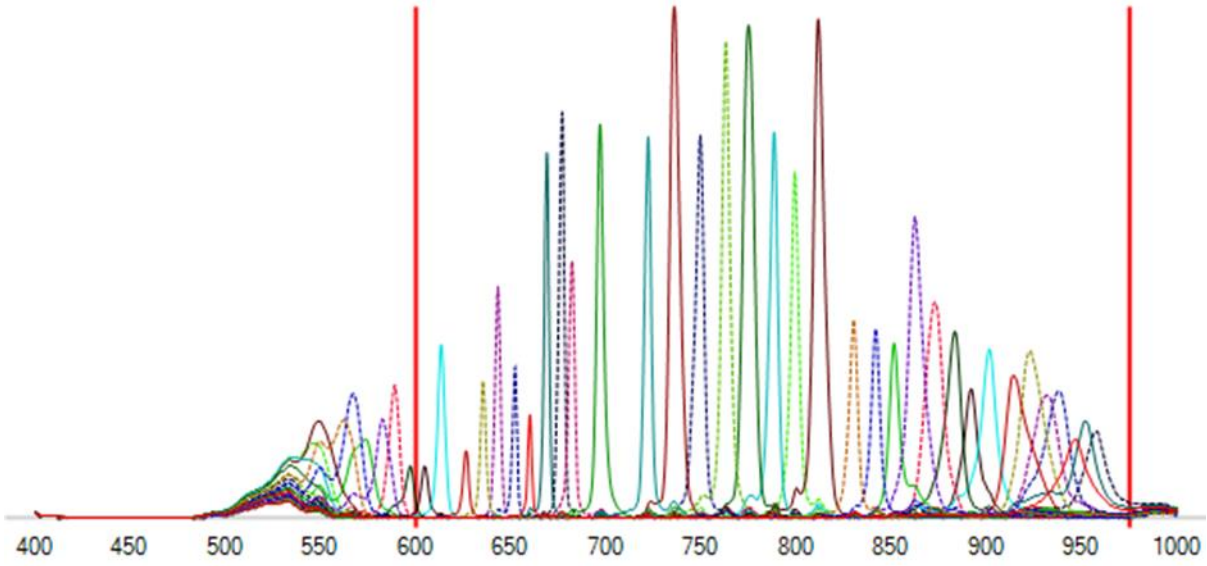


Figure 4-9, example filter response of the SM5X5-NIR Sensor, Gen 1

Several interference filters in case of the SM5X5 camera model do have two peak wavelengths in their response curves, the first and second order harmonics (usually below 675nm and above 875nm).

Bands with first order response in the range of 875 – 975 nm have a second order response in the range of 600-675 nm:

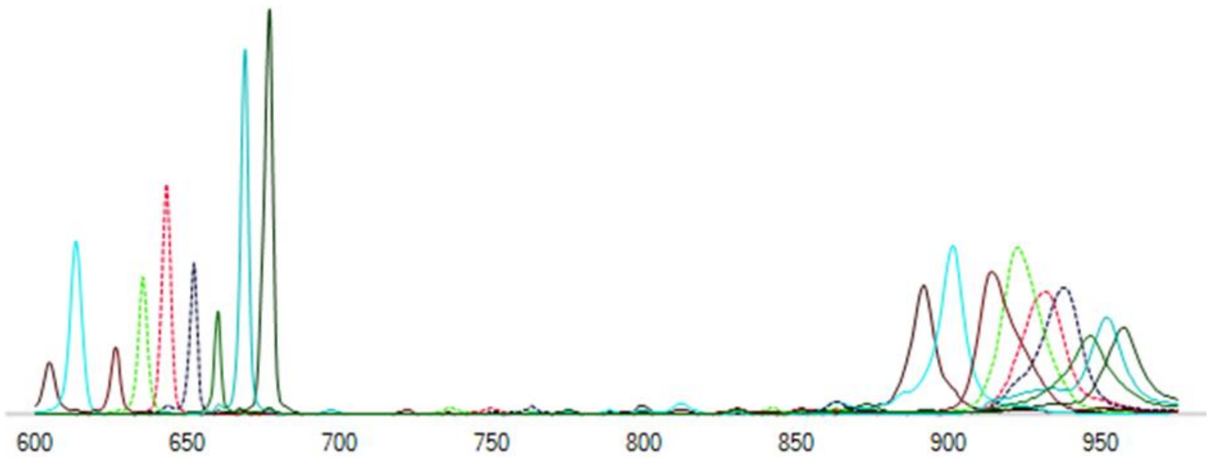


Figure 4-10, example filter response of the SM5X5-NIR Sensor – bands with first and second harmonics, Gen 1

4.1.3.1. Requirements:

It is recommended to use additional filters to retain one of the two peaks:

- 875 nm short pass filter: active wavelength range = 600-875 nm
- 675 nm long pass filter: active wavelength = 675-975 nm

The camera requires a broadband coated lens designed for wavelengths ranges of visible light and near infrared up to 975 nm.

4.1.4. Camera MQ022HG-IM-SM5X5 NIR (2nd Generation)

Wavelength range	665– 975 nm
# bands	25
Calibration file names	CMV2K-SSM5x5-665_975-x.x.x.x.xml

table 4-5, basic sensor specs, SM5X5-NIR, Gen 2

The sensors of the 2nd generation have the big advantage that the distances of the peaks are almost equidistant, and the position of the peaks differ from sensor to sensor by max. +/- 1-2 nm only.

The bands in the wavelength range of approx. 655-960 nm do not show any 2nd harmonics anymore.

However, the SM5X5 sensors of the 2nd generation no longer support the wavelength range of approx. 600-655 nm.

The CMV2K-SSM5x5 NIR sensor is a CMOSIS CMV2K sensor with 25 filters in a snapshot mosaic layout, active in the near infrared. The filter layout is organized in patterns of 5 rows and 5 columns. The 0-based index for the position of the band in the pattern, numbered from left to right, top to bottom. Index positions:

0	1	2	3	4
5	6	7	8	9
10	11	12	13	14
15	16	17	18	19
20	21	22	23	24

Figure 4-11, filter index positions, SM5X5-NIR

A custom made 600-975 nm band pass filter is built into the XIMEA xiSpec camera.

table 4-6 filter arrangement at sensor SM5X5-NIR (peak wavelength only exemplary)

Example filter response of the SM5x5 NIR Sensor (600-975 nm):

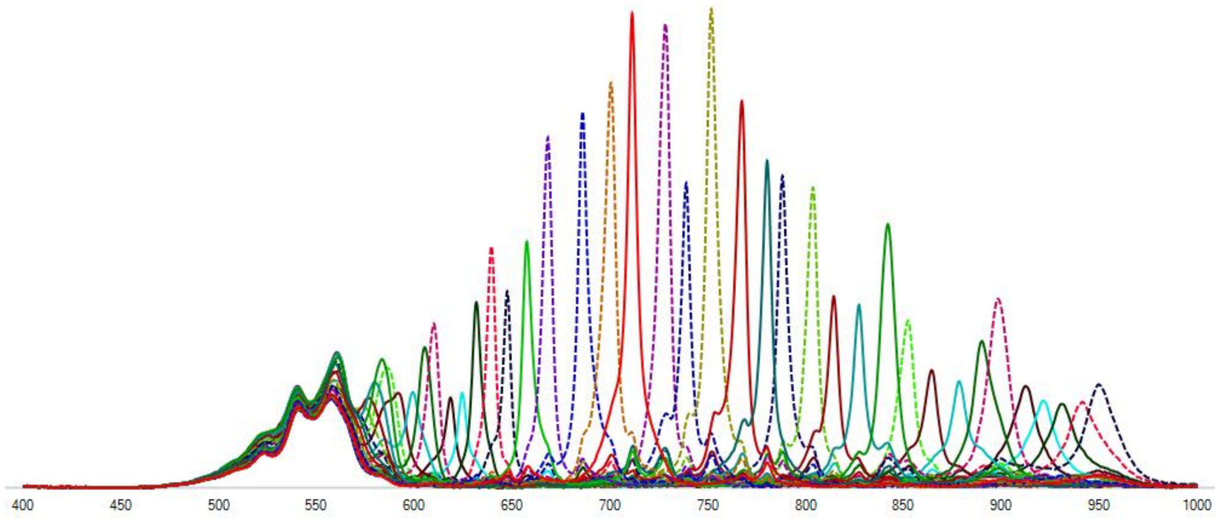


Figure 4-12, example filter response of the SM5X5-NIR Sensor, Gen 2

Several interference filters in case of the SM5X5 camera model do have two peak wavelengths in their response curves, the first and second order harmonics.

The following figure shows the typical peak positions of the SM5X5 Gen 2 sensor.

The peak at about 648-650nm is the 2nd harmonic of the band with the main peak at about 950nm (band 25 in the figure).

The peak at about 657-659nm is the first peak of the 25 bands that can be considered (band 1 in the figure).

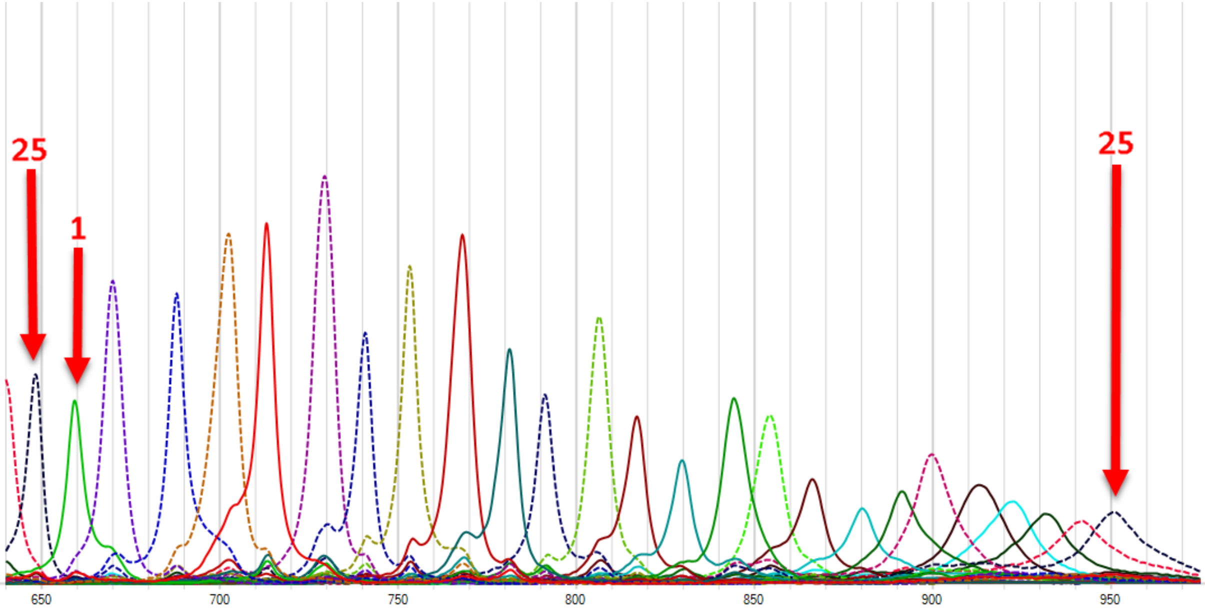


Figure 4-13, band positions of the SM5X5-NIR Sensor, Gen 2

In the following figure the influence of using a 650nm long-pass filter (together with the 600-975nm bandpass filter of the camera) is visualized. All 25 bands are represented in the effective spectrum. Unfortunately, a small part of the 2nd harmonic of band 25 remains.

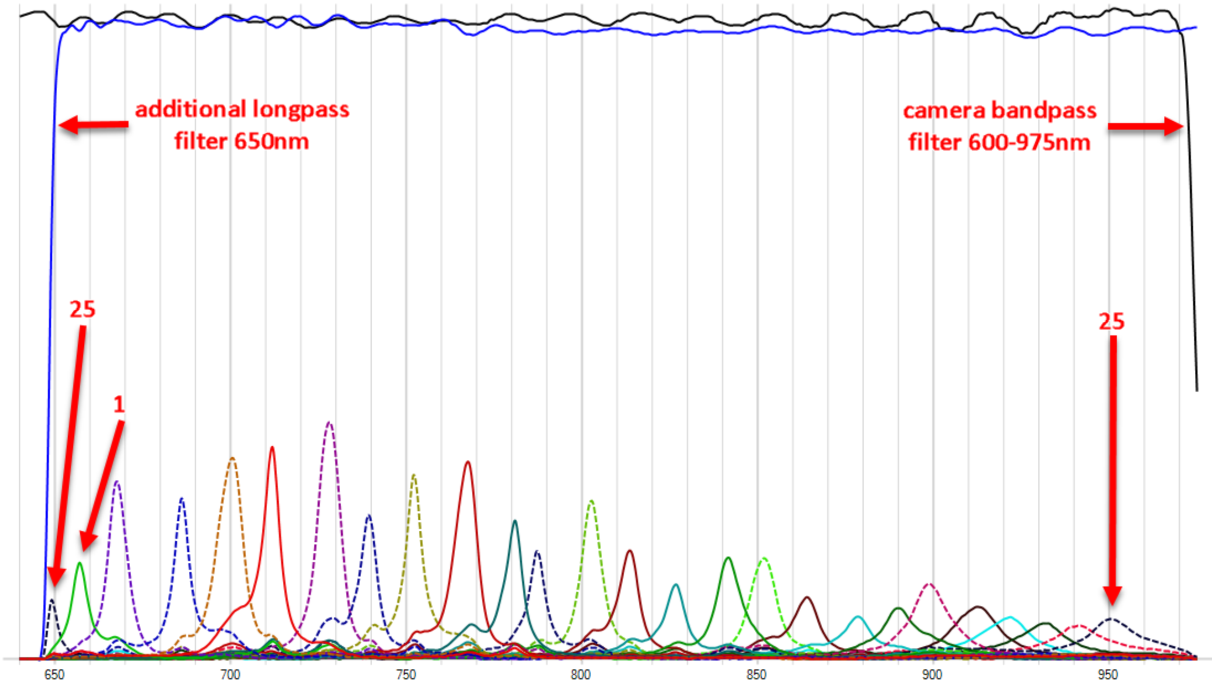


Figure 4-14, effective response curve SM5X5-NIR Sensor, Gen 2, with bandpass and additional 650nm long pass filter

Alternatively, a 660nm long-pass filter can be used. This filter corresponds to the current recommendation of IMEC. Unfortunately, band 1 will be almost completely filtered out.

Both long-pass filters are included in the XIMEA starter kit.

4.1.4.1. Requirements:

It is recommended to use additional filters to retain second order peaks:

- 650 nm long pass filter: active wavelength = 650-975 nm
- 660 nm long pass filter: active wavelength = 660-975 nm

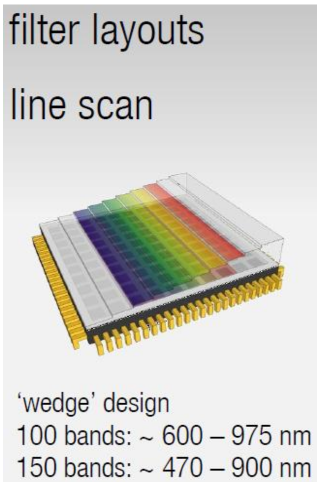
The camera requires a broadband coated lens designed for wavelengths ranges of visible light and near infrared up to 975 nm.

4.2. Line scan sensors

Two line scan hyperspectral imaging sensors are available:

- LS100 with 100+ spectral bands between 600 and 975 nm in approx. 4nm steps
- LS150 with 150+ spectral bands between 470 and 900 nm in approx. 3mm steps

The line scan filter layout has a wedge design. The *n* filters in the line scan layout are organized in *n* bands of a fixed height over the full width of the active area.



Typically, the width of the active area equals the width of the sensor. The height of the active area equals *n* times the height of the bands in pixels (e.g., 8 pixels). The band at the top of the active area has position index 0. The position index is incremented to the bottom of the active area, with the band at the bottom of the active area has position index *n-1*. The line scan wedge layout is summarized below:

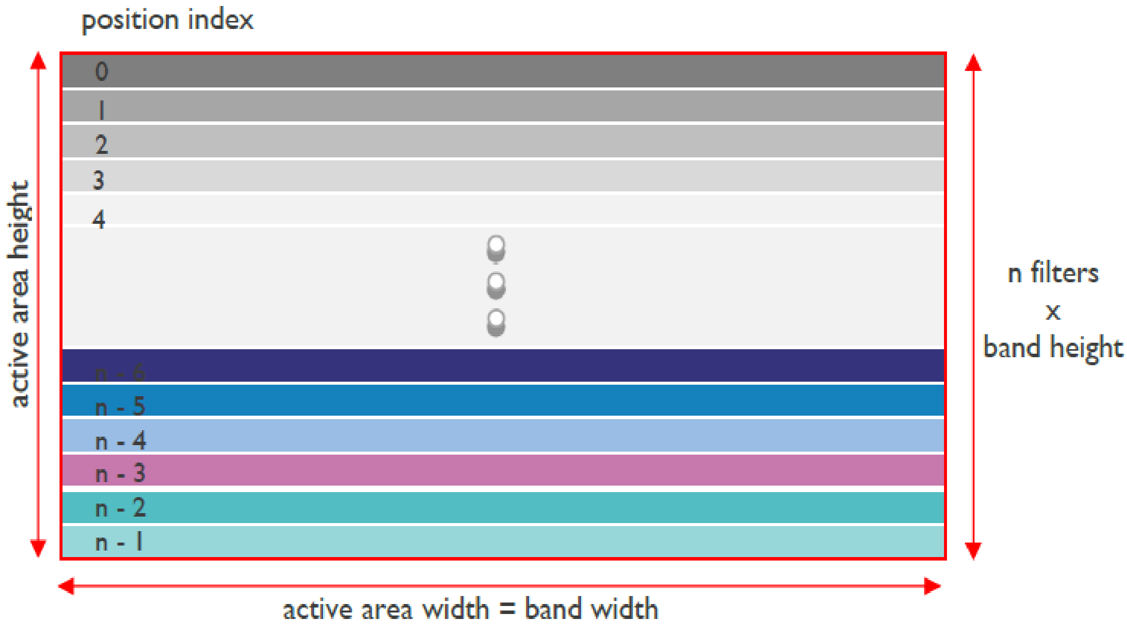


Figure 4-15, Principle structure of a line scan sensor (Source: imec)

Because of the organization of the filters in bands over the whole width of the sensor, this filter layout is best suited for line scan applications.

Note that the number of available bands does not necessarily coincide with the actual number of bands on the sensor. This is because some bands are used for production quality checks and future product development.

(Source: imec, "hyperspectral sensors, technology review", V1.1, 2017-10-25)

4.2.1. Camera MQ022HG-IM-LS100 NIR

Wavelength range	600 – 975 nm
# bands	100+ (max. 128)
Calibration file names	CMV2K-LS100-600_1000-x.x.x.x.xml

table 4-7, basic sensor specs, LS100

The CMV2K LS100 NIR sensor is a CMOSIS CMV2K sensor with 128 filters in a wedge pattern, active in the near infrared (600-975 nm). Each band is 8 rows high, covering 1024 rows of the sensor.

<u>Note</u>: At least 100 of the 128 bands are available for use on the sensor. The remaining bands are used for production quality checks and future product development. Typically, the available bands are band 13 to band 114.

A custom made 600-975 nm band pass filter is built into the XIMEA xiSpec camera.

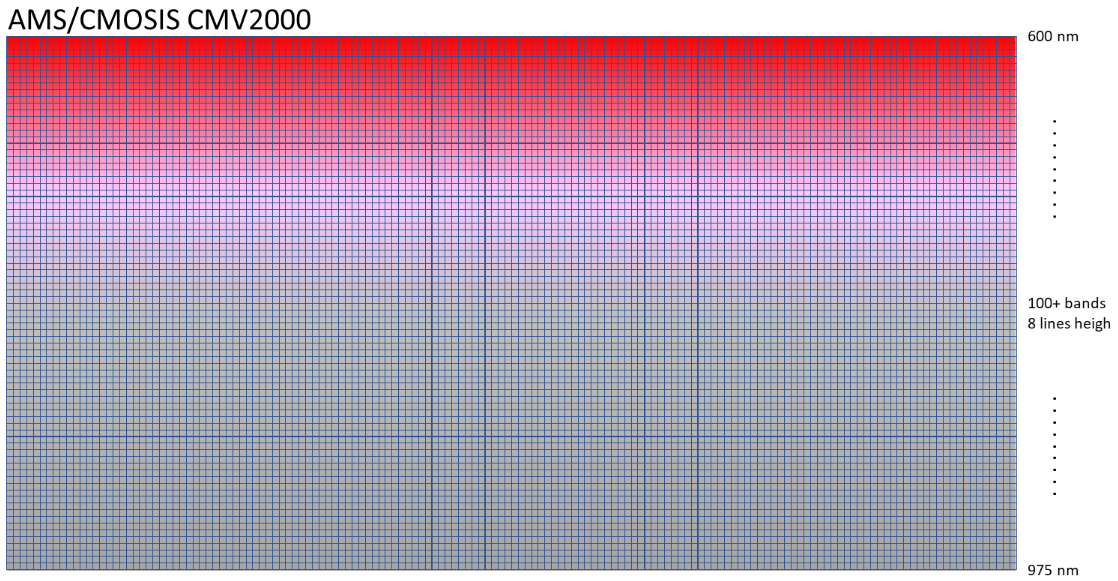


Figure 4-16, filter arrangement at sensor LS100

Example filter responses of the LS100+ NIR sensor in the active range of 600-1000nm:

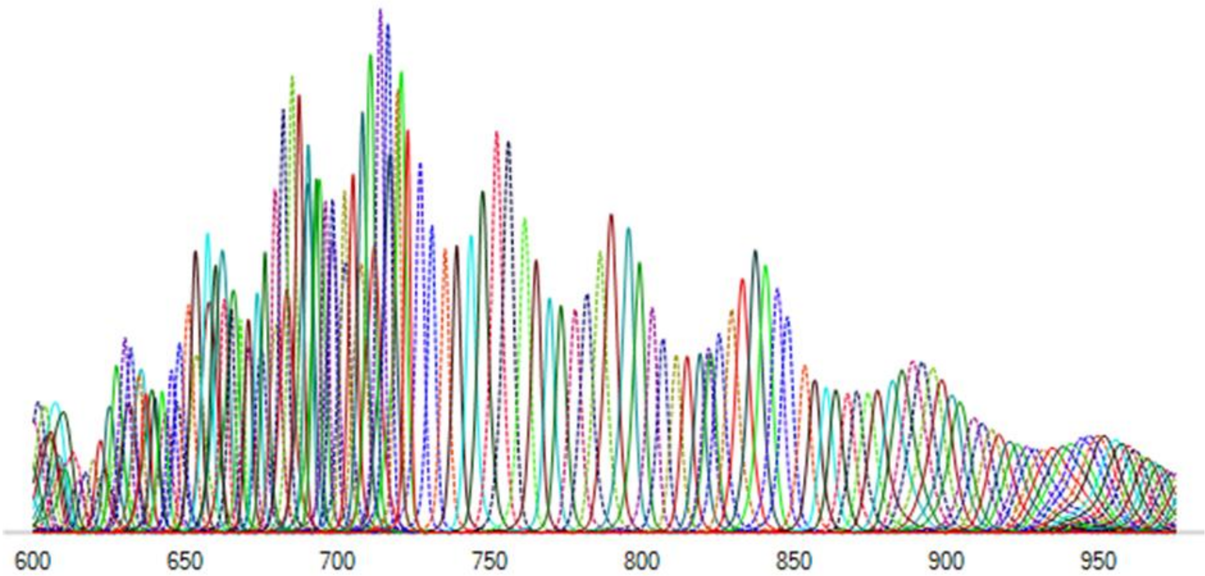


Figure 4-17, example filter response of the LS100 Sensor

Several interference filters in case of the LS100 camera model do have two peak wavelengths in their response curves, the first and second order harmonics.

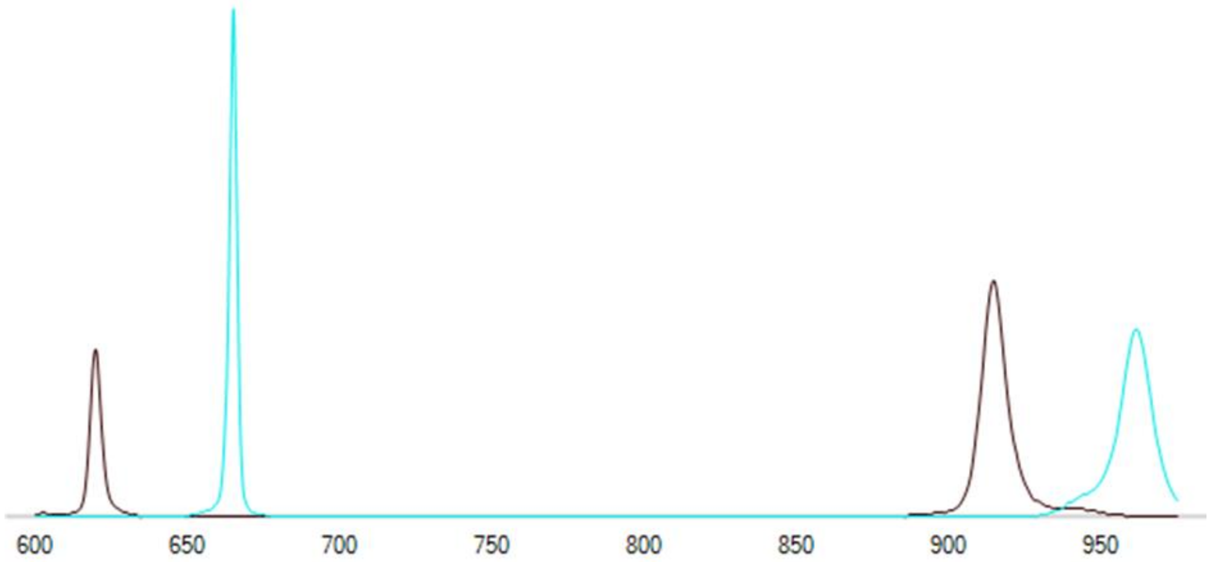


Figure 4-18, example filter response of the LS100 Sensor – bands with first and second harmonics

4.2.1.1. Requirements:

The camera requires a broadband coated lens designed for wavelengths ranges of visible light and near infrared up to 975 nm.

4.2.2. Camera MQ022HG-IM- LS150 NIR

Wavelength range	470 – 900 nm
# bands	150+ (max. 192)
Calibration file names	CMV2K-LS150-470_900-x.x.x.x.xml

table 4-8, basic sensor specs, LS150

The CMV2K LS150 VIS-NIR sensor is a CMOSIS CMV2K sensor with 64 filters active in the visual range (470-600 nm) and 128 filters active in the near infrared (600-900 nm). The filters are distributed over two separate active areas. Within each active area, the filters are organized in a wedge pattern in which each band covers 5 rows. The active areas are separated from each other by an empty interface zone of 120 rows. An overview of the filter layout is given in the figure below.

0	VIS
1	VIS
	...
62	VIS
63	VIS
	empty interface zone
64	NIR
65	NIR
	...
190	NIR
191	NIR

Figure 4-19, Principle structure of aLS150 line scan sensor with 2 filter zones (Source: imec)

Note: At least 150 of the 192 bands are available for use on the sensor. The remaining bands are used for production quality checks and future product development.

Note: The pixel response in the empty interface zone is not defined. These pixels are often fully saturated.

A custom made 460-910 nm band pass filter is built into the Ximea xiSpec camera.

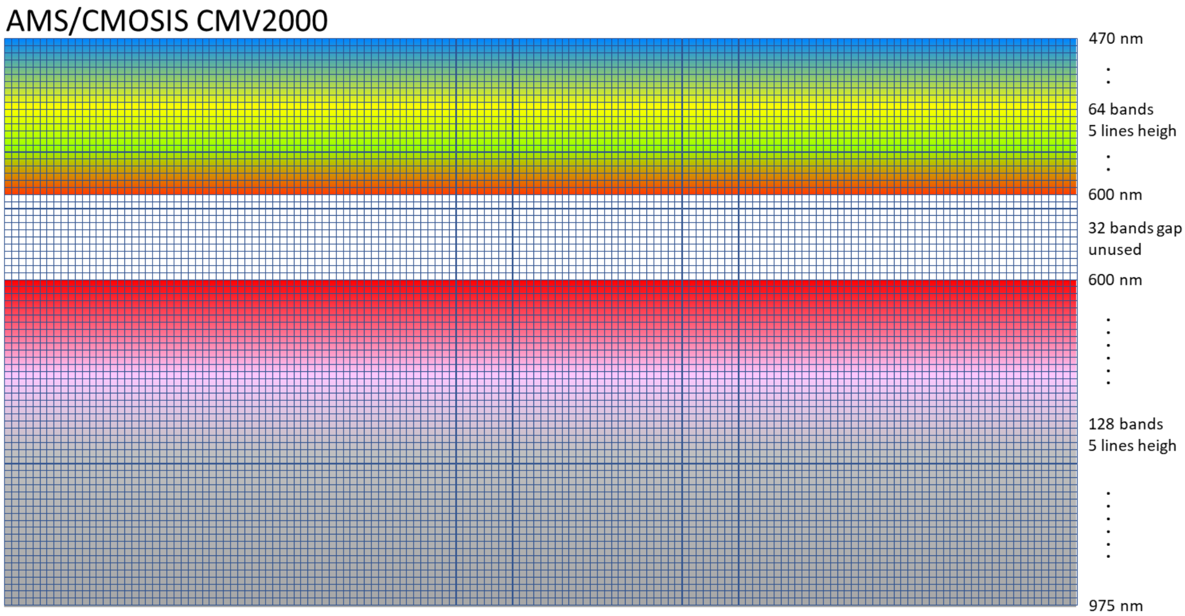


Figure 4-20, filter arrangement at sensor LS150

An example of the responses of the filters is given in the figure below for wavelengths in the range of 400 to 1000 nm. The sensor is designed for an active range of 470-900 nm.

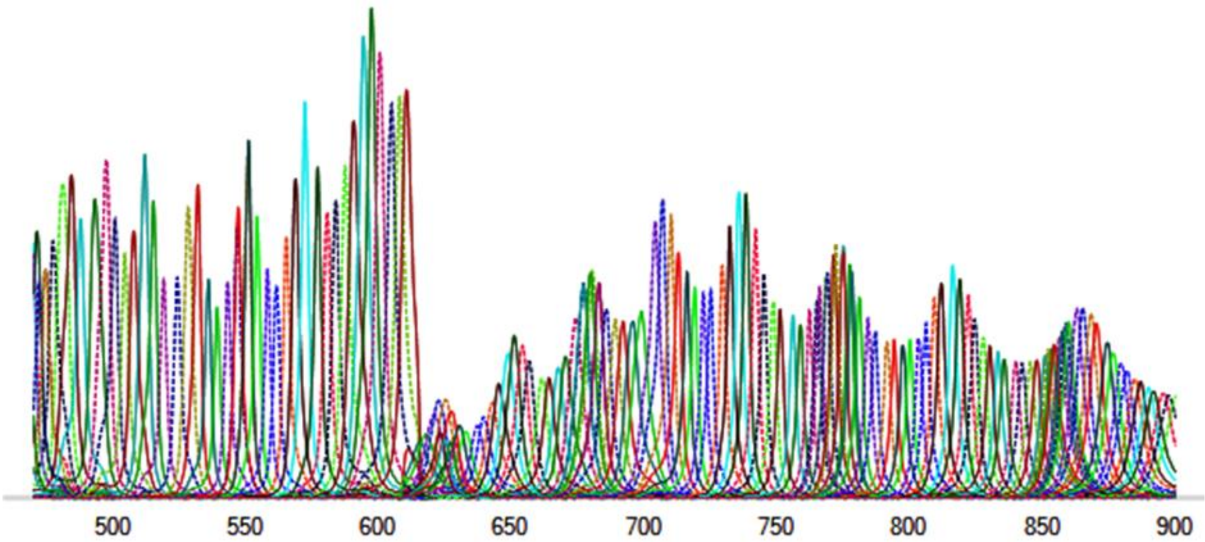


Figure 4-21, example filter response of the LS150 Sensor

Several interference filters in the second filter zone have two peak wavelengths in their responsivity curves, the first and second order harmonics.

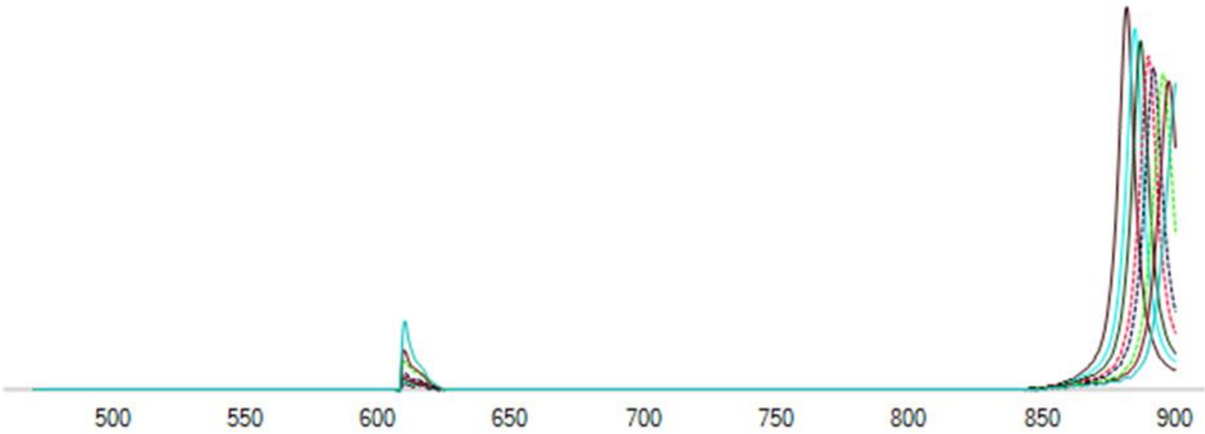


Figure 4-22, example filter response of the LS150 Sensor – bands with first and second harmonics

4.2.2.1. Requirements:

The camera requires a broadband coated lens designed for wavelengths ranges of visible light and near infrared up to 900 nm.

5. xiSpec starter kits

5.1. kits - scope of delivery

The following (optional) accessories are available:

Item P/N	Description
XISPEC-KIT-LS100-NIR XISPEC-KIT-LS150-VISNIR XISPEC-KIT-SM4X4-VIS	VIS/NIR lens 35mm focal length, with filter mount thread Lite Diffuse Reflectance target, Tripod bracket, Mini tripod USB3.0 cable 3.0 m, Trigger I/O cable 3m, PELI transport case
XISPEC-KIT-SM4x4-REDNIR	VIS/NIR lens 35mm focal length, with filter mount thread Filter mount with cut-off filter assembly 590nm long pass and 875nm short pass Lite Diffuse Reflectance target, Tripod bracket, Mini tripod USB3.0 cable 3.0 m, Trigger I/O cable 3m, PELI transport case
XISPEC-KIT-SM5x5-NIR Gen 1	VIS/NIR lens 35mm focal length, with filter mount thread Filter mount with cut-off filter assembly 675-nm long pass Filter mount with cut-off filter assembly 875 nm short pass Lite Diffuse Reflectance target, Tripod bracket, Mini tripod USB3.0 cable 3.0 m, Trigger I/O cable 3m, PELI transport case
XISPEC-KIT-SM5x5-NIR Gen 2	VIS/NIR lens 35mm focal length, with filter mount thread Filter mount with cut-off filter assembly 650nm long pass Filter mount with cut-off filter assembly 660nm long pass Lite Diffuse Reflectance target, Tripod bracket, Mini tripod USB3.0 cable 3.0 m, Trigger I/O cable 3m, PELI transport case

table 5-1, xiSpec starter kits

5.2. Lens

The lens is an industrial grade NIR corrected, broadband coated lens (425-1000 nm) C-mount lens from Edmund Optics with a filter mount thread (25.5 x 0.5mm) with manually aperture and focus control.

The standard lens has a focal length of 35mm. Lenses with focal lengths of 16mm and 25mm are available on request:

- 16mm: FOV horizontal: 38.9°, vertical: 21.2°, WD: 100mm - ∞, weight: 74g
- 25mm: FOV horizontal: 25.5°, vertical: 13.7°, WD: 100mm - ∞, weight: 48g
- 35mm: FOV horizontal: 18.3°, vertical: 9.8°, WD: 165mm - ∞, weight: 75g

Lens selection is a critical component of a hyperspectral imaging project. Longer focal lengths are recommended to decrease cross-talk between pixels.

Components:

Lens EdmundOptics VIS/NIR lens, C-Mount 35mm fixed focal length with M25.5x0.5mm filter thread (#67-716)
https://www.edmundoptics.com/imaging-lenses/fixed-focal-length-lenses/35mm-c-series-vis-nir-fixed-focal-length-lens/

Lens EdmundOptics VIS/NIR lens, C-Mount 25mm fixed focal length with M25.5x0.5mm filter thread (#67-715)
https://www.edmundoptics.com/imaging-lenses/fixed-focal-length-lenses/25mm-c-series-vis-nir-fixed-focal-length-lens/

Lens EdmundOptics VIS/NIR lens, C-Mount 16mm fixed focal length with M25.5x0.5mm filter thread (#67-714)
https://www.edmundoptics.com/imaging-lenses/fixed-focal-length-lenses/16mm-c-series-vis-nir-fixed-focal-length-lens/

5.3. Additional filters, XISPEC-KIT-SM4X4-REDNIR

A filter set is part of the SM4X4-REDNIR starter kit to limit the light to the recommended wavelength range:

- 590nm long pass (only wavelengths above 590nm will pass)
- 875nm short pass (only wavelengths below 875nm will pass).

5.3.1. Components:

Edmund Optics Filter Mount M25.5 x 0.5mm for 25mm diameter filters (#65-800)
http://www.edmundoptics.com/optics/optical-filters/optical-filter-accessories/m25-5-m30-5-mounts-for-25mm-diameter-filters/65800/

590nm long pass filter (Omega Rapid Edge RPE590LP):
https://www.omegafilters.com/product/2899

875 nm short pass filter (#86-106)
http://www.edmundoptics.com/optics/optical-filters/shortpass-edge-filters/high-performance-od-4-shortpass-filters/86106/

5.4. Additional filters, XISPEC-KIT-SM5X5-NIR Gen 1

It is recommended to use filters to avoid these double peaks (4.1.3 Camera MQ022HG-IM-SM5X5 NIR (1st Generation)).

Two filters are part of the SM5X5 Gen 1 starter kit:

- 675nm long pass (only wavelengths above 675nm will pass -> wavelength range 675 - 975 nm)
- 875nm short pass (only wavelengths below 875nm will pass -> wavelength range 600 - 875 nm).

5.4.1. Components:

Edmund Optics Filter Mount M25.5 x 0.5mm for 25mm diameter filters (#65-800)
http://www.edmundoptics.com/optics/optical-filters/optical-filter-accessories/m25-5-m30-5-mounts-for-25mm-diameter-filters/65800/

675nm long pass filter (#84-747):
http://www.edmundoptics.com/optics/optical-filters/longpass-edge-filters/high-performance-od-4-longpass-filters/84747/

875 nm short pass filter (#86-106)
http://www.edmundoptics.com/optics/optical-filters/shortpass-edge-filters/high-performance-od-4-shortpass-filters/86106/

5.5. Additional filters, XISPEC-KIT-SM5X5-NIR Gen 2

It is recommended to use filters to avoid these double peaks (4.1.4 Camera MQ022HG-IM-SM5X5 NIR (2nd Generation)).

Two filters are part of the SM5X5 Gen 2 starter kit:

- 650nm long pass (only wavelengths above 650nm will pass -> wavelength range 650 - 975 nm)
- 660nm long pass (only wavelengths above 660nm will pass -> wavelength range 660 - 975 nm).

5.5.1. Components:

Edmund Optics Filter Mount M25.5 x 0.5mm for 25mm diameter filters (#65-800)
http://www.edmundoptics.com/optics/optical-filters/optical-filter-accessories/m25-5-m30-5-mounts-for-25mm-diameter-filters/65800/

650nm long pass filter (Omega Rapid Edge RPE660LP):
https://www.omegafilters.com/product/2913

660nm long pass filter (Thorlabs Premium FELH0650):
https://www.thorlabs.com/thorproduct.cfm?partnumber=FELH0650

5.6. Lite Diffuse Reflectance target

In order to enable reference images, e.g. to measure the reference light for reflectance calculations and/or for all possible flat-field corrections, it is recommended to use a diffuse reflectance target

5.6.1. Component:

Lite Diffuse Reflectance target, Zenith Lite Target SG-3151-U
http://sphereoptics.de/en/wp-content/uploads/sites/3/2014/03/SphereOptics-Ultralight-Targets-Zenith-Lite.pdf

5.7. Standard camera accessories:

Several xiQ camera accessories to run the camera are part of the delivery:

- Tripod bracket part MQ-BRACKET-T (xiQ manual chapter 3.12)
- USB3.0 cable 3.0 m part CBL-U3-3M0 (xiQ manual chapter 3.9)
- Trigger I/O cable 3m part CBL-MQSYNC-3M0 (xiQ manual chapter 3.11)
- Mini tripod

Details are described in the xiQ technical manual:
http://www.ximea.com/downloads/usb3/manuals/xiq_technical_manual.pdf

6. USB-Stick

The delivery of each xiSpec camera includes a USB stick with the following content:

6.1. Technical manual

The technical manual of our xiQ series (2.3 Models Overview, sensor and models) is stored in the folder xiQ-Manual. This document is also available at: http://www.ximea.com/downloads/usb3/manuals/xiq_technical_manual.pdf

The installation of our API / SDK is described in chapter 5.3ff.

6.2. General info about xiSpec

Files available on the USB-Stick:

xiSpec documentation:	This manual in the main folder
general info from IMEC:	folder IMEC-Public

6.3. API / SDK / drivers:

Our API / drivers etc. are available for download for free:

Most recent beta version: http://www.ximea.com/support/documents/14
Stable version (and LINUX / MacOS files): http://www.ximea.com/support/documents/4

The version of the API package for Windows used to compile the xiSpec01 tool is stored in the subfolder XIMEA-API.

6.4. Sensor calibration data

The sensor specific calibration data (measured and calculated by IMEC) are stored in the folder xiSpec-calibration-data.

Some documentation is available in the main folder:

TR_sensor_calibration_files*.pdf

6.5. Analysis software

We have stored a tool scyven from NICTA, Australia on the USB-stick (subfolder NICTA-Scyven). This software can be used to analyze data stored in standard ENVI file formats (e.g. HDR/BSQ).

6.6. demo software xiSpec01 beta (Windows only)

The tool 11 demo software xiSpec01 beta – brief description is stored as a ready to use application in the subfolder xiSpec01-Beta.

7. Sensor Calibration data / files

7.1. Sensor calibration data

The sensor specific calibration data (measured and calculated by IMEC) are stored in the folder xiSpec-calibration-data on the USB-stick.

The calibration file documentation is available in the files:

Imec file format	File names new USB-sticks
Outdated	TR_sensor_calibration_files-Vxx.pdf
Most recent	TR_sensor_calibration_files.pdf - (as of 07/01/2019): Version V1.3, Mar. 21, 2019

table 7-1, calibration date, file names

7.2. Main sections

The calibration files consist of three main sections:

- sensor_info
  Basic information about the sensor used (AMS/CMOSIS CMV2000).

```
<sensor_info version="1">
     <width>2048</width>
     <height>1088</height>
     <pixel_pitch>5.5</pixel_pitch>
     <full_well_capacity_e>10443</full_well_capacity_e>
</sensor_info>
```

- filter_info
  Characteristics of the Fabry-Perot filters and info about the measured wavelength range.
- system_info
  Information about the additional components of the camera (bandpass filter) and spectral correction data.

7.3. Filter_info

The characteristics of the filters vary from sensor to sensor. The response curve of each filter on the sensor is measured after production in a monochromator setup using ortho-collimated light at discrete wavelengths from 400 -1000nm in steps of 1nm.

Typically, the filters do not cover the entire surface of the sensor. The area on the sensor covered with filters is called the active area. The positioning of the active area on the sensor is illustrated below.

Depending on the sensor model, the filters are organized in one or two filter zones.

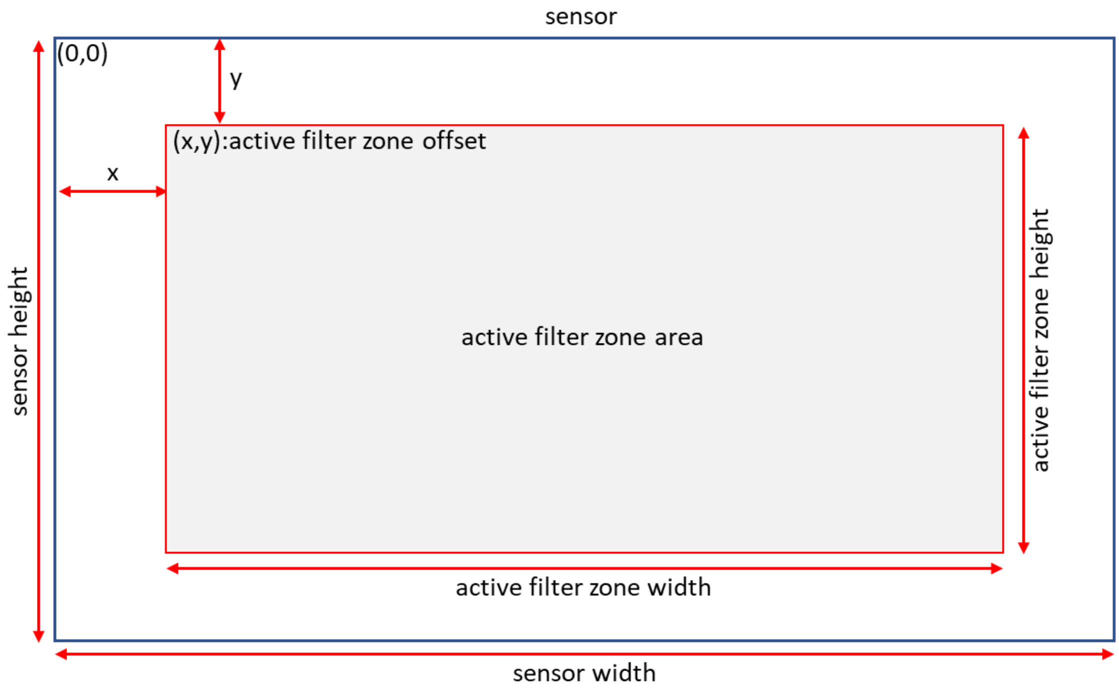


Figure 7-1, active filter area (1 filter zone)

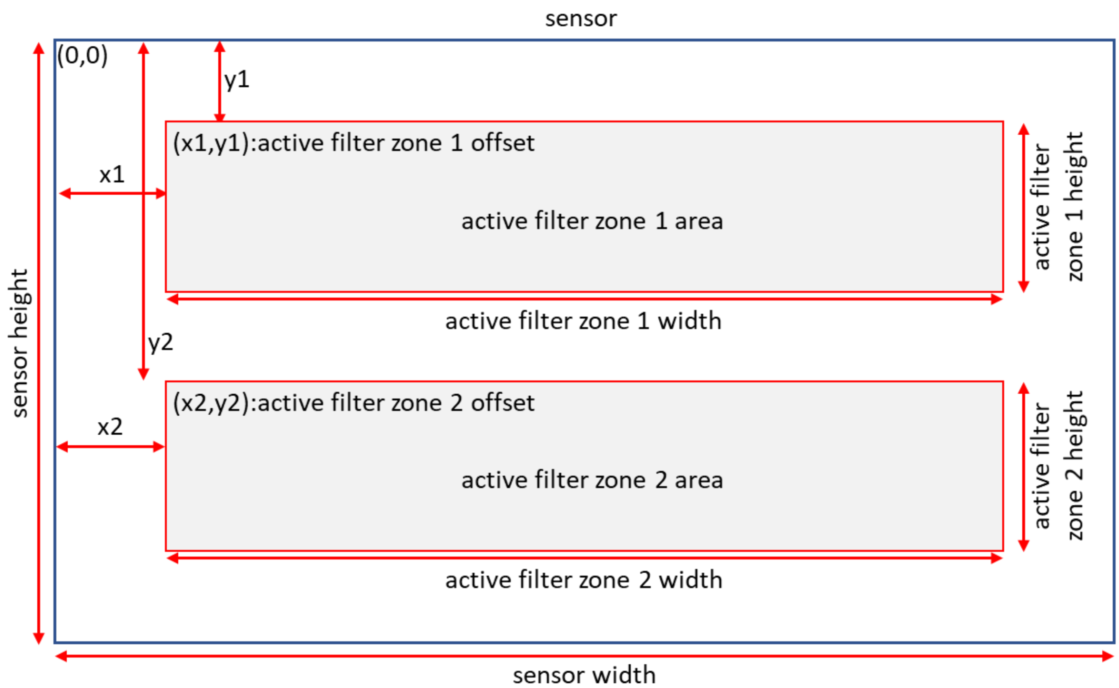


Figure 7-2, active filter areas (2 filter zones)

7.3.1. Filter_area

The filter area that can be used is declared in chapter “Tag filter_area” (chapter 3.3.1 or 3.6 dependent on the version of the calibration file description)

- offset_x: column offset of the filter area from the first column of the sensor
- offset_y: row offset of the filter area from the first row of the sensor
- width: width of the filter area
- height: height of the filter area

Example:

```
<filter_area version="0">
     <offset_x>0</offset_x>
     <offset_y>3</offset_y>
     <width>2045</width>
     <height>1080</height>
</filter_area>
```

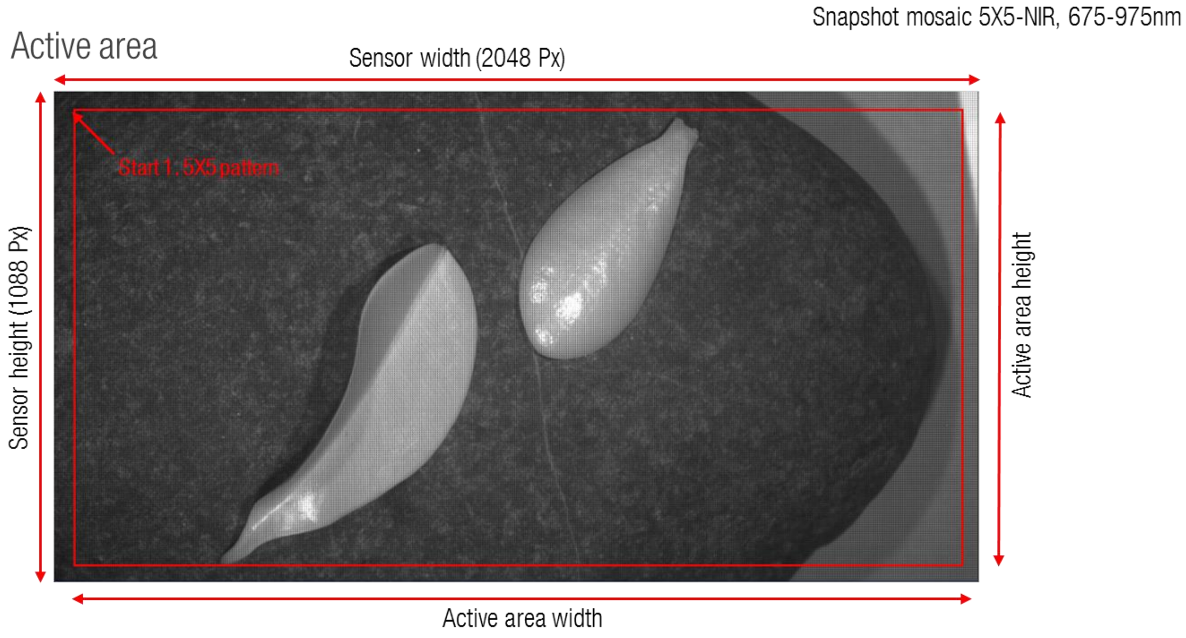


Figure 7-3, example filter area position

7.3.2. bands

The info about the individual bands is described in chapter “Tag bands.band”.

Pattern index:

Value “pattern_position_index” (old calibration file format) - or –

Value “index” (new calibration file format)

Example (old calibration file format, SM5X5)

```
<bands>
	<band version="2" pattern_position_index="0" selected="true">
		<peaks>
			<peak version="0" order="1">
				<wavelength_nm>901.4929840995129</wavelength_nm>
				<fwhm_nm>15.54302175790031</fwhm_nm>
				<QE>46.1030312359434</QE>
			</peak>
		</peaks>
		<response_composition version="0" nr_elements="601">
			<data>0.864536, 0.928963, …//….  0.890343</data>
		</response_composition>
		<response_decomposition version="0" nr_elements="601">
			<data>-0, 0, …//….  0</data>
		</response_decomposition>
	</band>
```

Example (new calibration file format, SM5X5)

```
<bands>
	<band version="3" index="0" selected="true">
		<peaks>
			<peak version="1" order="1" shape="Fabry-Perot">
				<wavelength_nm>889.9740572143232</wavelength_nm>
				<fwhm_nm>12.10204081632653</fwhm_nm>
				<QE>0.0617570698542027</QE>
				<contribution>0.3458108387442734</contribution>
			</peak>
		</peaks>
		<response nr_elements="601">0.00316754755, 0.00295955956, …//….
			0.00313380533</response>
	</band>
```

In some cases, there are two peak entries due to the 2nd harmonics of the Fabry-Perot interference filters. Example (new calibration file format, SM5X5):

```
<band version="3" index="1" selected="true">
	<peaks>
		<peak version="1" order="1" shape="Fabry-Perot">
			<wavelength_nm>896.8916512795672</wavelength_nm>
			<fwhm_nm>14.12244897959184</fwhm_nm>
			..
		</peak>
		<peak version="1" order="2" shape="Fabry-Perot">
			<wavelength_nm>609.1888980281287</wavelength_nm>
			<fwhm_nm>4.693877551020409</fwhm_nm>
			..
		</peak>
	</peaks>
	<response nr_elements="601">0.00526072218, 0.00472121181, …//….
		… </response>
</band>
```

In such cases, the peak to be used depends on the cut-off filters used (see below, SM5X5). If two peaks remain (e.g. also with SM4X4 sensors), the peak with the higher contribution can be used as the first approximation.

In the very latest calibration files always two peaks per band are stored. In this case, the 2nd peak corresponds either to the peak of the 2nd interference harmonic or to the peak of the highest crosstalk value. Example (SM5X5):

```
<band version="3" index="0" selected="true">
     <peaks>
          <peak version="1" order="1" shape="Fabry-Perot">
               <wavelength_nm>880.37744403999</wavelength_nm>
               <fwhm_nm>12.1694214876033</fwhm_nm>
               ..
          </peak>
          <peak version="1" order="2" shape="Fabry-Perot">
               <wavelength_nm>786.7071097368566</wavelength_nm>
               <fwhm_nm>6.404958677685952</fwhm_nm>
               ..
          </peak>
     </peaks>
     <response nr_elements="601"> … </response>
</band>


<band version="3" index="5" selected="true">
     <peaks>
          <peak version="1" order="1" shape="Fabry-Perot">
               <wavelength_nm>786.5595313669828</wavelength_nm>
               <fwhm_nm>6.03305785123967</fwhm_nm>
               ..
          </peak>
          <peak version="1" order="2" shape="Fabry-Perot">
               <wavelength_nm>735.6292491179285</wavelength_nm>
               <fwhm_nm>8.822314049586776</fwhm_nm>
               ..
          </peak>
     </peaks>
     <response nr_elements="601"> … </response>
</band>
```

7.3.3. Tag "response_composition" (old calibration files) or "response" (new calibration files)

Contains the spectral composition of a band's response as measured during the calibration. This information depicts the contribution of each wavelength in the illumination to the band's signal.

It is important to note that the response values in the calibration file were measured during sensor manufacture.

The xiSpec cameras always contain bandpass filters. In some setups (e.g. SM5X5) additional cut-offs are used.

The effective response values may differ significantly. They are calculated by multiplying the response values by the transmission values of the filters used.

The transmission values of the filters used are stored in the latest calibration files (Tags optical_component).

To understand the values of the RAW image it may help to visualize the sensor response values:

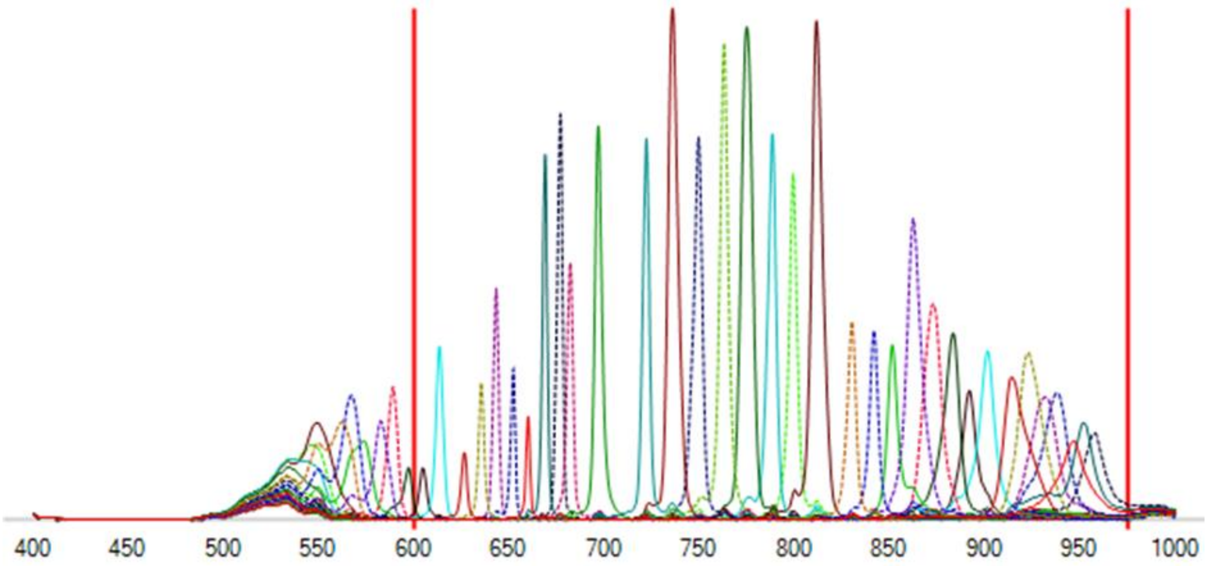


Figure 7-4, example filter response

7.4. system_info

The system information contains the information about the bandpass filters built into the xiSpec cameras and the data for spectral correction.

7.4.1. Optical_components

It is important to note that the response values in the calibration file were measured during sensor manufacture.

The xiSpec cameras always contain bandpass filters. In some setups (e.g. SM5X5) additional cut-offs are used.

The effective response values may differ significantly. They are calculated by multiplying the response values by the transmission values of the filters used.

The most important information, the transmission values of the filters used are stored in the sub-tag response.

```
<optical_component version="1">
      . . . . . .
      <type>bandpass_filter</type>
      <response nr_elements="601">0, 0,..0.9356, 0.9356, 0.93655,  … </response>
</optical_component>
```

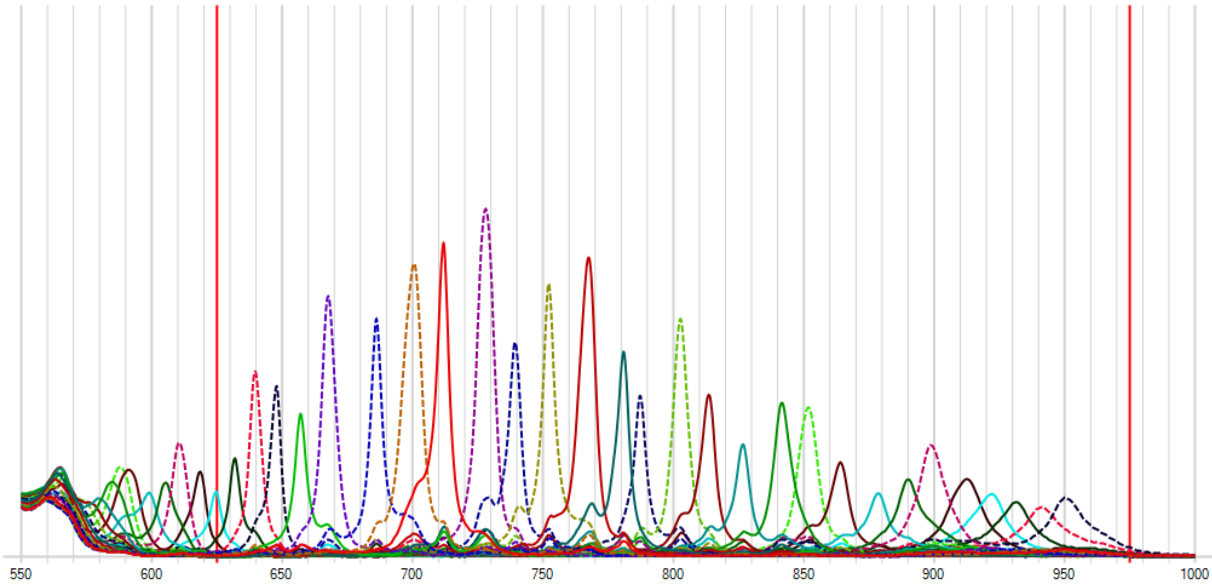


Figure 7-5, response curve, active wavelength range of sensor

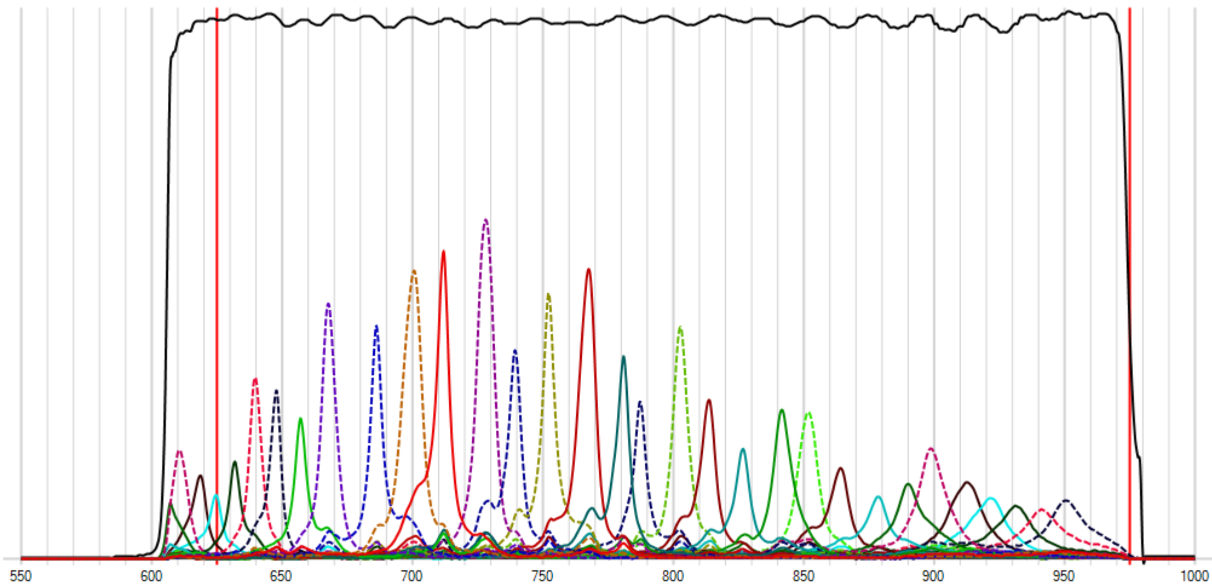


Figure 7-6, response curve under consideration of the camera filter glass

7.4.2. Correction_matrices

The response curves of the individual bands can contain various crosstalks to other bands, partly also due to further interference harmonics - with line scan sensors the second harmonics cannot be suppressed by additional filters.

The calibration data contain correction matrixes to correct the described effects.

The correction matrices can depend on additional external filters. If an additional filter is considered (e.g. SM5x5 sensors for excluding the double harmonics), another <optical_component> is described as part of the correction_matrix.

If another external filter (usually a long pass or short pass filter) is added, the transmission curve is also taken into account multiplicatively:

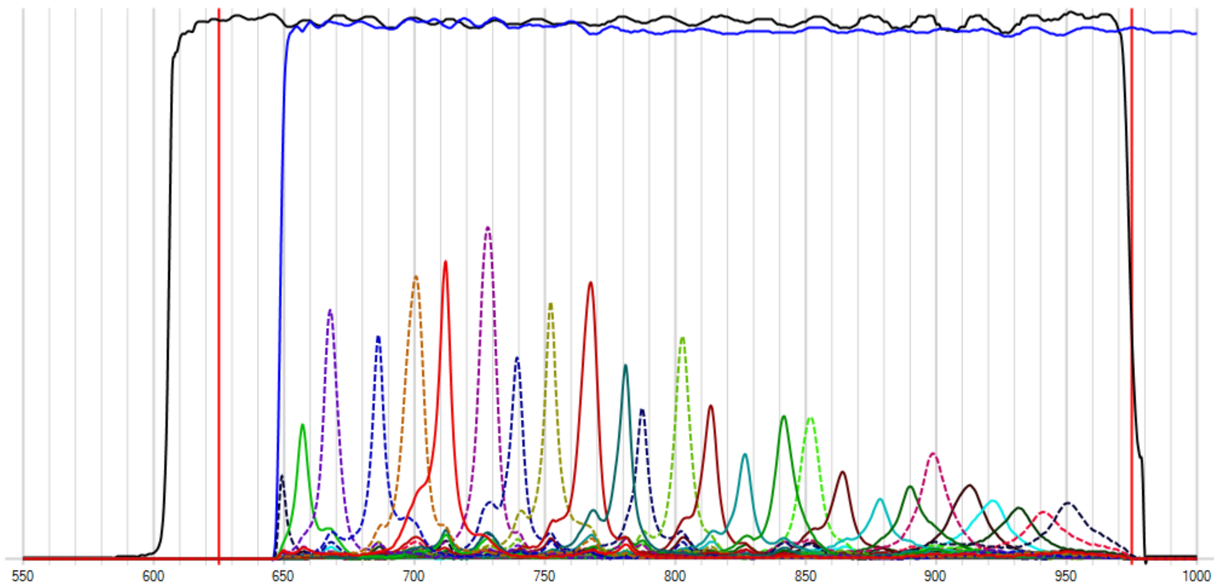


Figure 7-7, response curve under consideration of the camera filter glass and an additional external filter glass

The result of the spectral corrections are the so-called virtual bands, which represent ideal Gauss curves.

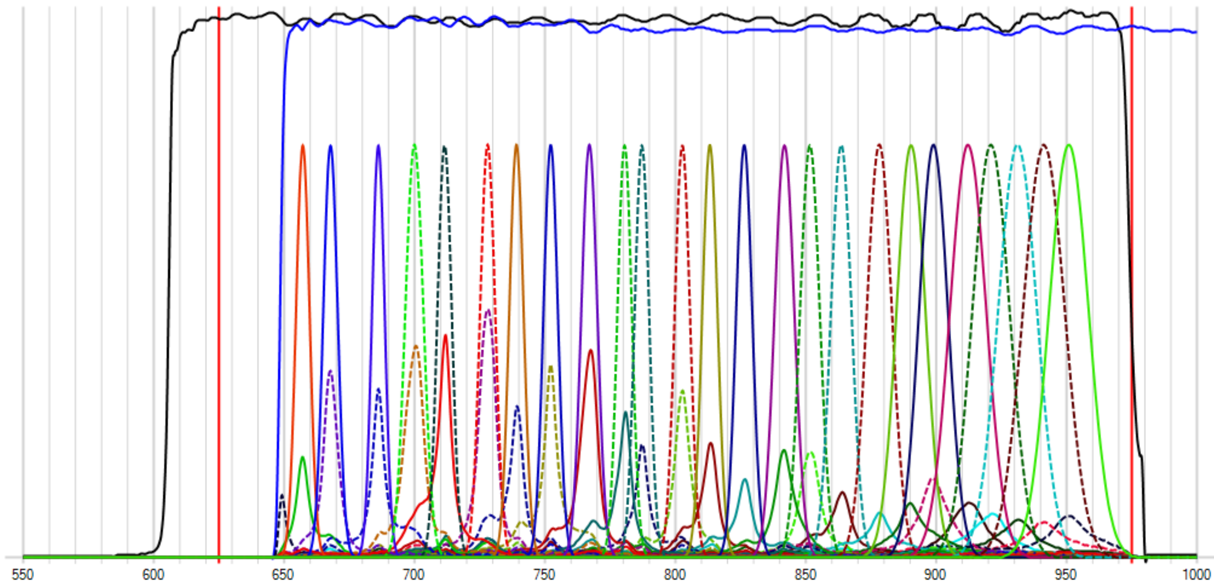


Figure 7-8, calculated virtual bands

Please note details in 9.6 Spectral correction / Correction matrix .

8. Data Acquisition

8.1. Snapshot mosaic camera – interpretation of the sensor calibration files

All needed info to interpret the calibration file and find the right peak wavelength position in the pattern are described in the calibration file, which is delivered together with the xiSpec camera.

8.1.1. RAW image interpretation / snapshot mosaic

Position of the index in the pattern structure:

"The 0-based index for the position of the band in the pattern, numbered from left to right, top to bottom."

Index positions in case of a SM4X4 sensors:

0	1	2	3
4	5	6	7
8	9	10	11
12	13	14	15

Index positions in case of a SM5X5 sensors:

0	1	2	3	4
5	6	7	8	9
10	11	12	13	14
15	16	17	18	19
20	21	22	23	24

Pattern interpretation

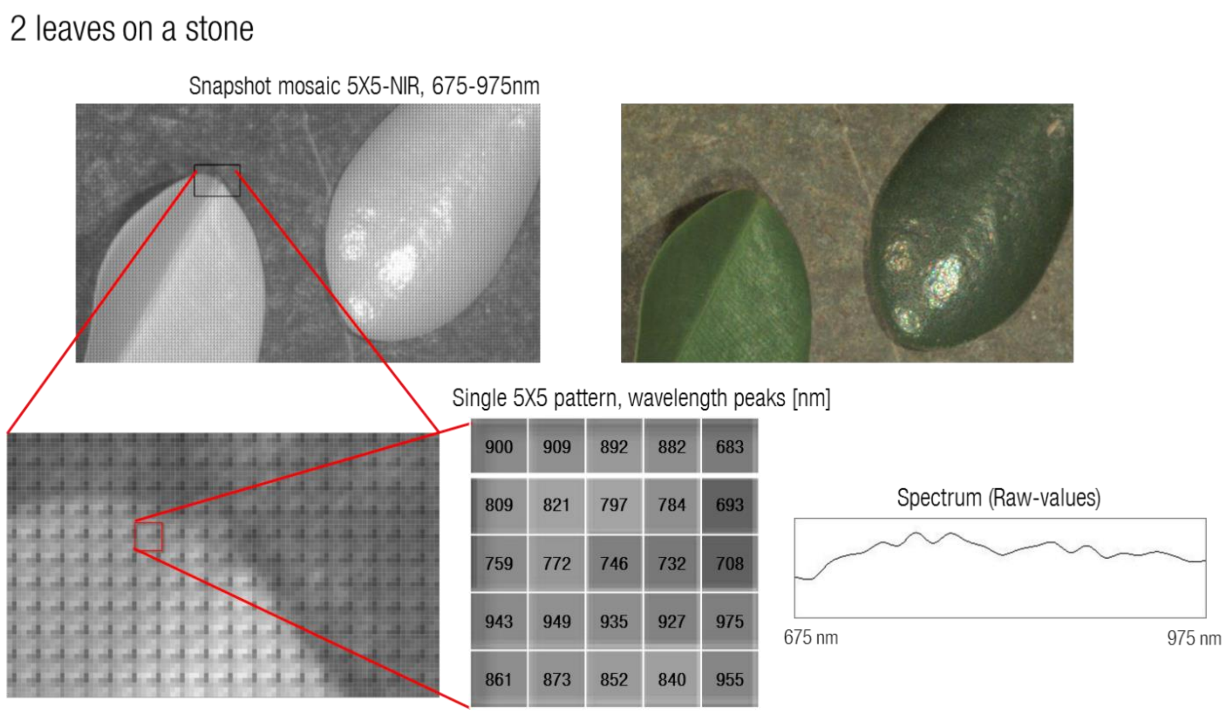


Figure 8-1, visualization and interpretation of a single filter pattern (example SM5X5 with a 675nm long pass filter)

8.1.2. Peak wavelength sort order

The index position only describes the position of the pixel on the sensor surface within the pattern. The index is different from the sort order of the peak wavelengths, which also depends on additional filters used.

Example (SM5X5 with an additional 675nm long pass filter)

900	909	892	882	683
809	821	797	784	693
759	772	746	732	708
943	949	935	927	975
861	873	852	840	955

These wavelengths would be sorted in the cube (w/o spectral correction) as follows, wavelength(index):

683(4), 693(9), 708(14), 732(13), 746(12), 759(10), 772(11), 784(8), 797(7), 809(5), 821(6), 840(23), 852(22), 861(20), 873(21), 882(3), 892(2), 900(0), 909(1), 927(18), 935(17), 943(15), 949(16), 955(24), 975(19)

8.2. Line scan sensors: Data acquisition, data cube and spectrum calculation

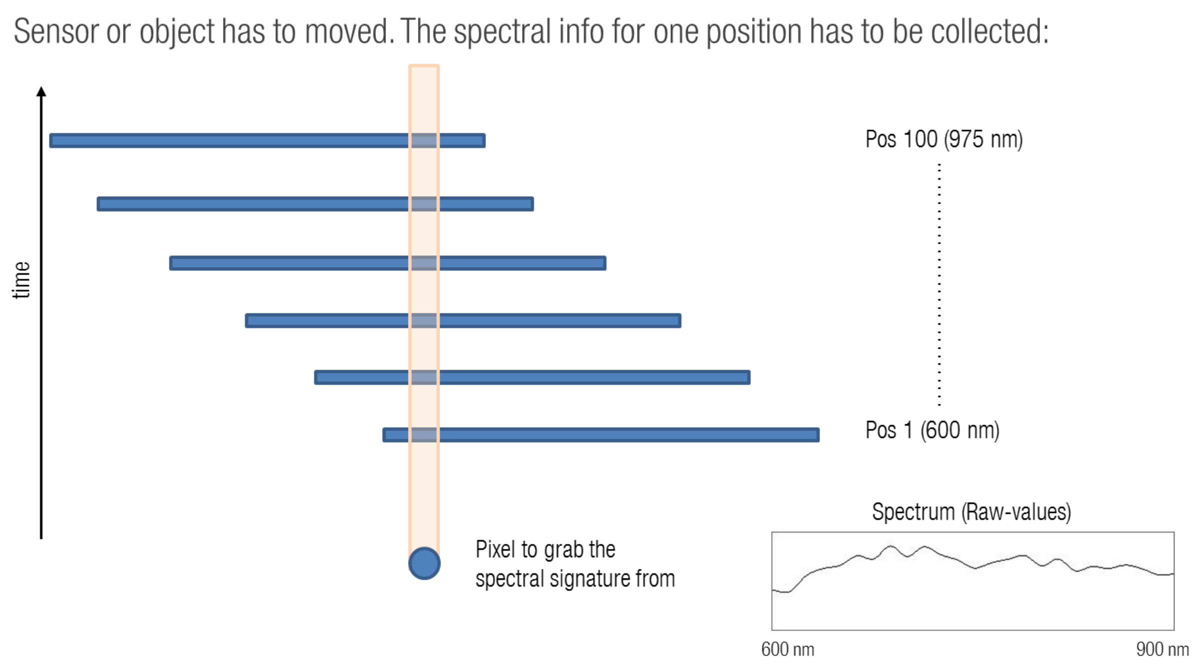


Figure 8-2, schematic sequence of data acquisition with movement of sensor / object

The line-scan sensor that is used in xiSpec cameras to acquire a hyperspectral representation of an object consists of a conventional sensor with specialized filters added on top. Each filter only transmits a small portion of the complete spectrum reflected by the scene. All this information is then combined with the known motion of the sensor or object to create a hyperspectral representation of the scene: a hypercube.

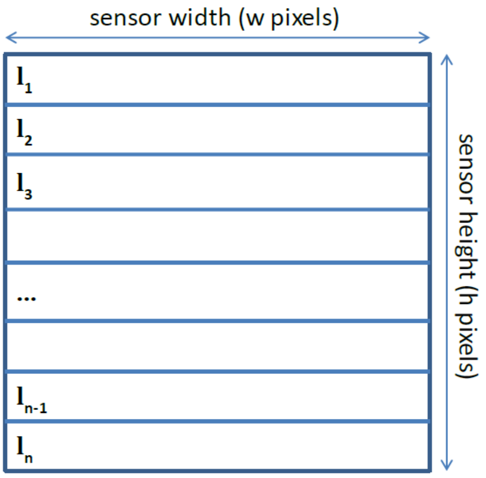


Figure 8-3, line scan (wedge) layout (Source: imec)

A representation of the wedge sensor is given above. It consists of a sensor with a resolution of w x h pixels, with n filter bands processed. Each band has a fixed height in pixels (see above) and a width of w pixels.

As explained the frequency-specific regions on the sensor are organized in adjacent bands. In order to capture the spectra of every point of an object, we must ensure that every point of the subject passes over each individual band. This is done by moving the object under the sensor or moving the sensor relative to the subject, perpendicular to the orientation of the wedge bands. This is illustrated below:

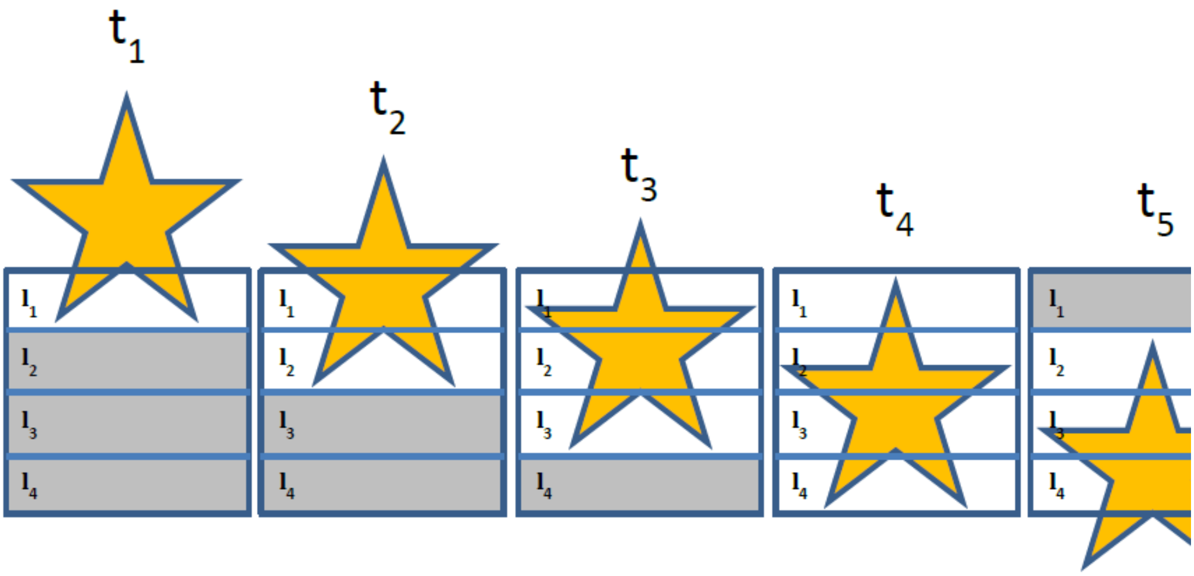


Figure 8-4, line scan sensor – scan phases (Source: imec)

A full scan of an object consists of a start-up phase (t1-t3), a steady-state phase (t4), and a shutdown phase (t5-t7). During the start-up phase and the shutdown phase (t1-t3 and t5-t7, respectively), not all captured data will be used for hypercube construction. This unused data is shown in grey in the figure above. During steady state (see t4), all captured data is used in the hypercube construction. The number of frames in steady state depends on the length of the object.

The construction of a hypercube from these wedge images is done by re-organization of the individual bands, in such a way that all bands of a specific wavelength, taken over consecutive frames, are stitched together, and this for every wavelength. This is illustrated in the figure below. A spectrum of a specific point on the object can be obtained by taking the information for that position over all bands.

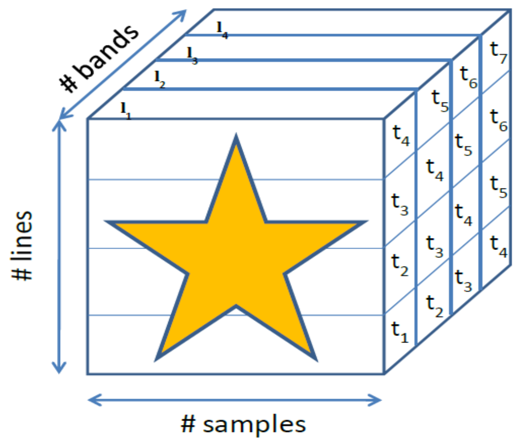
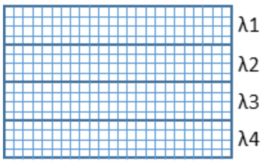


Figure 8-5, line scan sensor – data cube (Source: imec)

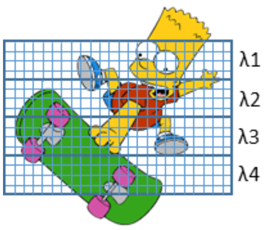
8.2.1.1. Example

We consider as an example a fictitious line scan sensor with 4 spectral bands, each 24 pixels wide and 4 pixels high. The total raw resolution of the sensor is 24 x 16 pixels:



The goal is to capture an object as a hyperspectral data cube that is larger than the camera could capture with an image.

The entire width of the object is captured with an image, but not the height.

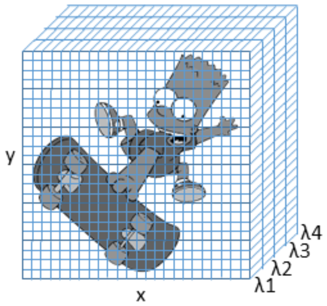


The camera provides an image of a part of the object. This image is always transferred to the computer as a RAW image.

No single transmitted image from a line scan camera can be used to calculate an HSI cube.

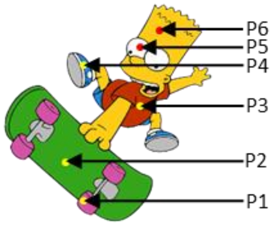
The upper quarter of the image contains only information about the wavelength λ1, the second quarter about the wavelength λ2, etc.

A hyperspectral data cube is a three-dimensional representation in which the spectral information for each pixel (in the x-y-plane) is stored as a third dimension.



We consider 6 different points, which are to be used to represent 6 different materials / spectral signatures:

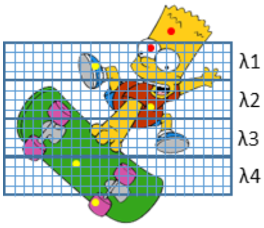
- P1: Wheel
- P2: Skateboard
- P3: T-Shirt
- P4: Shoe
- P5: Eyes
- P6: Skin



The signature vector of a point P is

$$\vec{P} = (\lambda_1, \lambda_2, \lambda_3, \lambda_4)$$

If we now analyze the image



we get the resulting spectral information for the 6 points:

P1 and P6: outside of the RAW image
P2: contains info for spectral position λ4 only
P3: contains info for spectral position λ2 only
P4 and P5: contain info for spectral position λ1 only

Not a single spectral vector is complete:

$$\overrightarrow{P1} = (?,?,?,?)$$

$$\overrightarrow{P2} = (?,?,?,\lambda_4)$$

$$\overrightarrow{P3} = (?,\lambda_2,?,?)$$

$$\overrightarrow{P4} = (\lambda_1,?,?,?)$$

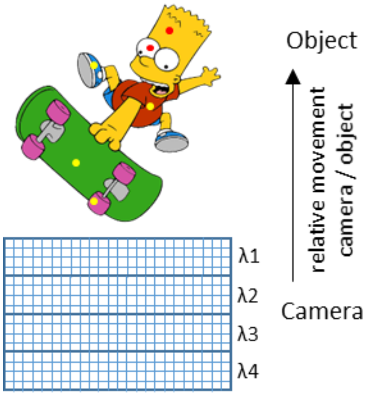
$$\overrightarrow{P5} = (\lambda_1,?,?,?)$$

$$\overrightarrow{P6} = (?,?,?,?)$$

In order to obtain the missing spectral data (other bands) for the object points, these points must also be recorded by the other areas of the sensor that are sensitive in these spectral bands.

To achieve this goal, the object and camera/sensor are moved relative to each other and several images are taken.

This means that all spectral data (bands) can be "collected" for the points of the object.



This process will now be explained in detail. Camera and object are moved relative to each other and several RAW images are recorded and evaluated.

The goal must be to record each point of the object at least once with the 4 different sensor areas (for the 4 peak wavelengths).

If several results for a spectral band are recorded for one pixel, solutions must be provided in the software implementation as to how these different measured values are processed in the calculation of the spectra.

In the following, the mean value is calculated from the various duplicate values.

We take several RAW pictures R1 - Rn.

The measured values for one of the points P1-P6 for the bands λ1-λ4 are called

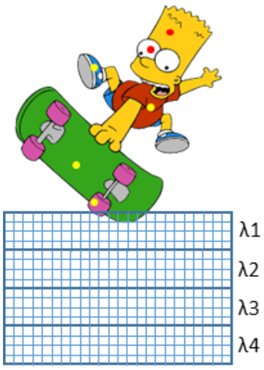
$$v_n^{Pm,\lambda k}$$

n: picture-#

m: # of the Point (P1-P6)

k: # of the band (λ1-λ4)

Picture 1



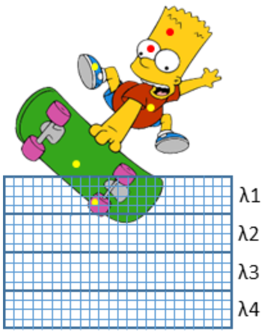
Measured values

-

Resulting vectors

$$\overrightarrow{P1} = (?,?,?,?)$$
$$\overrightarrow{P2} = (?,?,?,?)$$
$$\overrightarrow{P3} = (?,?,?,?)$$
$$\overrightarrow{P4} = (?,?,?,?)$$
$$\overrightarrow{P5} = (?,?,?,?)$$
$$\overrightarrow{P6} = (?,?,?,?)$$

Picture 2



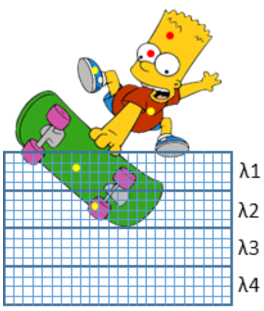
Measured values

$v_2^{P1,\lambda 1}$

Resulting vectors

$$\overrightarrow{P1} = (v_2^{P1,\lambda 1},?,?,?)$$
$$\overrightarrow{P2} = (?,?,?,?)$$
$$\overrightarrow{P3} = (?,?,?,?)$$
$$\overrightarrow{P4} = (?,?,?,?)$$
$$\overrightarrow{P5} = (?,?,?,?)$$
$$\overrightarrow{P6} = (?,?,?,?)$$

Picture 3



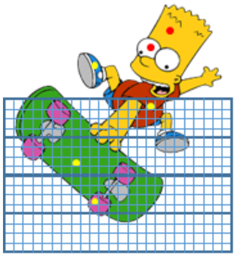
Measured values

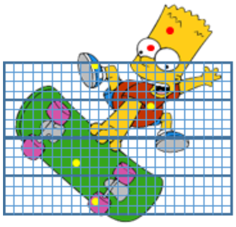
$v_3^{P1,\lambda 2}$

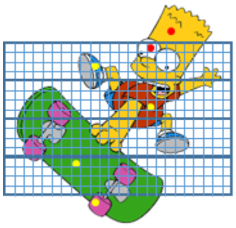
$v_3^{P2,\lambda 1}$

Resulting vectors

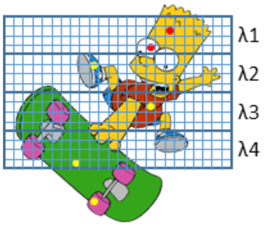
$$\overrightarrow{P1} = (v_2^{P1,\lambda 1}, v_3^{P1,\lambda 2},?,?)$$
$$\overrightarrow{P2} = (v_3^{P2,\lambda 1},?,?,?)$$
$$\overrightarrow{P3} = (?,?,?,?)$$
$$\overrightarrow{P4} = (?,?,?,?)$$
$$\overrightarrow{P5} = (?,?,?,?)$$
$$\overrightarrow{P6} = (?,?,?,?)$$

Picture 4	Measured values	Resulting vectors
	$v_4^{P1,\lambda3}$ $v_4^{P2,\lambda2}$ $v_4^{P3,\lambda1}$	$\overrightarrow{P1}=(v_2^{P1,\lambda1},v_3^{P1,\lambda2},v_4^{P1,\lambda3},?)$ $\overrightarrow{P2}=(v_3^{P2,\lambda1},v_4^{P2,\lambda2},?,?)$ $\overrightarrow{P3}=(v_4^{P3,\lambda1},?,?,?)$ $\overrightarrow{P4}=(?,?,?,?)$ $\overrightarrow{P5}=(?,?,?,?)$ $\overrightarrow{P6}=(?,?,?,?)$

Picture 5	Measured values	Resulting vectors
	$v_5^{P1,\lambda4}$ $v_5^{P2,\lambda3}$ $v_5^{P3,\lambda2}$ $v_5^{P4,\lambda1}$	$\overrightarrow{P1}=(v_2^{P1,\lambda1},v_3^{P1,\lambda2},v_4^{P1,\lambda3},v_5^{P1,\lambda4})$ $\overrightarrow{P2}=(v_3^{P2,\lambda1},v_4^{P2,\lambda2},v_5^{P2,\lambda3},?)$ $\overrightarrow{P3}=(v_4^{P3,\lambda1},v_5^{P3,\lambda2},?,?)$ $\overrightarrow{P4}=(v_5^{P4,\lambda1},?,?,?)$ $\overrightarrow{P5}=(?,?,?,?)$ $\overrightarrow{P6}=(?,?,?,?)$

Picture 6	Measured values	Resulting vectors
	$v_6^{P2,\lambda4}$ $v_6^{P3,\lambda2}$ $v_6^{P4,\lambda1}$ $v_6^{P5,\lambda1}$	$\overrightarrow{P1}=(v_2^{P1,\lambda1},v_3^{P1,\lambda2},v_4^{P1,\lambda3},v_5^{P1,\lambda4})$ $\overrightarrow{P2}=(v_3^{P2,\lambda1},v_4^{P2,\lambda2},v_5^{P2,\lambda3},v_6^{P2,\lambda4})$ $\overrightarrow{P3}=(v_4^{P3,\lambda1},\frac{v_5^{P3,\lambda2}+v_6^{P3,\lambda2}}{2},?,?)$ $\overrightarrow{P4}=(\frac{v_5^{P4,\lambda1}+v_6^{P4,\lambda1}}{2},?,?,?)$ $\overrightarrow{P5}=(v_6^{P5,\lambda1},?,?,?)$ $\overrightarrow{P6}=(?,?,?,?)$

Picture 7



Measured values

$v_7^{P2,\lambda 4}$

$v_7^{P3,\lambda 3}$

$v_7^{P4,\lambda 2}$

$v_7^{P5,\lambda 1}$

$v_7^{P6,\lambda 1}$

Resulting vectors

$$\overrightarrow{P1} = (v_2^{P1,\lambda 1}, v_3^{P1,\lambda 2}, v_4^{P1,\lambda 3}, v_5^{P1,\lambda 4})$$

$$\overrightarrow{P2} = (v_3^{P2,\lambda 1}, v_4^{P2,\lambda 2}, v_5^{P2,\lambda 3}, \frac{v_6^{P2,\lambda 4} + v_7^{P2,\lambda 4}}{2})$$

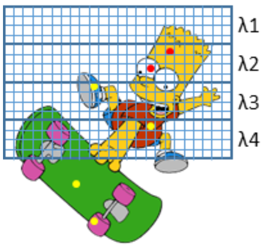
$$\overrightarrow{P3} = (v_4^{P3,\lambda 1}, \frac{v_5^{P3,\lambda 2} + v_6^{P3,\lambda 2}}{2}, v_7^{P3,\lambda 3}, ?)$$

$$\overrightarrow{P4} = (\frac{v_5^{P4,\lambda 1} + v_6^{P4,\lambda 1}}{2}, v_7^{P4,\lambda 2}, ?, ?)$$

$$\overrightarrow{P5} = (\frac{v_6^{P5,\lambda 1} + v_7^{P5,\lambda 1}}{2}, ?, ?, ?)$$

$$\overrightarrow{P6} = (v_7^{P6,\lambda 1}, ?, ?, ?)$$

Picture 8



Measured values

$v_8^{P3,\lambda 4}$

$v_8^{P4,\lambda 3}$

$v_8^{P5,\lambda 2}$

$v_8^{P6,\lambda 2}$

Resulting vectors

$$\overrightarrow{P1} = (v_2^{P1,\lambda 1}, v_3^{P1,\lambda 2}, v_4^{P1,\lambda 3}, v_5^{P1,\lambda 4})$$

$$\overrightarrow{P2} = (v_3^{P2,\lambda 1}, v_4^{P2,\lambda 2}, v_5^{P2,\lambda 3}, \frac{v_6^{P2,\lambda 4} + v_7^{P2,\lambda 4}}{2})$$

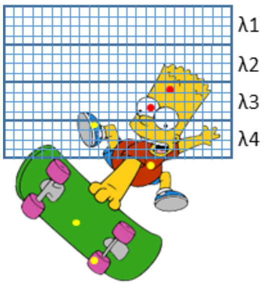
$$\overrightarrow{P3} = (v_4^{P3,\lambda 1}, \frac{v_5^{P3,\lambda 2} + v_6^{P3,\lambda 2}}{2}, v_7^{P3,\lambda 3}, v_8^{P3,\lambda 4})$$

$$\overrightarrow{P4} = (\frac{v_5^{P4,\lambda 1} + v_6^{P4,\lambda 1}}{2}, v_7^{P4,\lambda 2}, v_8^{P4,\lambda 3}, ?)$$

$$\overrightarrow{P5} = (\frac{v_6^{P5,\lambda 1} + v_7^{P5,\lambda 1}}{2}, v_8^{P5,\lambda 2}, ?, ?)$$

$$\overrightarrow{P6} = (v_7^{P6,\lambda 1}, v_8^{P6,\lambda 2}, ?, ?)$$

Picture 9



Measured values

$v_9^{P4,\lambda 4}$

$v_9^{P5,\lambda 3}$

$v_9^{P6,\lambda 3}$

Resulting vectors

$$\overrightarrow{P1} = (v_2^{P1,\lambda 1}, v_3^{P1,\lambda 2}, v_4^{P1,\lambda 3}, v_5^{P1,\lambda 4})$$

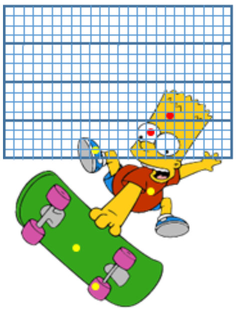
$$\overrightarrow{P2} = (v_3^{P2,\lambda 1}, v_4^{P2,\lambda 2}, v_5^{P2,\lambda 3}, \frac{v_6^{P2,\lambda 4} + v_7^{P2,\lambda 4}}{2})$$

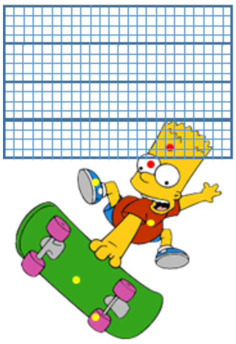
$$\overrightarrow{P3} = (v_4^{P3,\lambda 1}, \frac{v_5^{P3,\lambda 2} + v_6^{P3,\lambda 2}}{2}, v_7^{P3,\lambda 3}, v_8^{P3,\lambda 4})$$

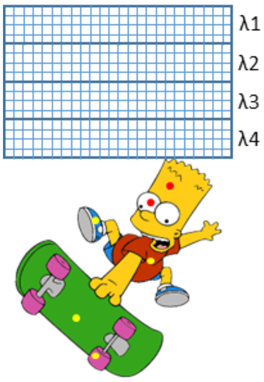
$$\overrightarrow{P4} = (\frac{v_5^{P4,\lambda 1} + v_6^{P4,\lambda 1}}{2}, v_7^{P4,\lambda 2}, v_8^{P4,\lambda 3}, v_9^{P4,\lambda 4})$$

$$\overrightarrow{P5} = (\frac{v_6^{P5,\lambda 1} + v_7^{P5,\lambda 1}}{2}, v_8^{P5,\lambda 2}, v_9^{P5,\lambda 3}, ?)$$

$$\overrightarrow{P6} = (v_7^{P6,\lambda 1}, v_8^{P6,\lambda 2}, v_9^{P6,\lambda 3}, ?)$$

Picture 10	Measured values	Resulting vectors
	$v_{10}^{P4,\lambda 4}$ $v_{10}^{P5,\lambda 4}$ $v_{10}^{P6,\lambda 3}$	$\overrightarrow{P1}=(v_2^{P1,\lambda 1},v_3^{P1,\lambda 2},v_4^{P1,\lambda 3},v_5^{P1,\lambda 4})$ $\overrightarrow{P2}=(v_3^{P2,\lambda 1},v_4^{P2,\lambda 2},v_5^{P2,\lambda 3},\frac{v_6^{P2,\lambda 4}+v_7^{P2,\lambda 4}}{2})$ $\overrightarrow{P3}=(v_4^{P3,\lambda 1},\frac{v_5^{P3,\lambda 2}+v_6^{P3,\lambda 2}}{2},v_7^{P3,\lambda 3},v_8^{P3,\lambda 4})$ $\overrightarrow{P4}=(\frac{v_5^{P4,\lambda 1}+v_6^{P4,\lambda 1}}{2},v_7^{P4,\lambda 2},v_8^{P4,\lambda 3},\frac{v_9^{P4,\lambda 4}+v_{10}^{P4,\lambda 4}}{2})$ $\overrightarrow{P5}=(\frac{v_6^{P5,\lambda 1}+v_7^{P5,\lambda 1}}{2},v_8^{P5,\lambda 2},v_9^{P5,\lambda 3},v_{10}^{P5,\lambda 4})$ $\overrightarrow{P6}=(v_7^{P6,\lambda 1},v_8^{P6,\lambda 2},\frac{v_9^{P6,\lambda 3}+v_{10}^{P6,\lambda 3}}{2},?)$

Picture 11	Measured values	Resulting vectors
	$v_{11}^{P6,\lambda 4}$	$\overrightarrow{P1}=(v_2^{P1,\lambda 1},v_3^{P1,\lambda 2},v_4^{P1,\lambda 3},v_5^{P1,\lambda 4})$ $\overrightarrow{P2}=(v_3^{P2,\lambda 1},v_4^{P2,\lambda 2},v_5^{P2,\lambda 3},\frac{v_6^{P2,\lambda 4}+v_7^{P2,\lambda 4}}{2})$ $\overrightarrow{P3}=(v_4^{P3,\lambda 1},\frac{v_5^{P3,\lambda 2}+v_6^{P3,\lambda 2}}{2},v_7^{P3,\lambda 3},v_8^{P3,\lambda 4})$ $\overrightarrow{P4}=(\frac{v_5^{P4,\lambda 1}+v_6^{P4,\lambda 1}}{2},v_7^{P4,\lambda 2},v_8^{P4,\lambda 3},\frac{v_9^{P4,\lambda 4}+v_{10}^{P4,\lambda 4}}{2})$ $\overrightarrow{P5}=(\frac{v_6^{P5,\lambda 1}+v_7^{P5,\lambda 1}}{2},v_8^{P5,\lambda 2},v_9^{P5,\lambda 3},v_{10}^{P5,\lambda 4})$ $\overrightarrow{P6}=(v_7^{P6,\lambda 1},v_8^{P6,\lambda 2},\frac{v_9^{P6,\lambda 3}+v_{10}^{P6,\lambda 3}}{2},v_{11}^{P6,\lambda 4})$

Picture 12	Measured values	Resulting vectors
	-	$\overrightarrow{P1}=(v_2^{P1,\lambda 1},v_3^{P1,\lambda 2},v_4^{P1,\lambda 3},v_5^{P1,\lambda 4})$ $\overrightarrow{P2}=(v_3^{P2,\lambda 1},v_4^{P2,\lambda 2},v_5^{P2,\lambda 3},\frac{v_6^{P2,\lambda 4}+v_7^{P2,\lambda 4}}{2})$ $\overrightarrow{P3}=(v_4^{P3,\lambda 1},\frac{v_5^{P3,\lambda 2}+v_6^{P3,\lambda 2}}{2},v_7^{P3,\lambda 3},v_8^{P3,\lambda 4})$ $\overrightarrow{P4}=(\frac{v_5^{P4,\lambda 1}+v_6^{P4,\lambda 1}}{2},v_7^{P4,\lambda 2},v_8^{P4,\lambda 3},\frac{v_9^{P4,\lambda 4}+v_{10}^{P4,\lambda 4}}{2})$ $\overrightarrow{P5}=(\frac{v_6^{P5,\lambda 1}+v_7^{P5,\lambda 1}}{2},v_8^{P5,\lambda 2},v_9^{P5,\lambda 3},v_{10}^{P5,\lambda 4})$ $\overrightarrow{P6}=(v_7^{P6,\lambda 1},v_8^{P6,\lambda 2},\frac{v_9^{P6,\lambda 3}+v_{10}^{P6,\lambda 3}}{2},v_{11}^{P6,\lambda 4})$

The result of this scanning process are complete spectra for all object points considered.

Stitching the individual bands of consecutive wedge frames together will only produce a good result if:

The object moves under the sensor perpendicular to the orientation of the wedge bands. Any misalignment can result in incorrectly stitched images, both spatially and spectrally.

The frame rate at which the camera captures images is in sync with the speed at which the object is moved under the camera.

8.2.2. Maximum line rate calculation

The highest speed at which the camera can be moved without losing information is the height of a spectral band (in pixels) from image to image.

This value multiplied by the maximum frame rate gives the highest number of lines that can be read per second.

Height of a band:

- LS100: 8 pixels
- LS150: 5 pixels

Maximum frame rate:

- Standard xiQ-USB3.0 camera series: 170 fps @ 8 bit
- xiX PCIe camera series: 322 fps @ 10 bit

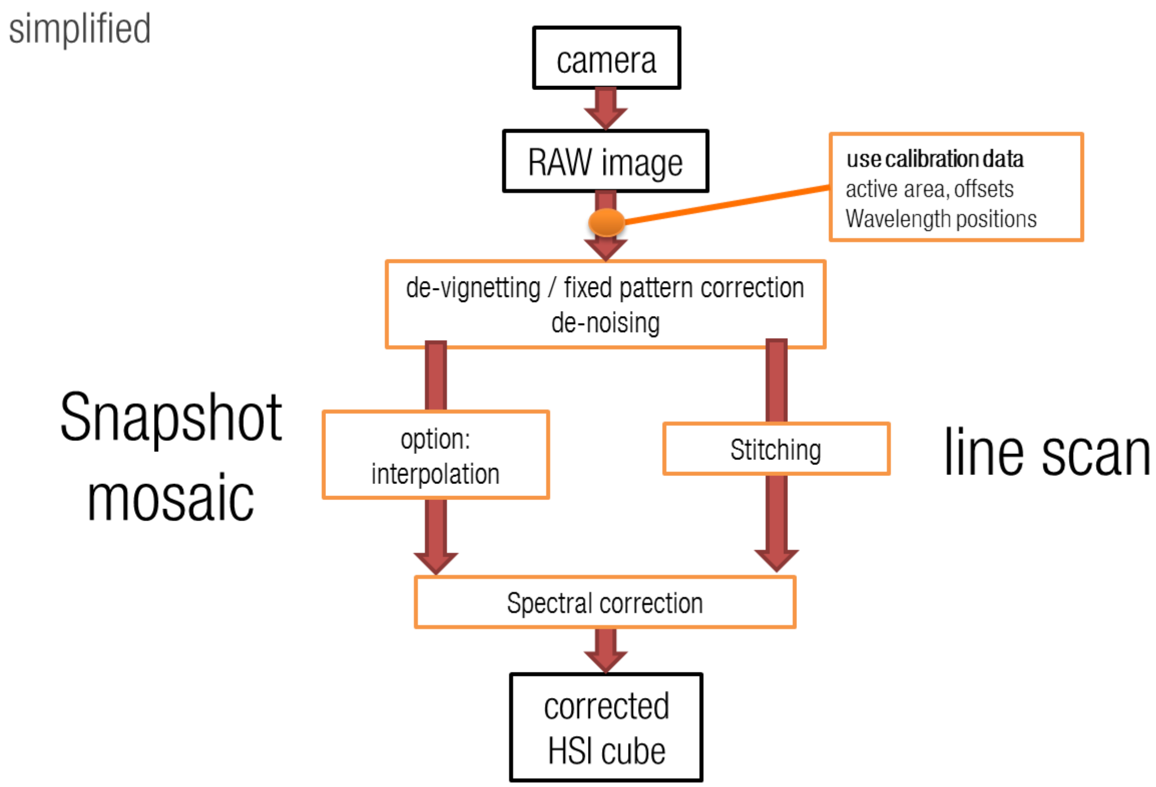
If the start-up and shutdown phases are not considered, the maximum line rate that can be achieved is:

Height of a band (in pixels) * Frame rate [lines / s]

lines / s	xiQ	xiX
LS100	1 360	2 576
LS150	850	1 610

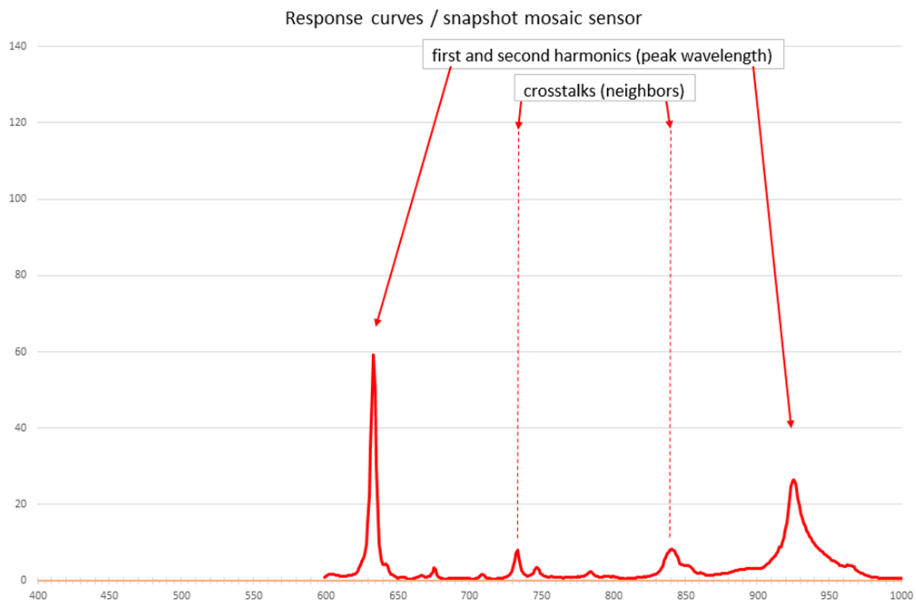
table 8-1, line scan sensors, max. line rate

9. Hyperspectral data correction



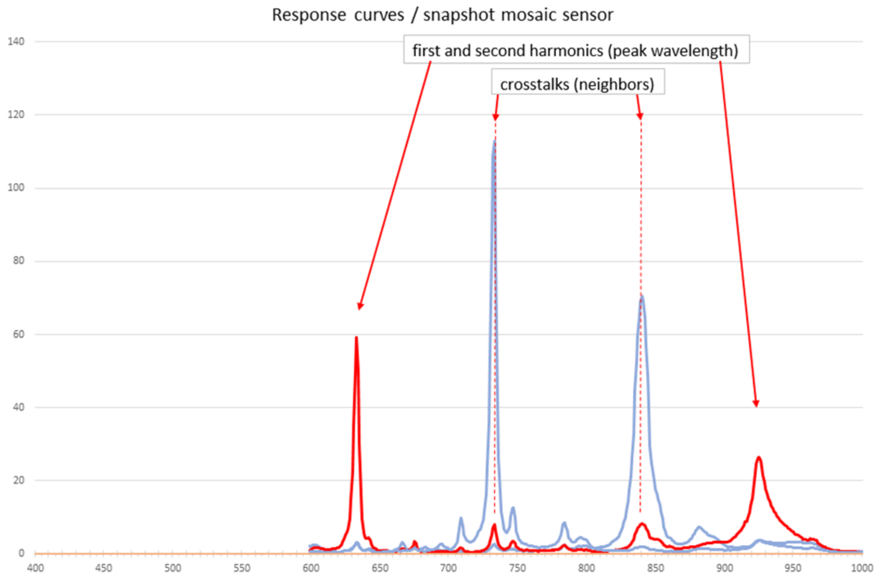
9.1. Data – spectral correction /snapshot mosaic sensor

The response curves have crosstalks with neighbors. Several curves have two peak wavelength (can be eliminated with long or short pass filters).



These sensors have significantly different degrees of cross talks between neighboring pixels dependent on the angle of the light rays to perpendicular to the sensor surface.

The response curves have crosstalks with neighbors. Several curves have two peak wavelength (can be eliminated with long or short pass filters).



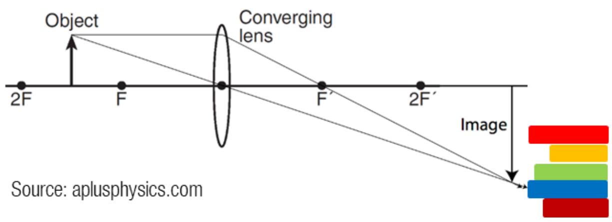
Position of the crosstalks are at the peak wavelength of neighbors.
This effect can be corrected by a correction matrix.

The response curves are determined during sensor production and stored in the sensor-specific calibration file. The calibration data are delivered together with the cameras. XIMEA can provide recalculated calibration data if required.

The response curves, which also show the crosstalk between adjacent pixels, are determined with collimated light that falls vertically on the sensor surface.

Cross talks (depending on the setup [camera, lens, aperture, distance to object and illumination]) can lead to significant changes of the spectral signature outside the sensor center:

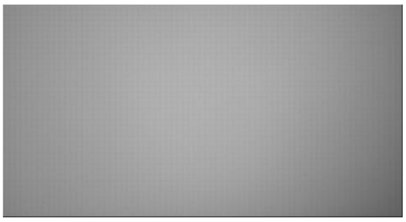
Standard lens:



Source: aplusphysics.com

at high angles:
peak shift
band-specific vignetting

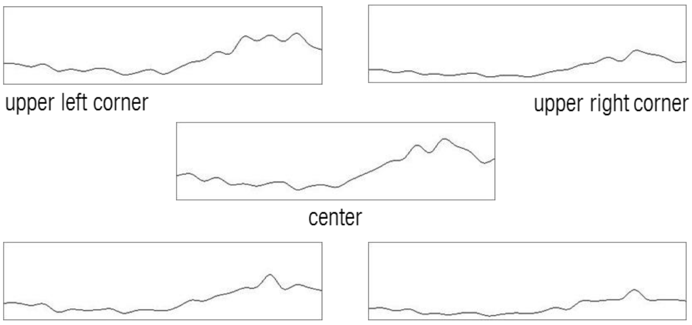
When using standard VIS-NIR lenses, a significant “vignetting” may occur:



f=2.8 (recommended aperture from imec)

Snapshot mosaic 5X5-NIR, 675-975nm,
Edmund Optics 35mm VIS-NIR lens
Halogen lighting

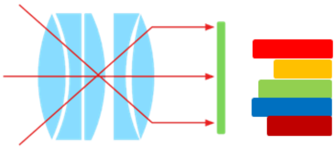
The “vignetting” has also an impact on the spectral curves:



It is recommended to a implement a white image / fixed pattern image correction for each band

This effect can be reduced using (sensor side) telecentric lenses:

Telecentric lenses:



Source: ivent.de

No peak shift and
band-specific vignetting

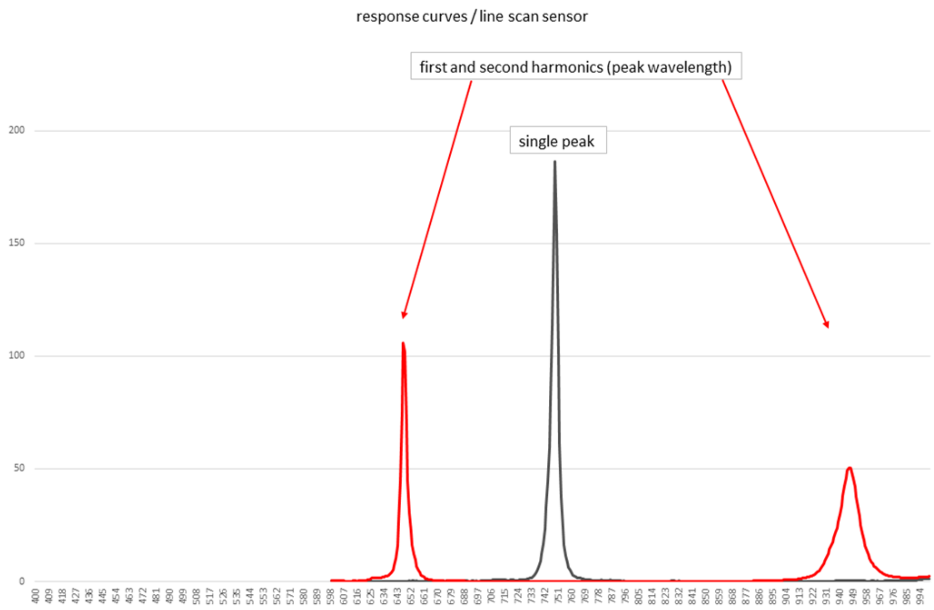
The reference values are measured by capturing images of a diffuse target, which reflects light of all wavelengths almost identically. (A diffuse reflectance target is part of XIMEA’s xiSpec starter kits).

This correction step is practically a band-specific “flat-field correction” in relation to the center of the sensor.

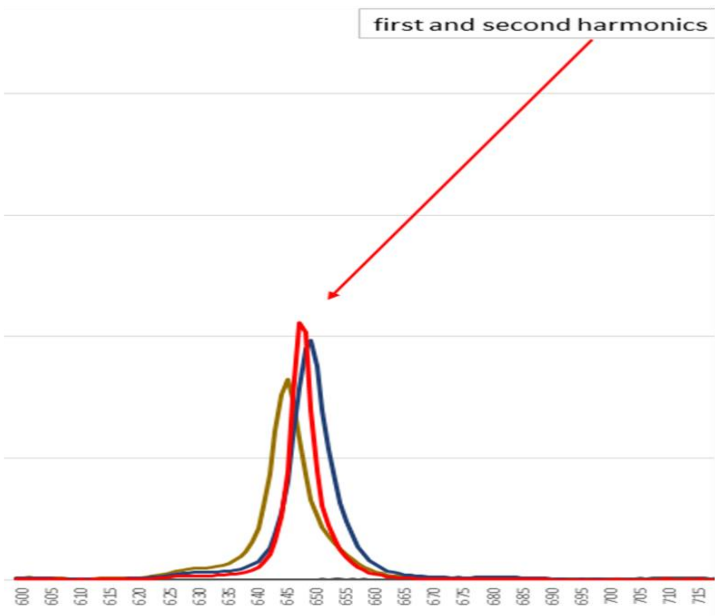
The cross talks can be corrected by multiplying the raw sensor spectra with a correction matrix.

9.2. Data – spectral correction / line scan mosaic

Some response curves have two peak wavelength (cannot be eliminated with long or short pass filters).



Some response curves have two peak wavelength (cannot be eliminated with long or short pass filters).



The position of the second harmonic (peak wavelength) is not the peak wavelength of another band.
This effect can be corrected by a correction matrix.

9.3. Requirements for the procedures described here

All following explanations / calculations assume that

- the sensor is operated in a range of a linear ratio of exposure time to gray value in the RAW image.
- All measurements are performed when the sensor is already heated to operating temperature.

9.4. Band specific flat field correction

In order to correct the effect of brightness distribution of the lighting, the influence of the lens (vignetting, aperture) and especially the spectral shifts to the corners due to increasing crosstalk, a band-specific "flat field" correction $f^b_{x_P,y_P}$ can be applied.

Parameter / values:

$o_{X,S}$	Sensor filter area offset x
$o_{Y,S}$	Sensor filter area offset y
w_S	Width of the filter area
h_S	Height of the filter area
n_S	Pattern size (height and width) of the Fabry-Perot filter pattern
$W_S * H_S$	Spatial resolution (width x height - in snapshot mosaic pattern)
$2m+1$	Size of the center for reference calculation (usually: 10 <= m <= 20)
x_M	Center of the spatial resolution, x
y_M	Center of the spatial resolution, y
$V^b_{x_P,y_P}$	Raw value of band b (0-based index) of the snapshot-mosaic pattern position x_P, y_P with $0 <= x_P < W_S$ and $0 <= y_P < H_S$
$x^b_{x_P,y_P}$	Sensor x-position of $V^b_{x_P,y_P}$ (0-based index)
$y^b_{x_P,y_P}$	Sensor y-position of $V^b_{x_P,y_P}$ (0-based index)
V^b_{ref}	Reference value for band b
$f^b_{x_P,y_P}$	Correction value for pixel / band RAW value $V^b_{x_P,y_P}$

With:

$$x_M = \left[\frac{W_S}{2}\right]$$

$$y_M = \left[\frac{H_S}{2}\right]$$

$$x^b_{x_P,y_P} = o_{X,S} + x_P * n_S + b - \left[\frac{b}{n_S}\right] * n_S$$

$$y^b_{x_P,y_P} = o_{Y,S} + y_P * n_S + \left[\frac{b}{n_S}\right]$$

$$V^b_{ref} = \frac{\sum_{x=x_M-m}^{x_M+m} \sum_{y=y_M-m}^{y_M+m} V^b_{x,y}}{(2m+1)^2}$$

$$f^b_{x_P,y_P} = \frac{V^b_{ref}}{V^b_{x_P,y_P}}$$

$[.]$ Gauß bracket notation

9.5. Reflectance calculation

The values read from the sensor is the captured radiance of an object.

The quantum efficiency (QE) of the sensor (sensor plus interference filter) depends on the wavelength. Radiance values therefore do not represent the light absorption or reflectance curves of materials used in literature.

In order to eliminate the influence of the entire setup (QE, transmission values of the optical path and the spatial and spectral variance of the illumination), the so-called reflectance can be calculated.

Basically, the object radiance is divided by a reference radiance. The reference values are measured by capturing images of a diffuse target, which reflects light of all wavelengths almost identically. These reflectance targets are often matt surfaces made of barium sulphate.

Due to different brightness levels of the object and the reference target, the exposure (integration) times may be different as well.

N	Number of spectral bands
$\vec{R} = (r_1, \ldots, r_N)$	Reflectance spectrum (vector), N -dimensional
$\vec{S}_O = (o_1, \ldots, o_N)$	Radiance spectrum (vector) of the object, N -dimensional
$\vec{S}_{\mathrm{Ref}} = (\rho_1, \ldots, \rho_N)$	Radiance spectrum (vector) of the white reference target, N -dimensional
t_O	Exposure time of the object spectrum
t_{Ref}	Exposure time of the reference spectrum

$\vec{R} = (r_1, \ldots, r_N)$ is calculated as:

$$r_i = \frac{o_i}{\rho_i} \frac{t_{\mathrm{Ref}}}{t_O}$$

The black value of the xiSpec cameras is usually set in such a way that it is not necessary to consider black images (when the camera is closed) for the reflectance calculation.

If dark images are to be used in the calculation after all, this can be achieved by using two dark images:

$\vec{D}_O = (d_1^O, \ldots, d_N^O)$	Dark image radiance spectrum, exposure time of the object spectrum
$\vec{D}_{\mathrm{Ref}} = (d_1^{\mathrm{Ref}}, \ldots, d_N^{\mathrm{Ref}})$	Dark image radiance spectrum, exposure time of the reference spectrum

$\vec{R} = (r_1, \ldots, r_N)$ is then calculated as:

$$r_i = \frac{o_i - d_i^O}{\rho_i - d_i^{\mathrm{Ref}}} \frac{t_{\mathrm{Ref}}}{t_O}$$

For the calculation of the reflectance, the band specific flat-field correction described above can be omitted.

9.6. Spectral correction / Correction matrix

The procedures described here require a calibration file / matrix which has been created with the latest procedures (starting around December 2017)! The most recent calibration file/matrix description must be used to interpret the calibration data correctly.

The application of this spectral correction requires a previously performed reflectance calculation!

In the case of the SM4X4, SM5X5 Gen 2, LS100 and LS150 sensors, the calibration files contain the data for one correction matrix. For the SM5X5 Gen 1 sensors it is recommended to use an additional filter to avoid the 2nd harmonics. Two correction matrixes are stored for the two recommended wavelength ranges (600-875 nm and 675-975 nm).

The matrixes can only be used if the original state of the XIMEA cameras (XIMEA camera bandpass filters) and one of the additional filters of the XIMEA starter kits (SM5X5: 675nm long pass or 875nm short pass filter) are used.

Please note that the number of the generated (so called virtual) bands in the spectrum may vary depending on the sensor and filter set used. As mentioned before: In some cases, the peak wavelengths are very close, the response curves overlap almost completely.

In such cases, one effective spectral band will be generated to allow quantitative analyses. The number of spectral bands contained in the corrected spectrum can therefore be lower than the number of pixels in the sensor pattern.

The following number of bands are usually created in the corrected cube:

- SM4x4 VIS: 15 - 16 bands
- SM4x4 REDNIR: 15 - 16 bands
- SM5x5 NIR (600-875 nm), Gen 1: 23 - 25 bands
- SM5x5 NIR (675-975 nm), Gen 1 24 - 25 bands
- SM5x5 NIR (665-975 nm), Gen 2 24 - 25 bands

N_S	Number of bands on the sensor surface
N_C	Number of the (virtual) bands in the corrected spectrum
$M^{N_C \times N_S}$	Correction matrix $M^{N_C \times N_S}$ with N_C rows and N_S columns
$\overrightarrow{S_S}$	Uncorrected (reflectance / sensor) spectrum (vector) with N_S elements
$\overrightarrow{S_C}$	Corrected spectrum (vector) with N_C elements

$\overrightarrow{S_C}$ is calculated as:

$$\overrightarrow{S_C} = M^{N_C \times N_S} \times \overrightarrow{S_S}$$

Please note:

- The elements $\lambda_{C,n}$ in $\overrightarrow{S_C} = \left(\lambda_{S,1}, \ldots, \lambda_{S,N_C}\right)$ are sorted by wavelength.
- The elements $\lambda_{S,n}$ in $\overrightarrow{S_S} = \left(\lambda_{S,1}, \ldots, \lambda_{S,N_S}\right)$ are sorted by their sensor pattern position (index+1) (!) to use the regular correction matrix $M^{N_C \times N_S}$ (stored in the calibration file).

If $\overrightarrow{S_S}$ is sorted by wavelength either the elements in $\overrightarrow{S_S}$ or the columns in $M^{N_C \times N_S}$ have to be re-sorted!

9.6.1. Example correction data / virtual bands (part of the sensor calibrations files):

N_C (virtual) bands of the corrected spectrum are defined in the section <correction_matrix> in the sensor calibration file:

```
<correction_matrices>
 <correction_matrix version="4" timestamp="20180213T233647.371419">
 . . . . . .
       <virtual_bands>
             <virtual_band version="1">
                   <wavelength_nm> $\lambda_{v,1}$ </wavelength_nm>
                   <fwhm_nm> $\varpi_1$ </fwhm_nm>
                   <coefficients nr_elements=" $N_S$ "> $f_{1,1}$ , $f_{1,2}$ , $f_{1,3}$ , . . . ., $f_{1,N_S}$ </coefficients>
             </virtual_band>
             <virtual_band version="1">
                   <wavelength_nm> $\lambda_{v,2}$ </wavelength_nm>
                   <fwhm_nm> $\varpi_2$ </fwhm_nm>
                   <coefficients nr_elements=" $N_S$ "> $f_{2,1}$ , $f_{2,2}$ , $f_{2,3}$ , . . . ., $f_{2,N_S}$ </coefficients>
             </virtual_band>
             <virtual_band version="1">
                   <wavelength_nm> $\lambda_{v,3}$ </wavelength_nm>
                   <fwhm_nm> $\varpi_3$ </fwhm_nm>
                   <coefficients nr_elements=" $N_S$ "> $f_{3,1}$ , $f_{3,2}$ , $f_{3,3}$ , . . . ., $f_{3,N_S}$ </coefficients>
             </virtual_band>
             . . . . .
             . . . . .
             <virtual_band version="1">
                   <wavelength_nm> $\lambda_{v,N_C}$ </wavelength_nm>
                   <fwhm_nm> $\varpi_{N_C}$ </fwhm_nm>
                   <coefficients nr_elements=" $N_S$ "> $f_{N_C,1}$ , $f_{N_C,2}$ , $f_{N_C,3}$ , . . . ., $f_{N_C,N_S}$ </coefficients>
             </virtual_band>
       </virtual_bands>
 </correction_matrix>
</correction_matrices>
```

The correction matrix is:

$$M^{N_C \times N_S} = \begin{pmatrix} f_{1,1} & f_{1,2} & f_{1,3} & .. & .. & f_{1,N_S} \\ f_{2,1} & f_{2,2} & f_{2,3} & .. & .. & f_{2,N_S} \\ f_{3,1} & f_{3,2} & f_{3,3} & .. & .. & f_{3,N_S} \\ .. & .. & .. & .. & .. & .. \\ f_{N_C,1} & f_{N_C,2} & f_{N_C,3} & .. & .. & f_{N_C,N_S} \end{pmatrix}$$

Uncorrected (sensor) spectrum:

The elements $\lambda_{S,n}$ in $\overrightarrow{S_S}$ are sorted by their sensor pattern position

1	2	..	..
..	..	..	..
..	..	..	..
..	..	..	N_S

$$\overrightarrow{S_S} = \left(\lambda_{S,1}, ..., \lambda_{S,N_S}\right)$$

Corrected spectrum

The elements $\lambda_{C,n}$ in $\overrightarrow{S_C}$ are sorted by wavelength. These wavelengths are the peaks of the virtual bands (see the example correction matrix / virtual bands above).

$$\overrightarrow{S_C} = M^{N_C \times N_S} \times \left(\lambda_{S,1}, ..., \lambda_{S,N_C}\right) = \left(\lambda_{v,1}, ..., \lambda_{v,N_C}\right) \text{ [virtual band peaks]}$$

10. Development:

A software solution must be used / developed that is able to acquire the RAW data from the camera and read and interpret the calibration date. An API/SDK to acquire the RAW data and control the camera is available for free. Please note that additional software components or own image processing is required to generate the so-called hyperspectral cubes.

You can get our technical manual for the xiQ camera series for more details at:
http://www.ximea.com/downloads/usb3/manuals/xiq_technical_manual.pdf

10.1. API / SDK / drivers:

Our API / drivers etc. are available for download for free:

Most recent beta version: http://www.ximea.com/support/documents/14

Stable version (and LINUX / MacOS files): http://www.ximea.com/support/documents/4

Link to our API: http://www.ximea.com/support/wiki/apis/APIs

C/C++ manual: http://www.ximea.com/support/wiki/apis/XiAPI_Manual

C# manual: http://www.ximea.com/support/wiki/apis/XiAPINET_Manual

Part of the driver/API is the standard viewer xiCamTool.

After installation of the API you'll find some samples (with complete source code) at:

C:\XIMEA\Examples (Windows):

xiSample C: how to start
xiAPI.NET C#: how to start

Please do not use MONO modes. Only RAW8 or RAW16 will deliver the original sensor data. MONO8 / MONO16 is a post-processed format. Please note

https://www.ximea.com/support/projects/apis/wiki/XiApi_Manual#XI_PRM_IMAGE_DATA_FORMAT-or-imgdataformat

http://www.ximea.com/support/projects/apis/wiki/XiApi_Manual#Data-Format-Dependency-Table

You can set the output bit depth using:

http://www.ximea.com/support/projects/apis/wiki/XiApi_Manual#XI_PRM_SENSOR_DATA_BIT_DEPTH-sensor_bit_depth

http://www.ximea.com/support/projects/apis/wiki/XiApi_Manual#XI_PRM_OUTPUT_DATA_BIT_DEPTH-output_bit_depth

http://www.ximea.com/support/projects/apis/wiki/XiApi_Manual#XI_PRM_IMAGE_DATA_BIT_DEPTH-image_data_bit_depth

It is recommended to use the data packing to increase the transfer speed in case of a bit depth of 10 or 12 bits.

If you need to change the exposure time during your operation, please use the parameter
http://www.ximea.com/support/projects/apis/wiki/XiApi_Manual#XI_PRMM_DIRECT_UPDATE

10.2. Access to the sensor calibration files

IMEC measures every multi-/hyperspectral sensor individually. The resulting calibration files will be delivered together with the sensor.

XIMEA stores the calibration files in a file system of the camera. The files can be read using API functions. Additionally, the calibration files are delivered on a USB-stick.

IMEC changed the filenames and esp. the file format several times. As a consequence, the file size raised significantly. Due to the restricted size of the file system all calibration files are now stored in a zipped format.

10.2.1. File name schematics

In first deliveries only one calibration file named sens_calib.dat has been delivered (in case of the SSM5x5 sensor only the original measured values with a wavelength range 600-1000 nm, not the three files described below).

The various file format definitions are described in the appendices (TR_sensor_calibration_files[-Vxx].pdf).

Please note the orientation of the calibration files have to be interpreted as this has been flipped between V01 (from bottom to top) and V02 (top to bottom).

Beginning with the second version of the calibration files, the file name structure changed:

New filename structure (IMEC original):

CMV2K-<Type>-<W-Range>-<SENS-SerNr>.xml

Type: sensor type:

- SSM4x4 Snapshot mosaic 4x4, 16 bands VIS
- SSM5x5 Snapshot mosaic 5x5, 25 bands NIR
- LS100 Line scan, 100 bands NIR
- LS150 Line scan, 150 bands VISNIR
-

W-Range: Active wavelength range:

- 470_620 in case of a SSM4x4 sensor
- 600_1000in case of a LS100 sensor
- 470_900 in case of a LS150 sensor
- SM5X5 Sensor Gen 1
  - 600_1000
  - 600_875
  - 675_975
- SM5X5 Sensor Gen 2
  - 665_975

SENS-SerNr: Sensor serial number

- 4 numbers, separated by dots, e.g. 4.2.16.0

Examples for valid filenames:

- CMV2K-LS100-600_1000-4.2.12.5.xml
- CMV2K-SSM5x5-675_975-5.4.4.6.xml
- CMV2K-SSM5x5-600_1000-5.3.14.4.xml (SM5x5, Gen 1)
- CMV2K-SSM5x5-665_975-13.8.15.10.xml (SM5x5, Gen 2)

SSM5X5 Gen 1:

Old Versions:

In case of SSM5x5 sensors three files are delivered, one for each wavelength range:

- 600_1000 nm: original measurement data
- 600-875 nm data calculated for one of the recommended wavelength ranges
- 675_975 nm data calculated for one of the recommended wavelength ranges

It is recommended to use the file fitting to the used filter setup.

Most recent Versions:

Only one file (600_1000) is delivered. This file contains all information as described in the documentation TR_sensor_calibration_files.pdf

The sensor measurement data and the calculated datasets (virtual bands) for both recommended wavelength ranges are stored in this file.

10.2.2. File storing in the file system

Examples of file system content:

10.2.2.1. First delivery phase

Only one file is stored, the original sensor calibration file without wavelength range or camera filter specific calculations. The file name is sens_calib.dat in every case.

```
Directory of 'mmf1/*'
03-Mar-2015 11:15:28        158167 sens_calib.dat
          1 files
     158167 bytes
```

10.2.2.1.1. Content of the file sens_calib.dat beginning with the second delivery phase

The file no longer contains the calibration file. Due to backward compatibility (find the files in the file system) the file name is reused with different content.

It is a directory / translation table:

IMEC calibration file name <-> file name in cameras file system

<file_name> is the name of the original calibration file from IMEC

<file_link> is the name of the file in the file system, please note the file extension (xml or zip)

10.2.2.1.2. Calibration file naming schematics, starting with the second delivery phase

According to the changes in the filenames, content and size several different ways of storing the calibration files have been realized.

The calibration files are stored using the filename-structure:

<Type>-<Wavelength Range>-<Sens-SerNr>.[xml I zip]

Details see below.

10.2.2.2. Second Delivery phase, e.g. snapshot mosaic camera SM5x5,

The file sens_calib.dat still exists. The content isn't the calibration file, it is a "directory". The calibration files are stored in XML-format.

Please note: in very rare cases, the filename of the file *600_875* (only SM5x5-cameras) has been stored using the wrong file extension *.xmll.

```
Directory of 'mmf1/*'
26-Jun-2015 13:26:45        352374 SSM5x5-600_875-5.2.3.9.xml
26-Jun-2015 13:26:27        355566 SSM5x5-675_975-5.2.3.9.xml
26-Jun-2015 13:26:38        207658 SSM5x5-600_1000-5.2.3.9.xml
26-Jun-2015 13:26:26           463 sens_calib.dat
          5 files
     916229 bytes
```

Content of the file sens_calib.dat:

```
<calibrations>
     <calibration>
          <file_name>CMV2K-SSM5x5-675_975-5.2.3.9.xml</file_name>
          <file_link>SSM5x5-675_975-5.2.3.9.xml</file_link>
     </calibration>
     <calibration>
          <file_name>CMV2K-SSM5x5-600_1000-5.2.3.9.xml</file_name>
          <file_link>SSM5x5-600_1000-5.2.3.9.xml</file_link>
     </calibration>
     <calibration>
          <file_name>CMV2K-SSM5x5-600_875-5.2.3.9.xml</file_name>
          <file_link>SSM5x5-600_875-5.2.3.9.xml</file_link>
     </calibration>
</calibrations>
```

10.2.2.3. Third delivery phase, e.g. snapshot mosaic camera SM4x4 / line scan camera LS100

The calibration files are stored compressed in ZIP-format.

Please note: in very rare cases, the filename of the file *600_875* (only SM5x5-cameras) has been stored using the wrong file extension *.zipp.

```
Directory of 'mmf1/*'
13-Jan-2016 12:11:58         63016 SSM4x4-470_620-9.2.4.11.zip
13-Jan-2016 12:11:58           174 sens_calib.dat
          2 files
      63190 bytes


Directory of 'mmf1/*'
19-Oct-2015 14:30:46        527535 LS100-600_1000-4.2.12.12.zip
19-Oct-2015 14:30:46           176 sens_calib.dat
          2 files
     527711 bytes
```

Content of the file sens_calib.dat:

```
<calibrations>
     <calibration>
          <file_name>CMV2K-SSM4x4-470_620-9.2.4.11.xml</file_name>
          <file_link>SSM4x4-470_620-9.2.4.11.zip</file_link>
     </calibration>
</calibrations>
```

10.2.3. API implementation

10.2.3.1. API function to get the sensor serial number which is used to build the file names:

C / C++

```
char sensor_sn [100] = "";
xiGetParamString(xiH, XI_PRM_DEVICE_SENS_SN , sensor_sn, 99);
```

.NET

```
String xi_sensor_sn;
xiH.GetParam(PRM.DEVICE_SENS_SN, out xi_sensor_sn);
```

10.2.3.2. API function to read files from the file system

C / C++

Set the file name to be used

```
char xi_filename[MAX_PATH]="sens_calib.dat";   // e.g.
xiSetParamString(xiH, XI_PRM_FFS_FILE_NAME, \
xi_filename, sizeof (xi_filename));
```

Read a file

```
#define BUFFER_LENGTH      1024000
char *buffer_InOut;
int  i_filelength = 0;
buffer_InOut = (char*) calloc(BUFFER_LENGTH, 1);
xiGetParamString(xiH, XI_PRM_READ_FILE_FFS, buffer_InOut, \
BUFFER_LENGTH);
i_filelength = strlen(buffer_InOut);
```

.NET

Set the file name to be used

```
String internalFileName_used;
internalFileName_used = "sens_calib.dat"; // e.g.
xiH.SetParam(PRM.FFS_FILE_NAME, internalFileName_used);
```

read a text file:

```
String buffer;
buffer = "";
xiH.GetParam(PRM.READ_FILE_FFS, out buffer);
fileLength = buffer.Length;
```

read a binary file (zip-container)

```
byte[] bufferZipped;
int unzippedLength;

bufferZipped = xiH.GetParamByteArr(PRM.READ_FILE_FFS);
fileLength = bufferZipped.Length;
```

10.2.3.3. API functions to read the directory from the file system

Example code to get the info about the files in the file system:

C / C++

```
int        num_free = 0;              // free space
int        num_used = 0;              // used space
int        a_xiq_directory = 0; // number of entries
int        file_length;
char       file_name [MAX_PATH];

// get FFS info
xiGetParamInt(xiH, XI_PRM_FREE_FFS_SIZE, &num_free);
xiGetParamInt(xiH, XI_PRM_USED_FFS_SIZE, &num_used);
xiGetParamInt(xiH, XI_PRM_FFS_FILE_ID XI_PRM_INFO_MAX, &a_xiq_directory);

for (int i_xiq_directory=0; i_xiq_directory <= a_xiq_directory;      \
      i_xiq_directory++)
{
      xiSetParamInt(xiH, XI_PRM_FFS_FILE_ID, i_xiq_directory);
      xiGetParamString(xiH, XI_PRM_FFS_FILE_NAME, file_name, MAX_PATH);
      xiGetParamInt(xiH, XI_PRM_FFS_FILE_SIZE, &file_length);

      // do something
}
```

.NET

```
class DirectoryEntry
{
    public string name;
    public int size;
}
List<DirectoryEntry> directory = new List<DirectoryEntry>();

int free_ffs_size, used_ffs_size, maxID_directory;
myCam.GetParam(PRM.FREE_FFS_SIZE, out free_ffs_size);
myCam.GetParam(PRM.USED_FFS_SIZE, out used_ffs_size);

myCam.GetParam(PRM.FFS_FILE_ID + PRMM.MAX, out maxID_directory);

for (int ii=0; ii<=maxID_directory; ii++)
{
      string buffer = "";
      int fileLength = 0;
      DirectoryEntry directoryEntry = new DirectoryEntry();

      myCam.SetParam(PRM.FFS_FILE_ID, ii);
      myCam.GetParam(PRM.FFS_FILE_NAME, out buffer);
      directoryEntry.name = buffer;
      myCam.GetParam(PRM.FFS_FILE_SIZE, out fileLength);
      directoryEntry.size = fileLength;

      directory.Add(directoryEntry);
}
```

11. demo software xiSpec01 beta – brief description

11.1. Focus / Content

We will describe the steps to store images in ENVI file format for any further data analysis, e.g. using scyven or MATLAB. Use of this program with a line scan camera is not defined.

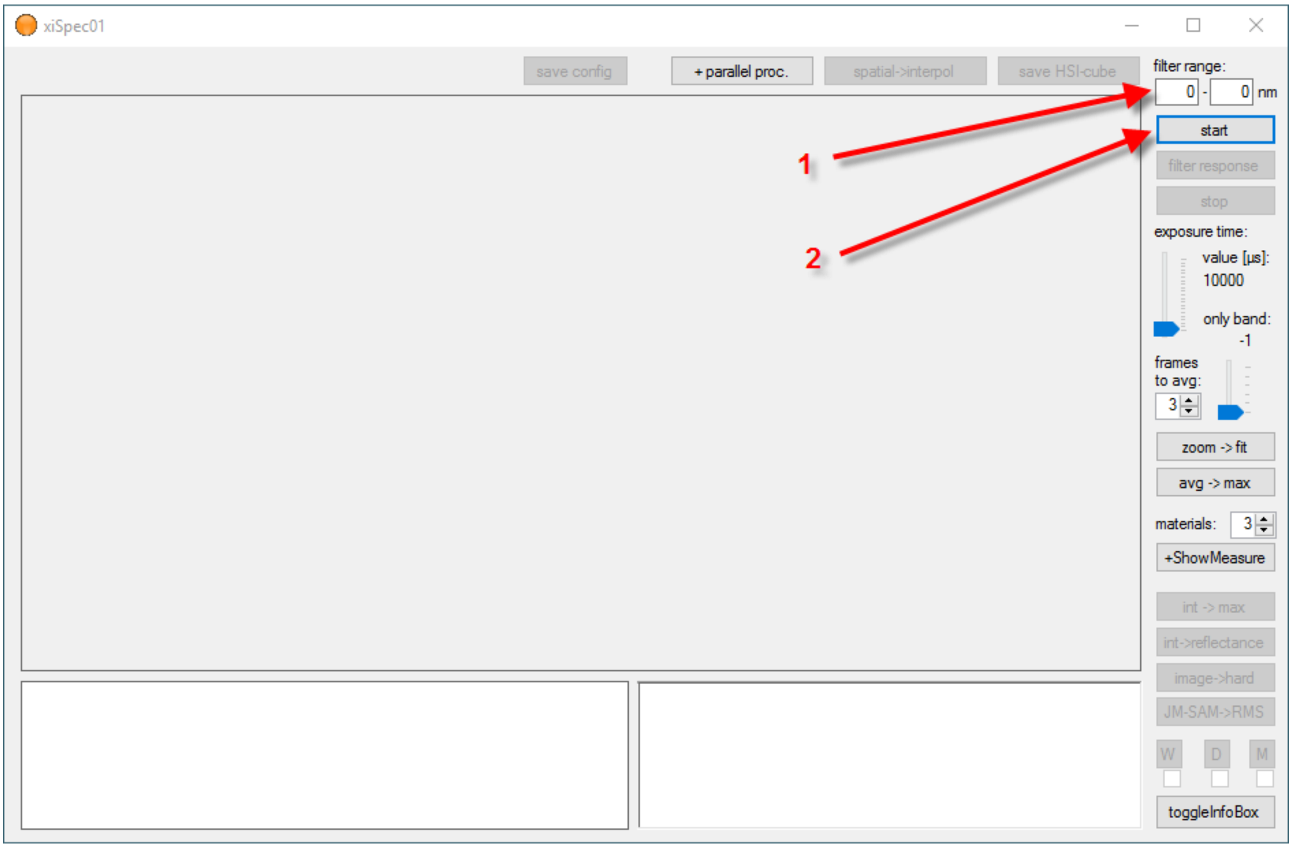
11.2. System requirements:

Operation system: Windows 7, 8, 8.1 and 10

XIMEA camera drivers in a compatible version is installed. An installation file will be distributed together with the xiSpec01 program on the USB drive included with a purchase from XIMEA.

11.3. Program start / preparation:

Start the program xiSpec01, the following windows will appear:



11.3.1. Step 1: Preparation: Type in the used filter range.

Correct values:

SM5X5-NIR camera (Gen 1):

- 600 – 975 nm: no additional filter used
- 600 – 875 nm: additional 875 nm short pass filter used
- 675 – 975 nm: additional 675 nm long pass filter used
- 0 – 0 nm: default: 675-975nm will be used

SM5X5-NIR camera (Gen 2):

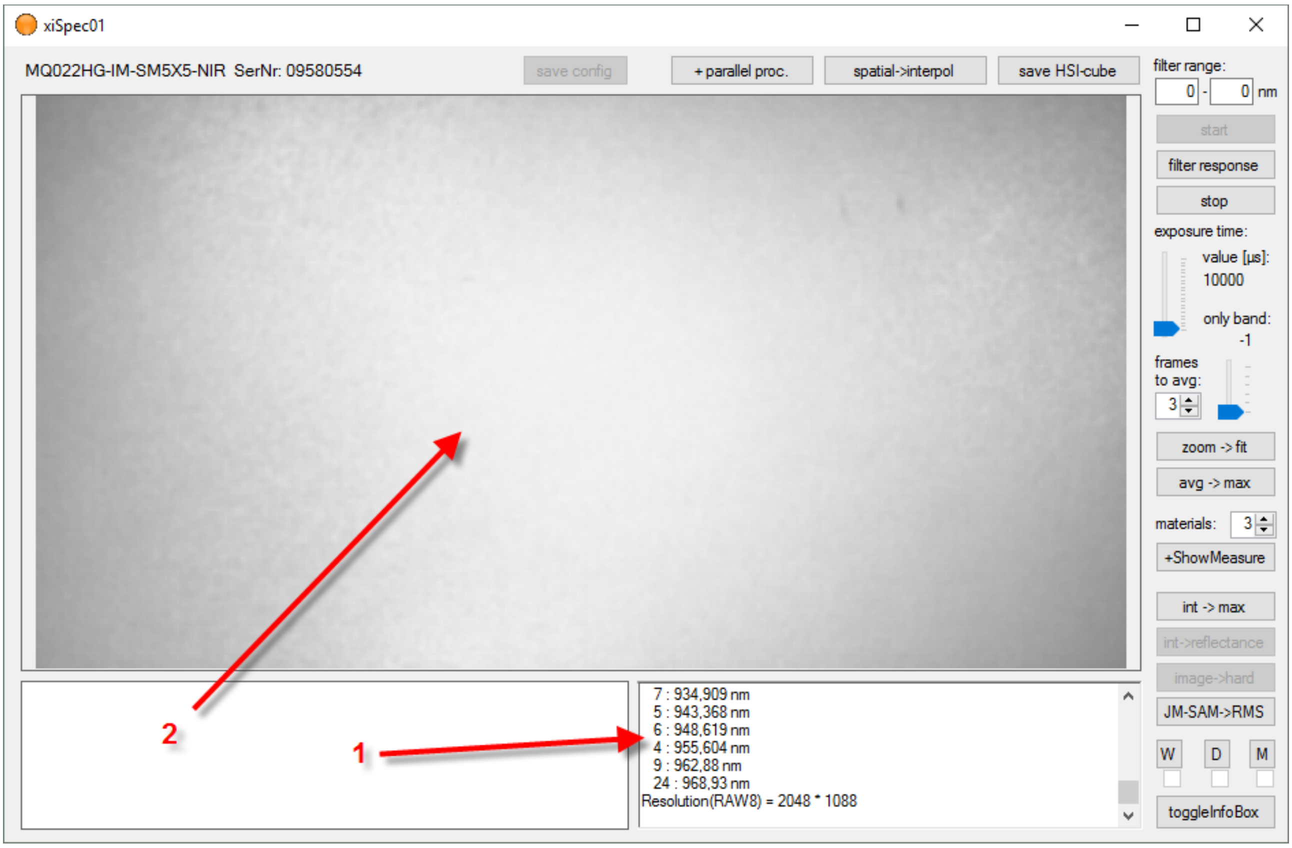
- 650 – 975 nm: additional 650 nm long pass filter used
- 660 – 975 nm: additional 660 nm long pass filter used
- 0 – 0 nm: default: 650-975nm will be used

SM4X4-VIS camera:

- 450 – 650 nm (cameras produced in 2015 or 2016)
- 475 – 640 nm (cameras produced from 2017)
- 0 – 0 nm: default:
  - 450 – 650 nm (cameras produced in 2015 or 2016)
  - 475 – 640 nm (cameras produced from 2017)

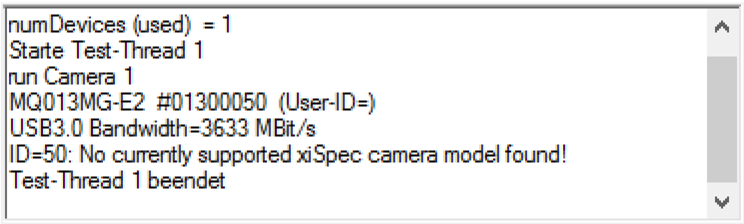
11.3.2. Step 2: start connecting the camera

Camera initialization



1: statistics window

A small window with some statistic info will displayed. If any error occurs (e.g. non compatible camera connected) error messages will be displayed and the image grabbing will be stopped:



Using the button “toggleInfoBox” in the lower right corner, this statistics window can be disabled / enabled.

2. A grayscale image will be displayed in the main windows.

11.4. Basics

11.4.1. Image resolution modes:

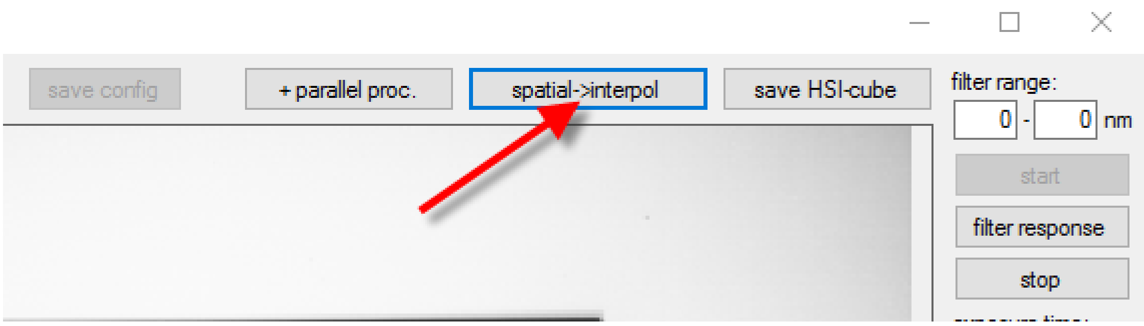
Several resolution modes are available:

- Spatial resolution
- Interpolated resolution
- RAW image

You can toggle through these modes:

spatial -> interpol(ated) -> RAW -> spatial …….

using this button:

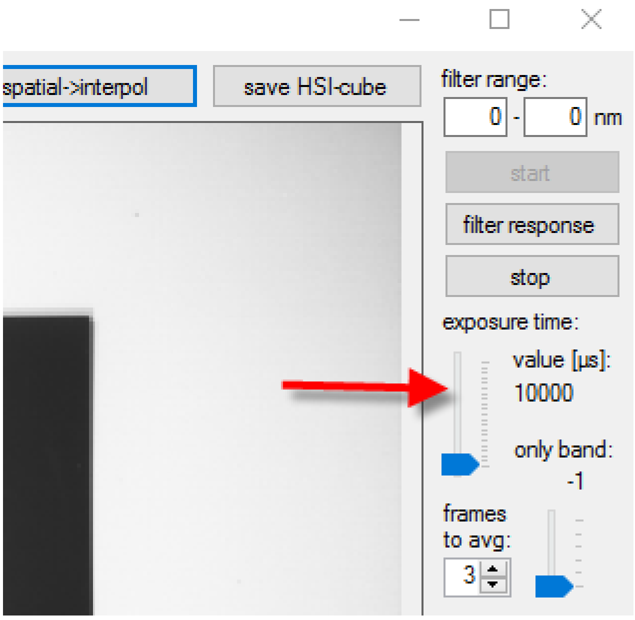


Button text:

Current mode -> next mode after pressing the button

11.4.2. Exposure time

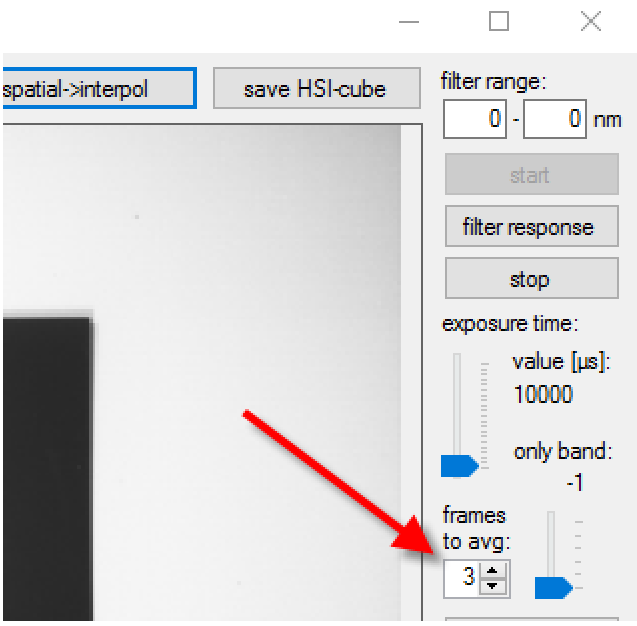
The exposure time (values in µs) can be changed using the slider “exposure time”:



After selecting this element (mouse click) the mouse, mouse wheel and the keys UP and DOWN on the keyboard can be used to adjust the exposure time.

11.4.3. Frames to average

Several frames can be used to calculate an average to reduce sensor noise or flickering illumination (e.g. halogen bulb lamps connected to 50 Hz electrical power line):



11.4.4. Display modes

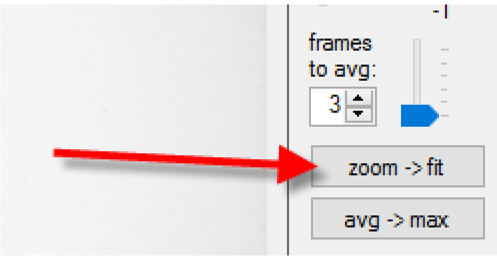
Two standard display modes are usable:

- Zoom
- Fit

Zoom: the mouse wheel can be used to zoom in and out.

Fit: the image fits into the main image windows

You can toggle through these modes using the button:



Button text:

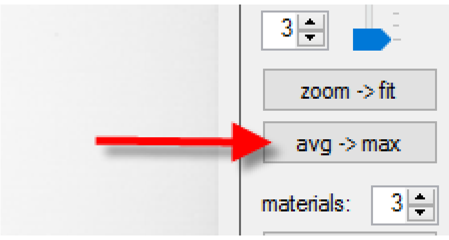
Current mode -> next mode after pressing the button

11.4.5. Displayed value modes

Three standard displayed value modes are usable:

- Avg (average)
- Max (maximum)
- Min (minimum)

You can toggle through these modes using the button:



Button text:

Current mode -> next mode after pressing the button

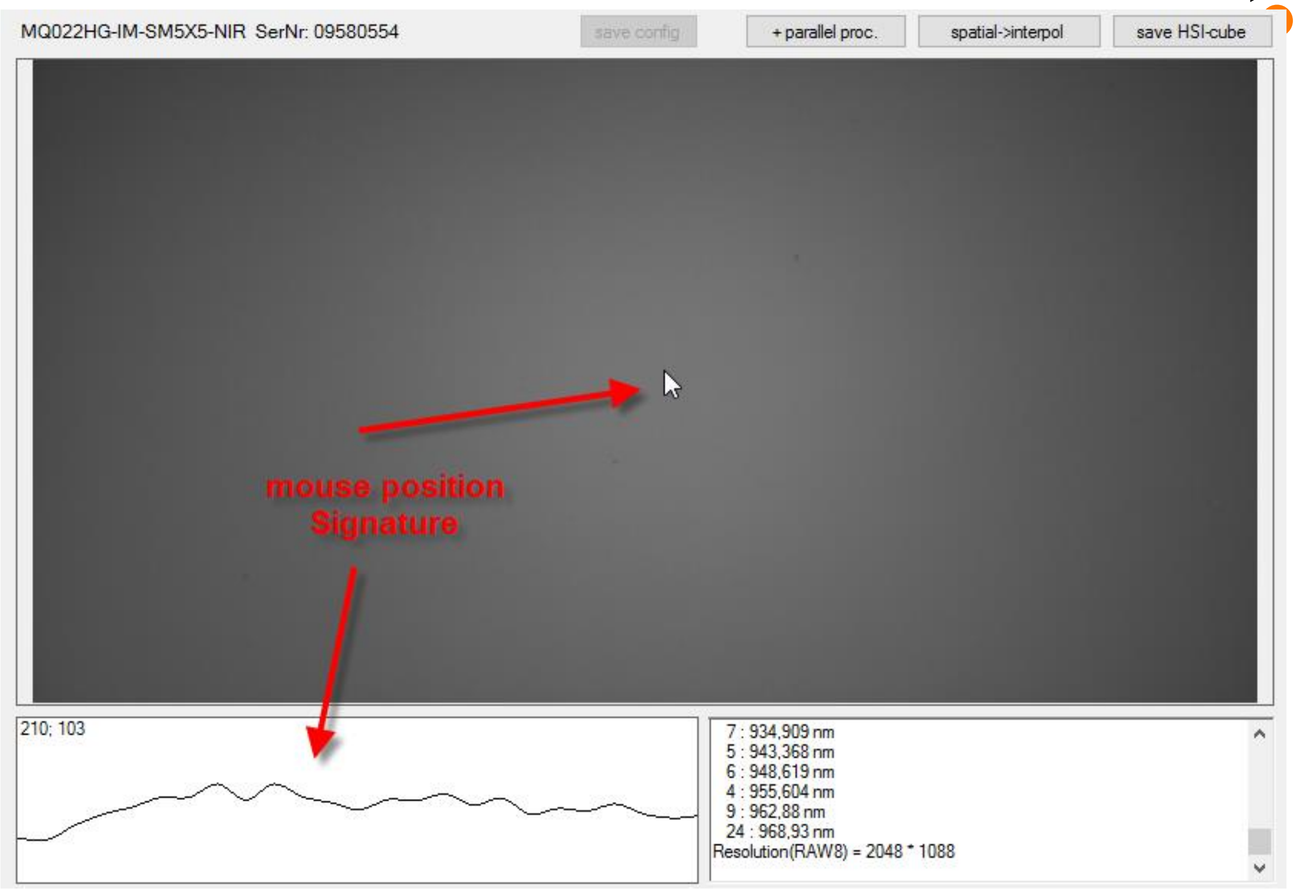
Each image-pixel represents a hyperspectral signature with 16 or 25 bands with the values (x_1, x_2, … x_n).

In spatial and interpolated resolution modes this mode has the following effect: the brightness of the image pixel is calculated:

- Average: $(x_1 + x_2 + \ldots + x_n) / n$
- Maximum: max (x_i)
- Minimum: min (x_i)

11.4.6. Spectral response / signature

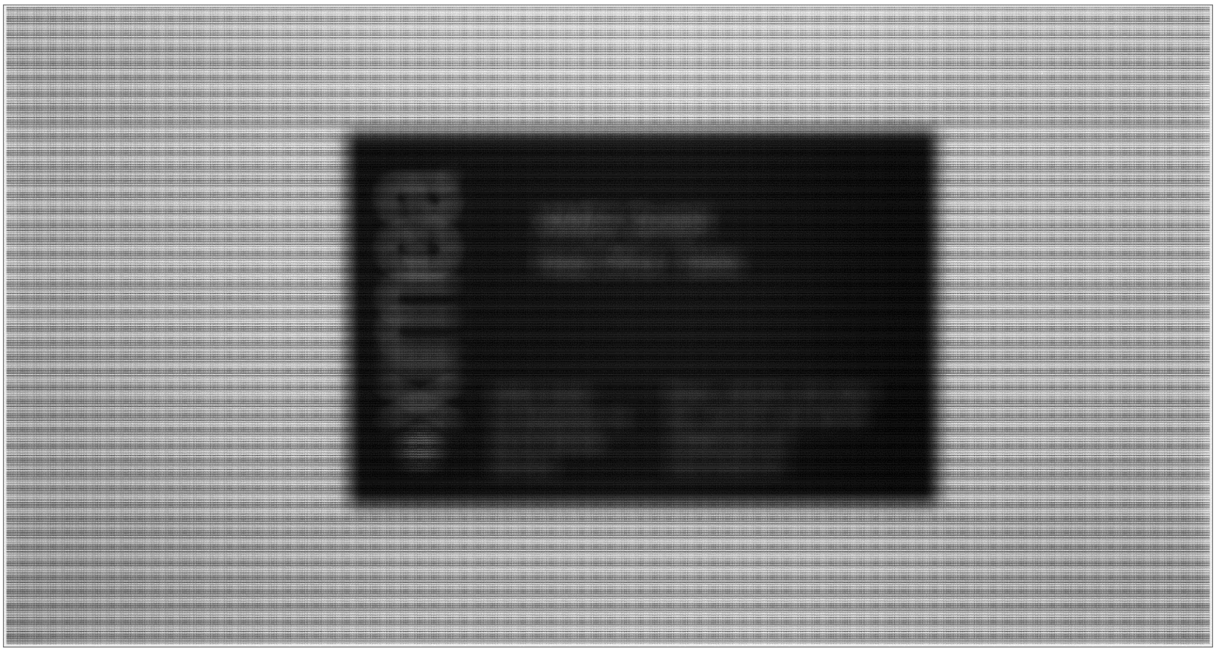
In spatial and interpolated resolution modes the spectral signature of the pixel at the mouse position will displayed in the lower left windows:



11.5. White image / vignetting calibration

Please focus the image. The fastest way is to use the RAW image resolution mode (CamTool works for this as well). Please adjust the exposure time if needed:

Before:



After: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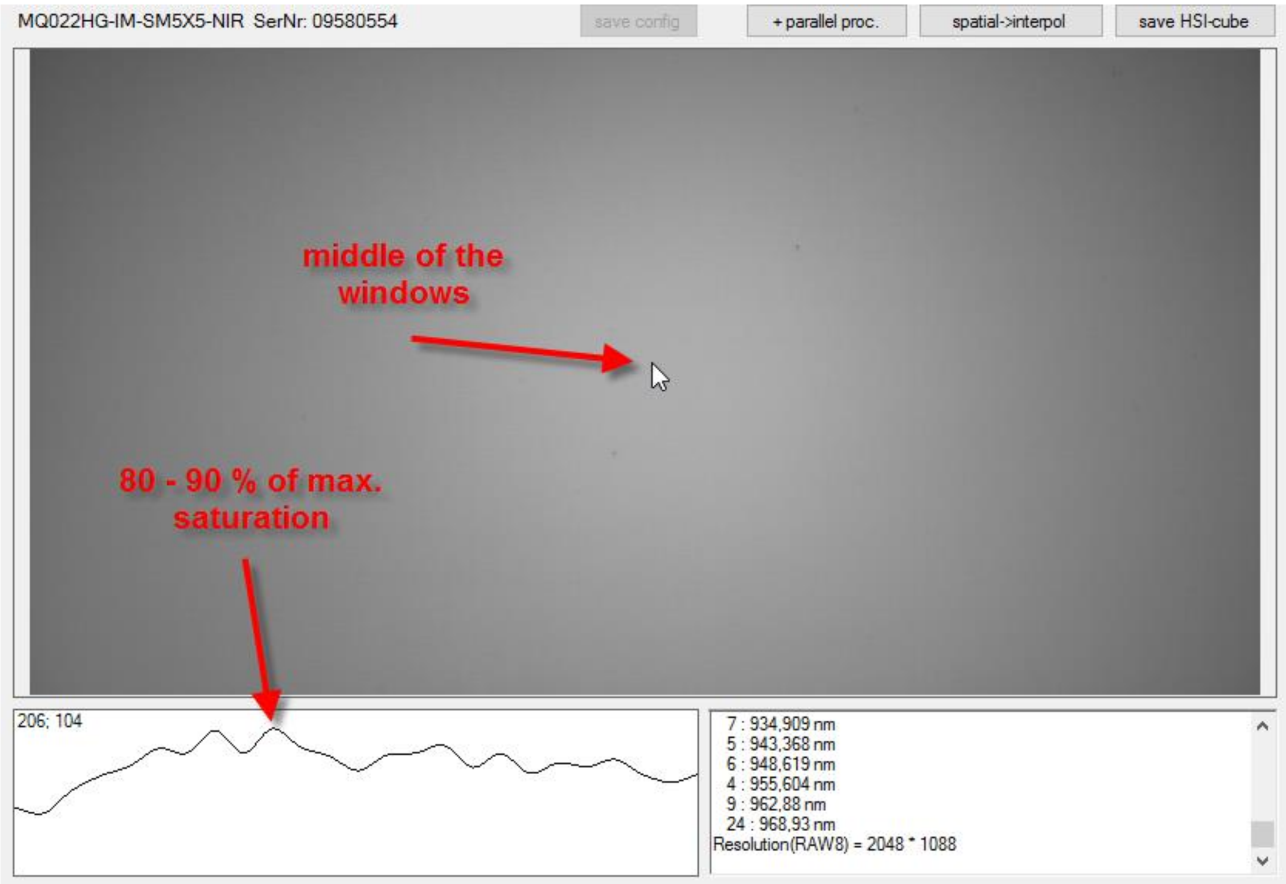
Switch to the spatial resolution mode and please place the white calibration target in the field of view.

Please adjust the exposure time. The easiest way is:

- Activate the exposure time slider (mouse click)
- Move the mouse in the middle of the image windows
- Use the keys UP and DOWN to change the values in 500 µs steps
- Use the mouse wheel for fine tuning

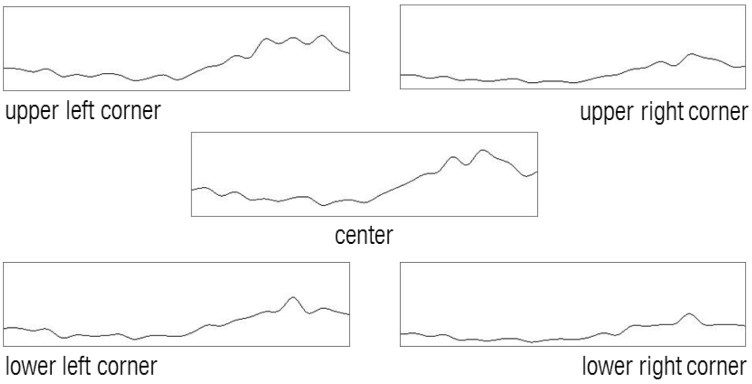
Please select an exposure time the max. value of the signature has a value between 80 – 90 % of the saturation level (max value).



Change the value of frames to average if needed.

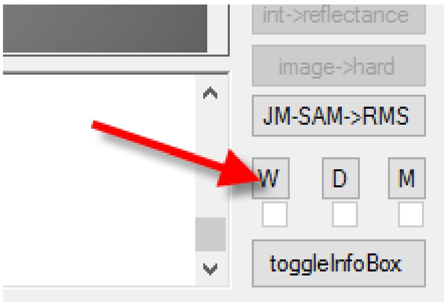
You will see different brightness levels in the middle and the edges of the image (see above).

If you have a look to the signatures in the middle and the edges different signatures will be visible:

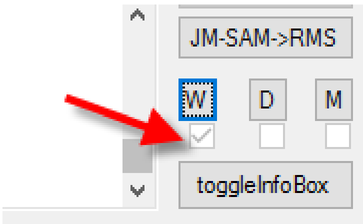


Both effects (brightness differences and different signatures) can be corrected.

Please use the White calibration button:



The check box below will change the status:

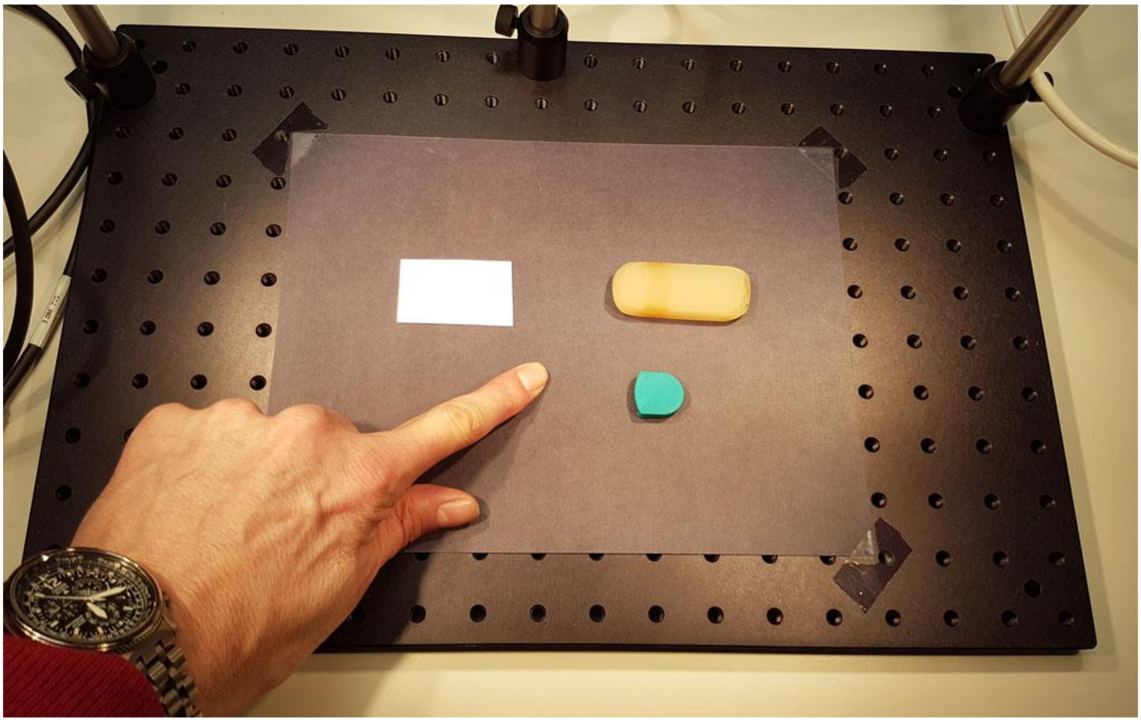


and the effects mentioned above are corrected:

Please remove the white calibration target and store it safely.

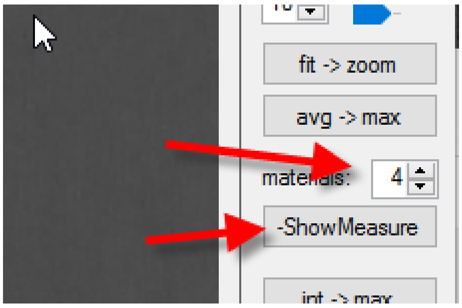
11.6. Learn spectral signatures, material discrimination

Place some materials to learn their signatures for alive demo:

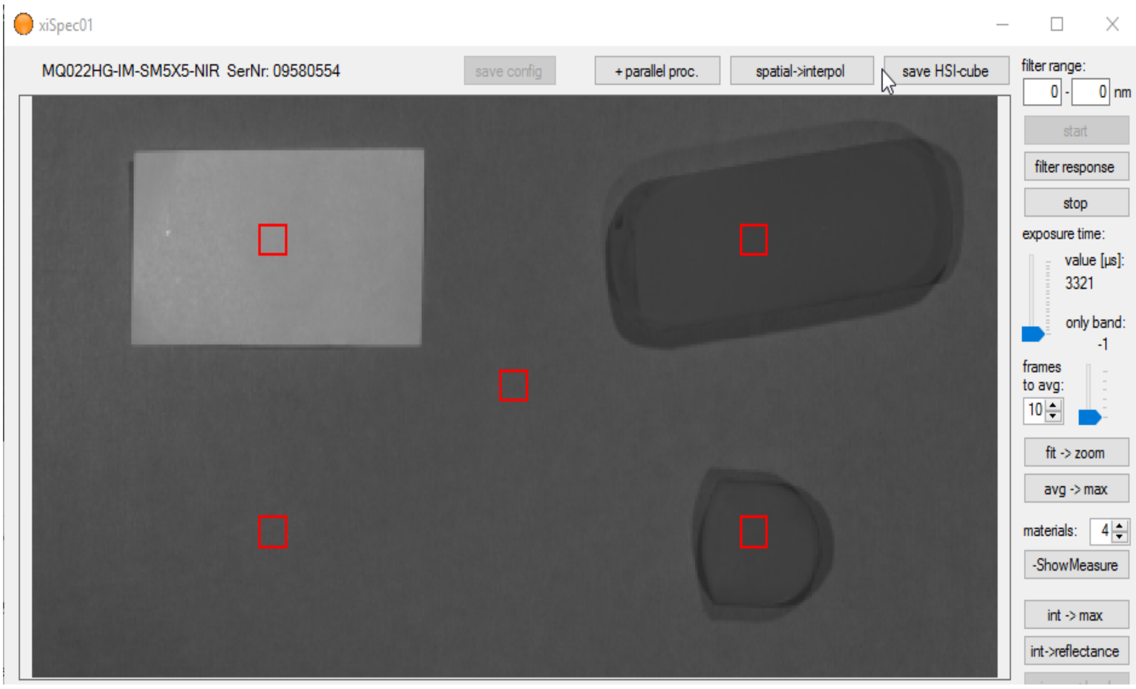


In this case 4 materials has to be learned. It is recommended to learn the signature of a finger, too. Otherwise the skin signature in not know. If some materials will be moved during the live presentation the displayed color of the hand would be represented by the color of another (learned) signatures (often from paper).

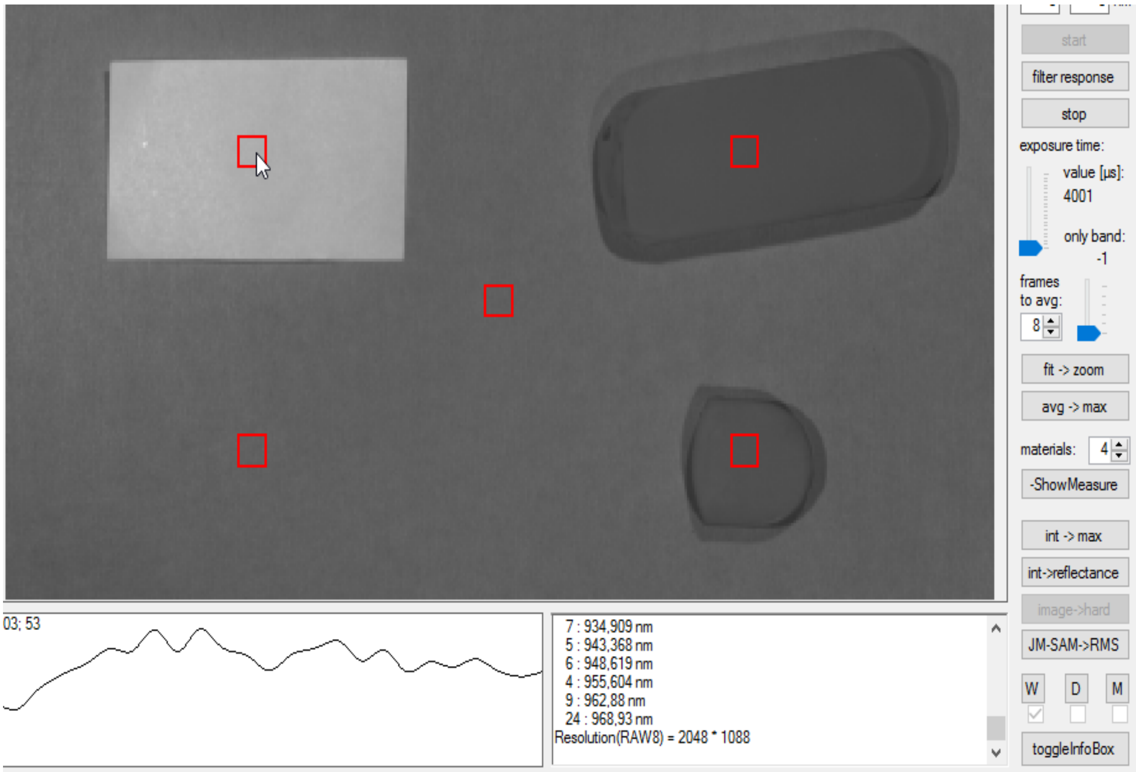
Select (e.g.) 4 materials and show the measurement fields:



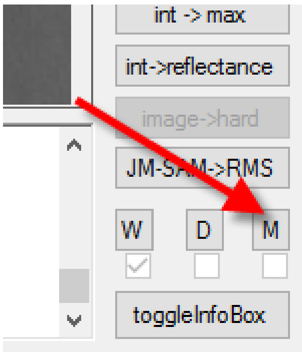
The measurement fields will be displayed now (here w/o the finger)



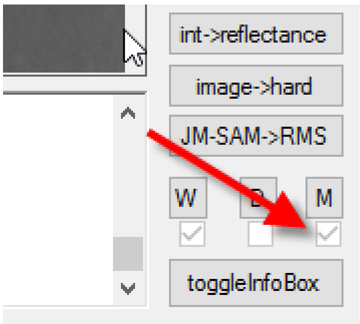
Readjust the exposure time: approx. 90 % saturation level of the brightest material signature – in this case the white paper:



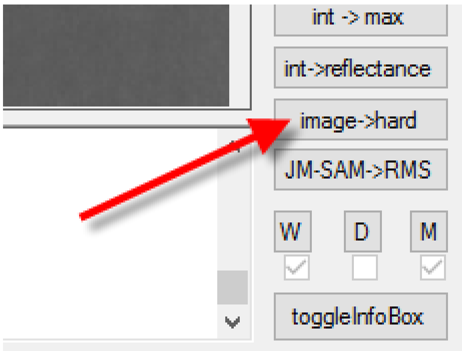
And learn the material signatures (with the finger), using the measurement button:



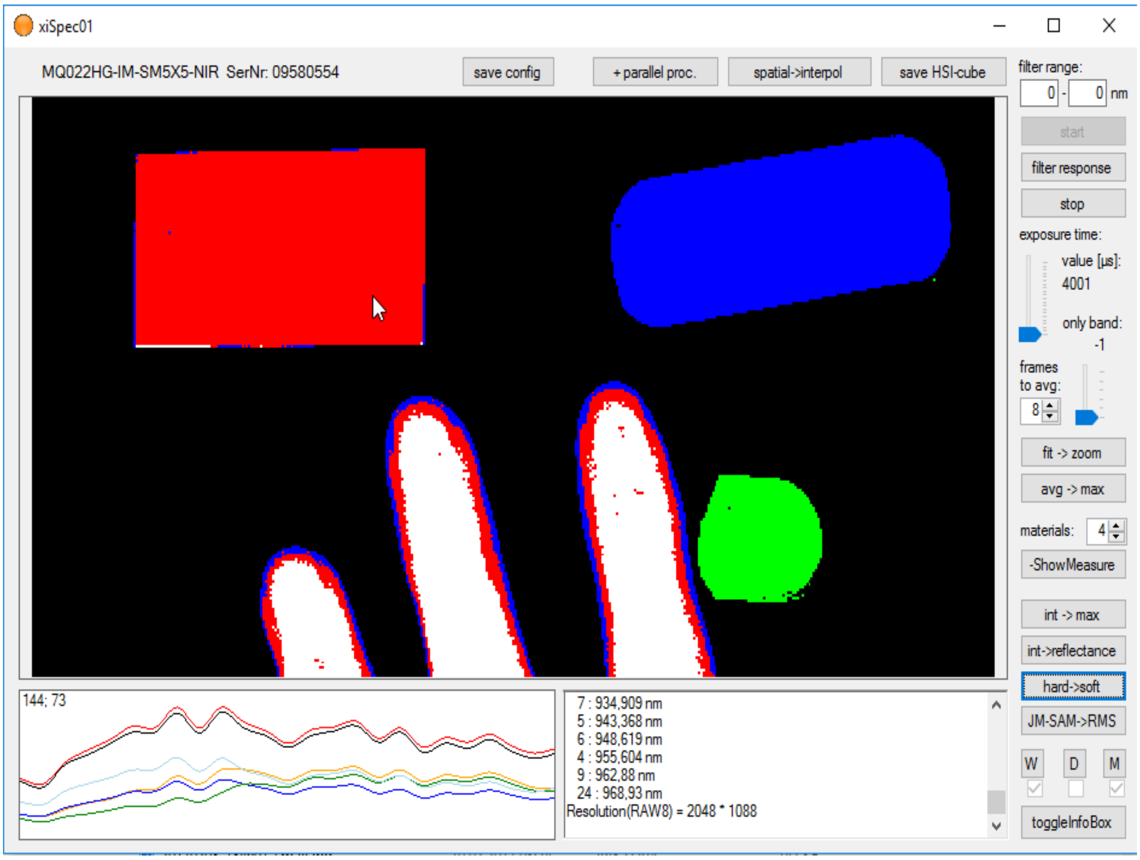
The check box below will change the status:



The material discrimination mode can now be used. Switch the discrimination mode from image to hard:



Results:

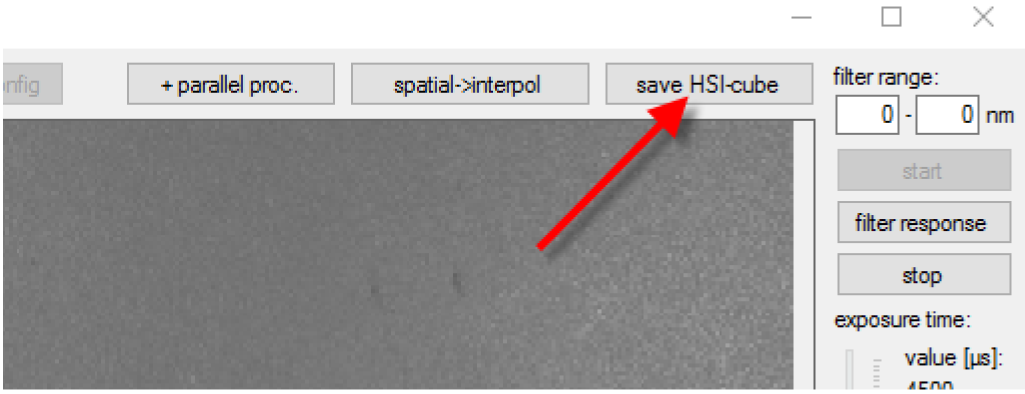


Displayed signatures in the lower left window:

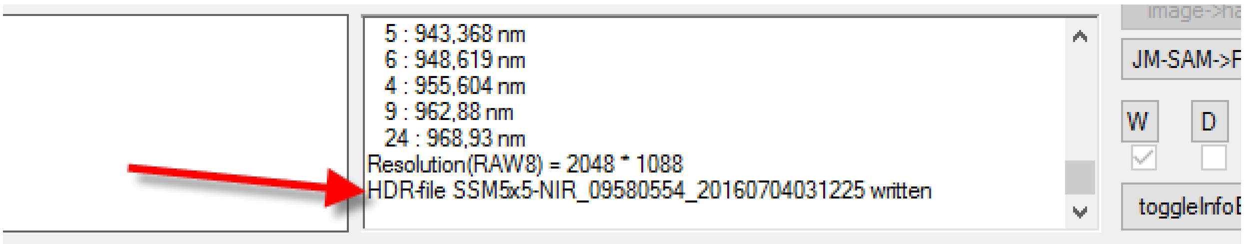
- Red: material learned in the upper left measurement field – displayed in red
  Blue: material learned in the upper right measurement field – displayed in blue
  Green: material learned in the lower right measurement field – displayed in green
  Light blue: material learned in the lower left measurement field – displayed in white
  Yellow: material learned in the center measurement field (background) – displayed in black
  Black: signature at the current mouse position

11.7. Store HSI cubes in ENVI file format

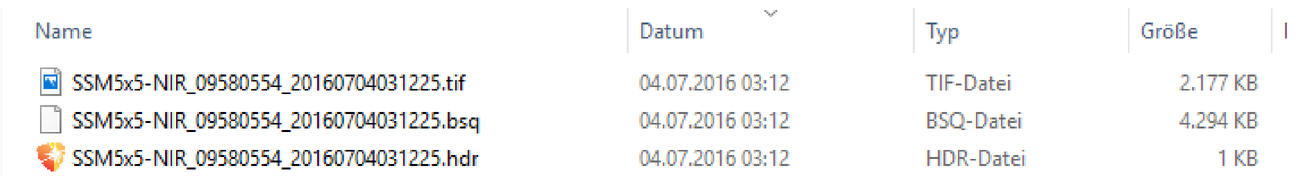
Images can be stored in ENVI file format HDR/BSQ using the button “save HSI-cube”:



An additional line will be displayed in the statistics windows after storing an HSI-cube:



Three files will be stored in the subfolder “images”:



File names:

<Model>_<SerNr>_<Date><Time>.<Extension>

Model:

One of these values:

- SM5x5-NIR
- SM4x4-VIS

SerNr:

Camera serial number

Date:

YYYYMMDD

Time:

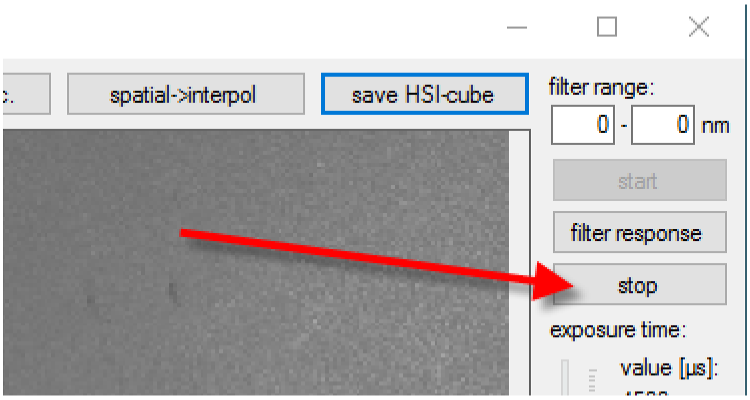
HHMMSS

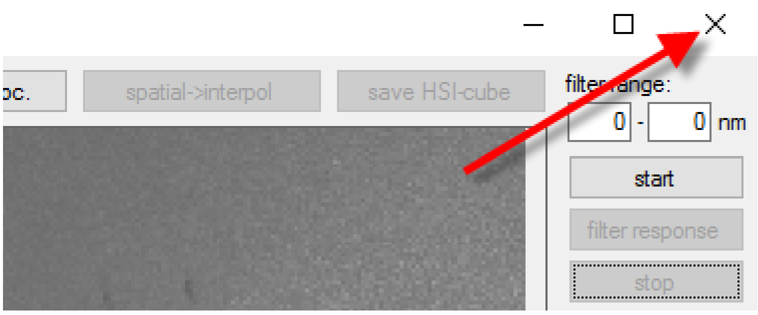
Extension:

- TIF RAW images after white image correction
- HDR part of the ENVI files: text description
- BSQ part of the ENVI files: binary data

11.8. Stop / quit the program

Please stop the image acquisition before quitting the program:





12. Appendix

12.1. Copyright

13. list of figures

14. list of tables

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