

Spectral Filter Arrays Technology

Adapted from the T2C short course at
[Color and Imaging Conference](#), 25th Color and Imaging Conference,
[Society for Imaging Science and Technology](#),
September 11-15, 2017, Lillehammer, Norway

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- <http://www.ok.sc.e.titech.ac.jp/index.shtml>

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- Researcher at NTNU (Sabbatic 2016-2019)
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- Associate Professor at Université de Bourgogne since 2010
- LE2I
- <http://le2i.cnrs.fr/>

This presentation is intended for pedagogical purpose.
If you see borrowed material that is not properly acknowledged,
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Outlines

- 1-Generalities (20 min) (JB)
 - Intro on multispectral imaging
 - SFA definition and components
 - Imaging pipeline definition
- 2-Practical instantiations, databases and applications (40 min) (all of us)
 - Incl. a topo on architecture (PJ)
 - Five-bands camera in the visible domain (Y)
 - RGB-NIR camera (Y)
 - Eight-bands camera visible-NIR (JB/PJ)
 - Other state-of-the art
- 3-Demosaicing, pattern and data processing (30 min) (Yusuke)
 - Incl. color or spectral correction when NIR/visible overlap.
- 4-Insight on image quality (20 min)(PJ)
 - Incl. HDR
 - Incl. no-reference metrics tentative
- 5-Wrap up, future directions and questions (10 min) (all of us)

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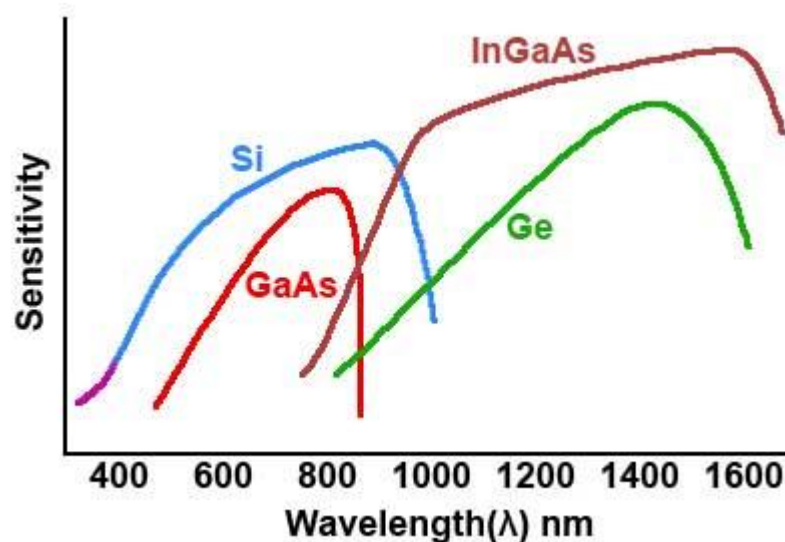
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Multispectral imaging

Images with more spectral information than Red, Green and Blue

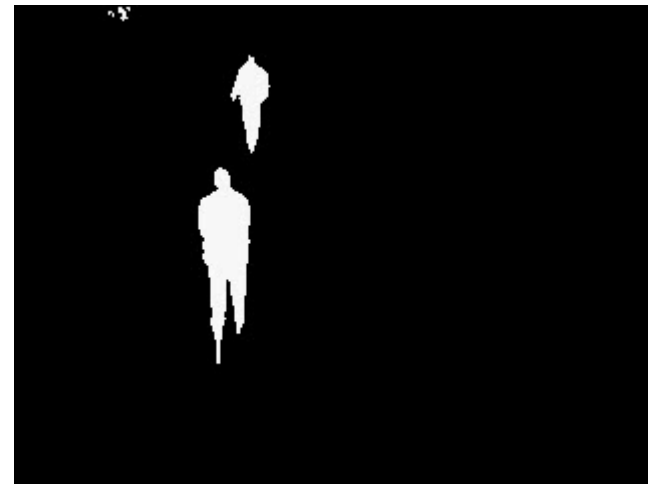
Extended sensing range on the electromagnetic spectrum, *i.e.* beyond visible



Why?

Better object surface properties estimation

Computer vision,
spectral analysis,
color imaging



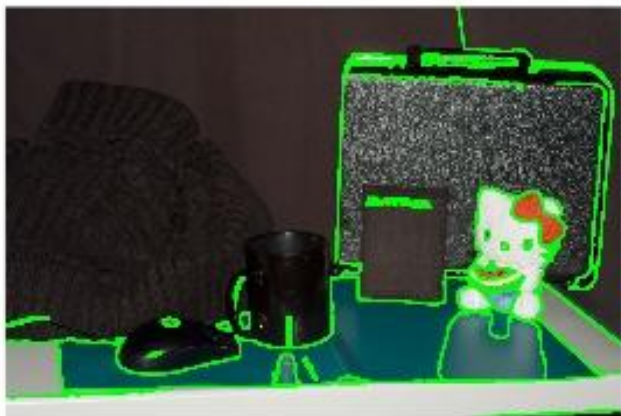
Why?



Material properties
On the left, color image.
On the right, NIR image.

Courtesy of PJ Lapray

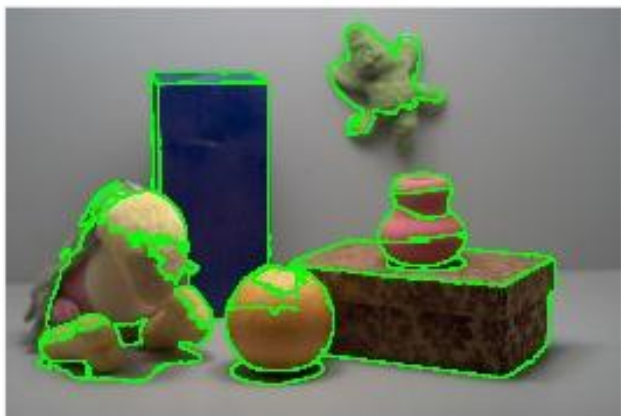
Why?



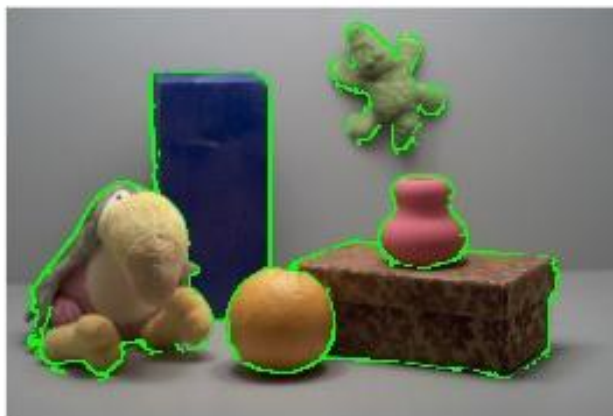
(g)



(h)



(i)



(j)

Object segmentation
in an image.

On the left, using
color.

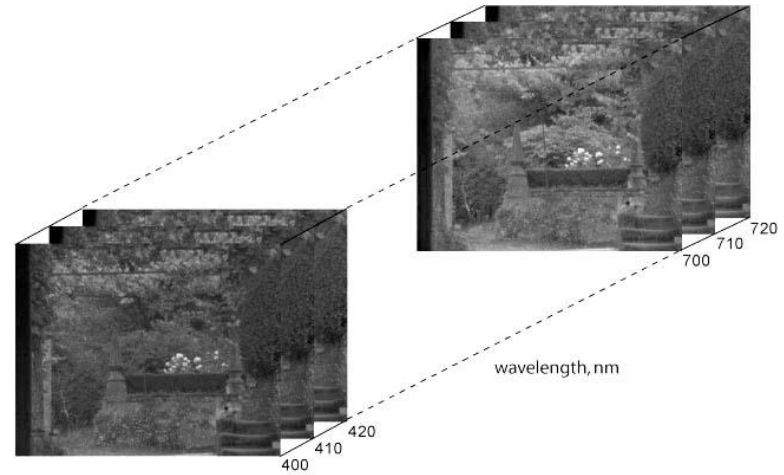
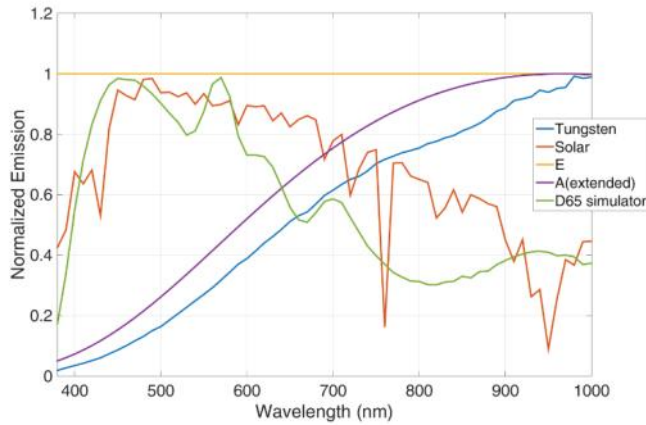
On the right, using
color and NIR.

Image from Neda
Salamati, EPFL 2013

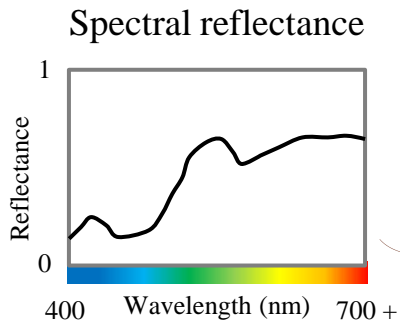
Sensing the world



Light

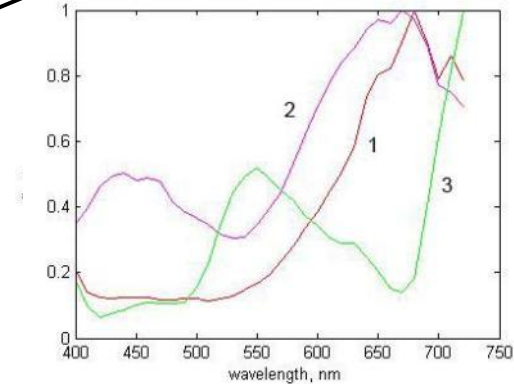


Radiant spectral power distribution



Spectral reflectance

Object

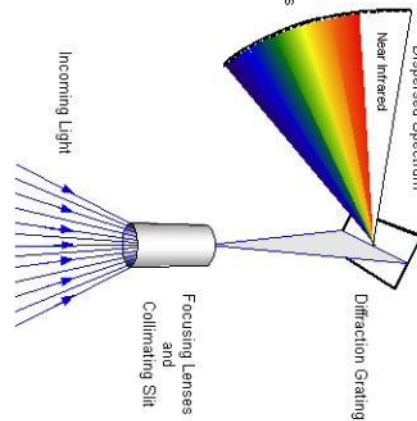
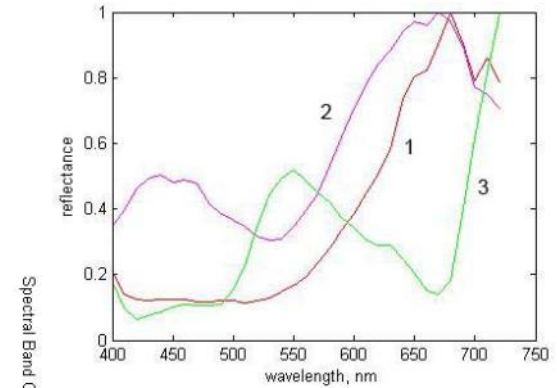
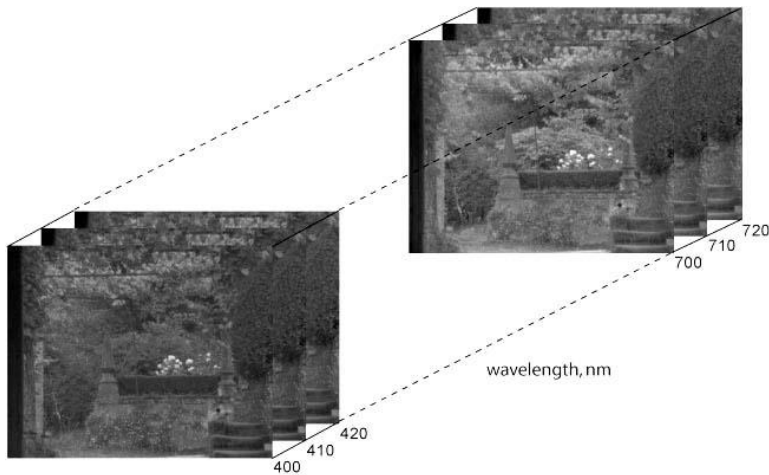


Images from:
http://personalpages.manchester.ac.uk/staff/d.h.foster/Tutorial_HSI2RGB/Tutorial_HSI2RGB.html

Sensing the world



Optical spectrometry

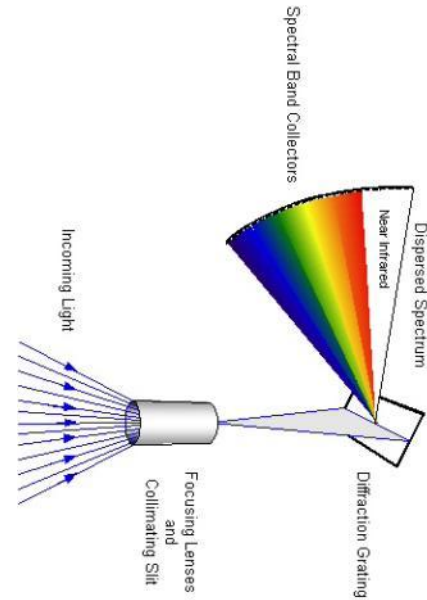
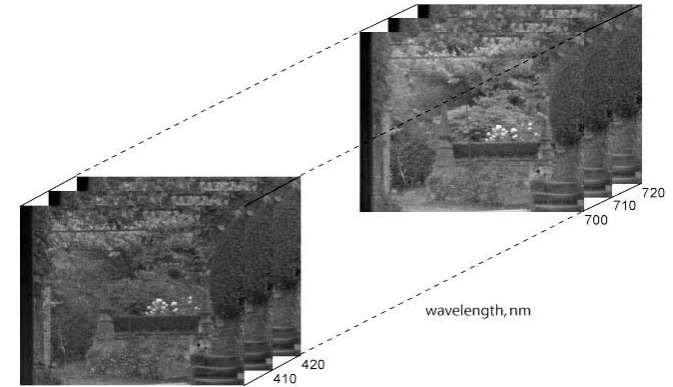
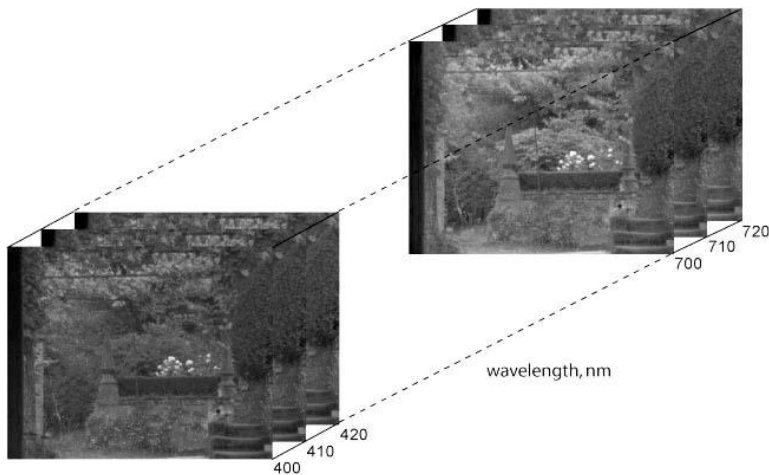


Images from:
http://personalpages.manchester.ac.uk/staff/d.h.foster/Tutorial_HSI2RGB/Tutorial_HSI2RGB.html

Sensing the world



Hyperspectral imaging



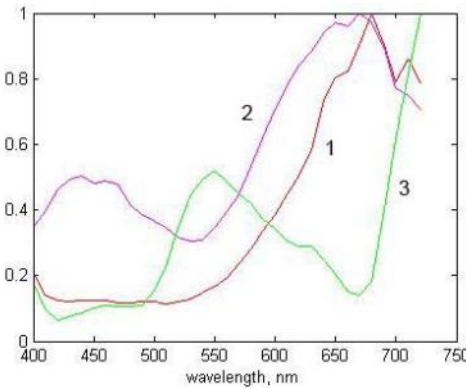
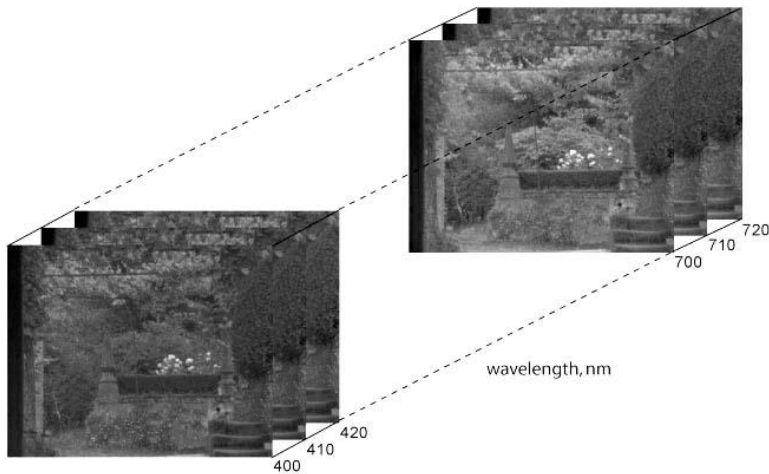
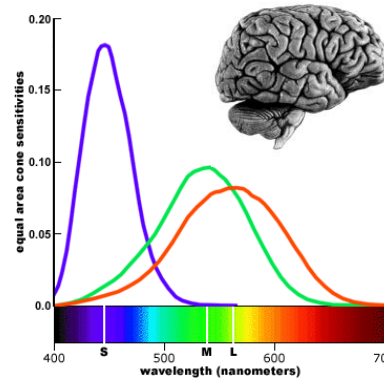
Images from:
http://personalpages.manchester.ac.uk/staff/d.h.foster/Tutorial_HSI2RGB/Tutorial_HSI2RGB.html

Sensing the world

Light



Human color vision



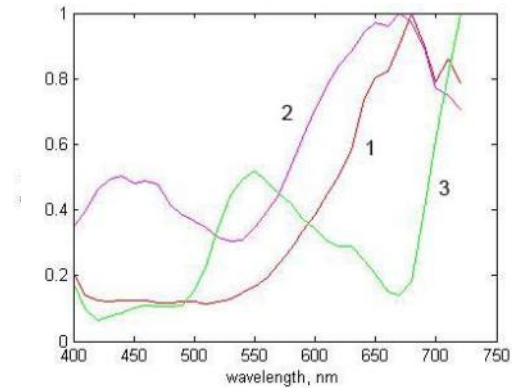
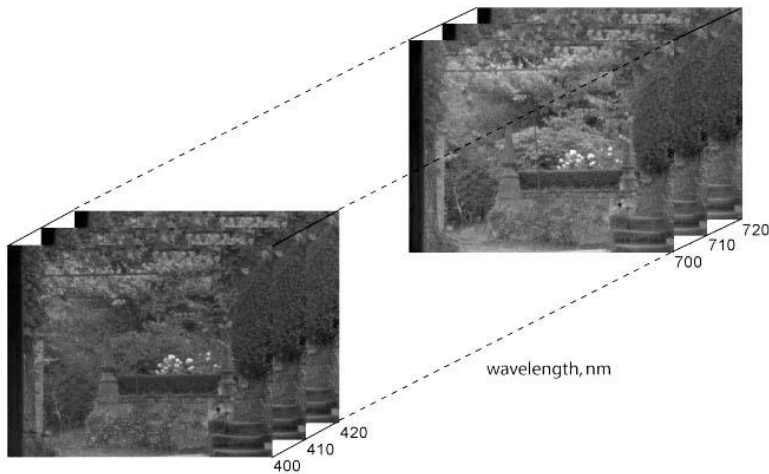
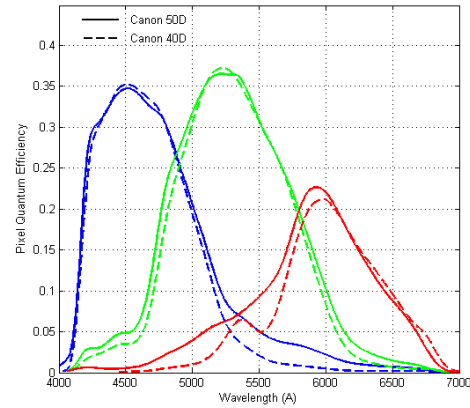
Images from:
http://personalpages.manchester.ac.uk/staff/d.h.foster/Tutorial_HSI2RGB/Tutorial_HSI2RGB.html

Sensing the world

Light



Color Imaging

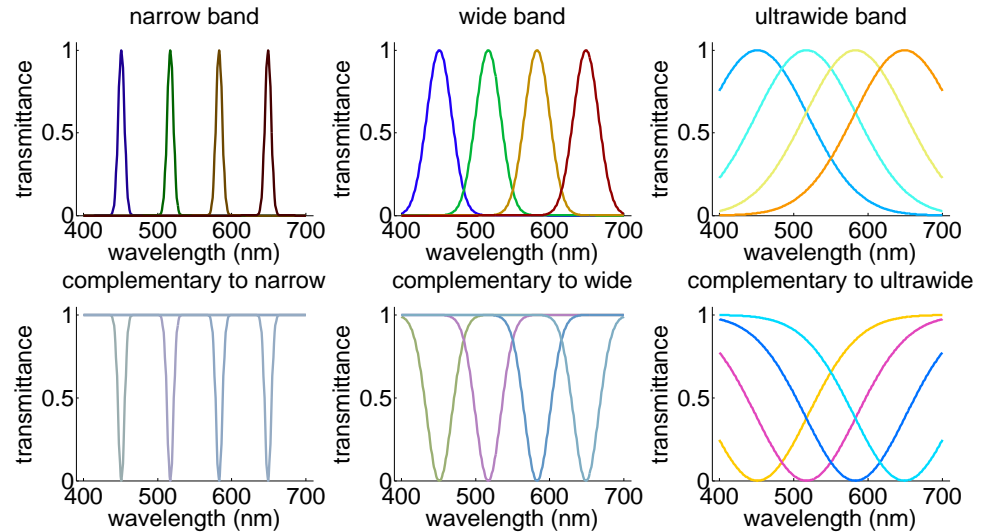
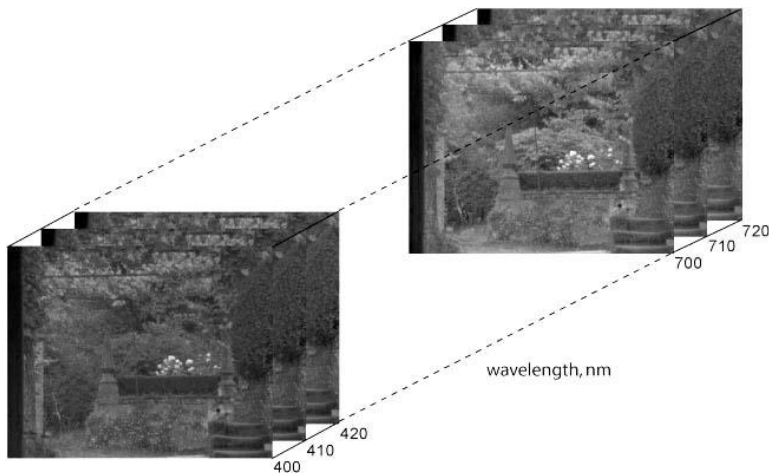
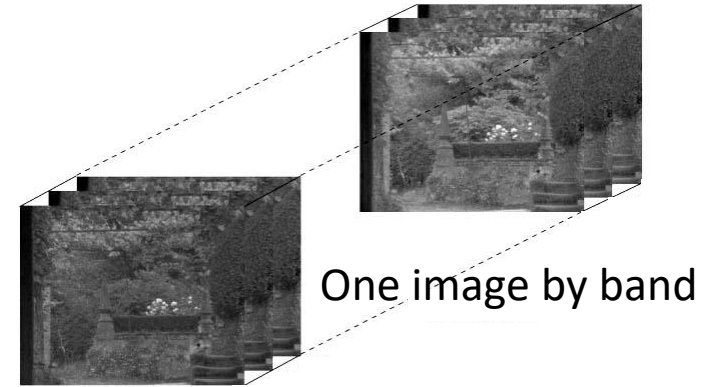


Images from:
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Sensing the world



Multispectral imaging



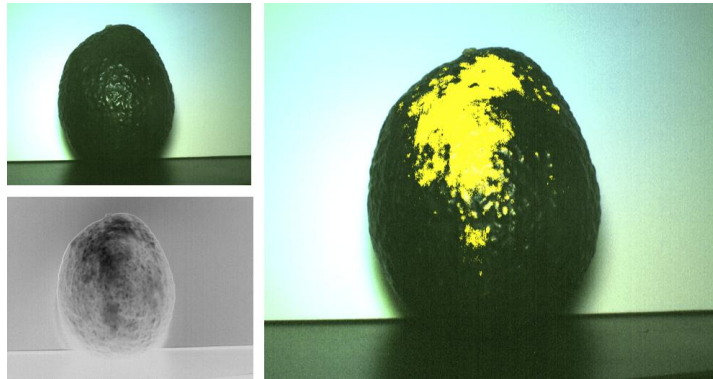
Images from:
http://personalpages.manchester.ac.uk/staff/d.h.foster/Tutorial_HSI2RGB/Tutorial_HSI2RGB.html

Multispectral imaging

- Hyper VS. Multi
 - Number and distribution of bands
 - Electromagnetic range (VIS-NIR)
- Goals – different uses of the same information
 - Spectral reconstruction (Calibration, ND->MD, $M > N$)
 - Band specific or general information (Problem dependent, computer vision)
 - Accurate color imaging and relighting (Transform ND->3D)

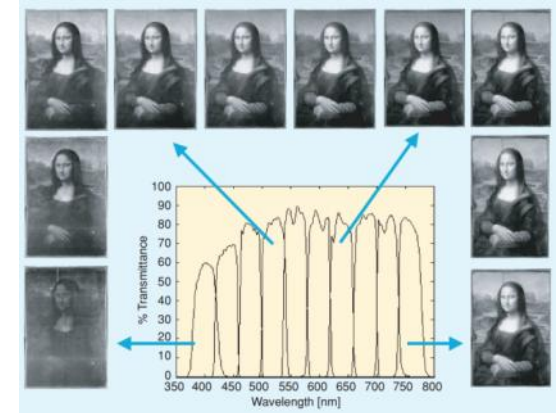
Example of applications

Food inspection



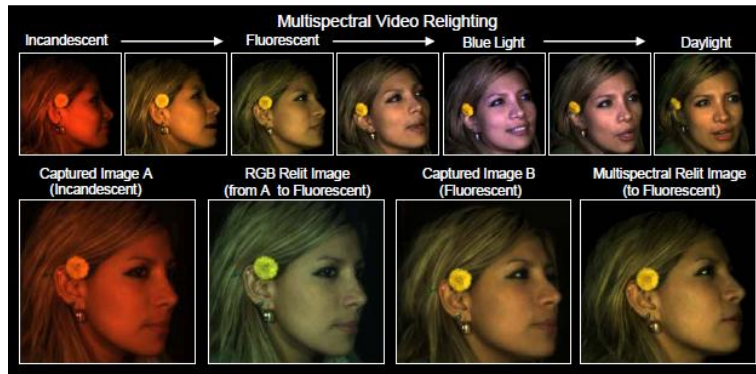
Goel et al., UbiComp2015

Digital archive



Ribes et al., SPM2008

Color reproduction



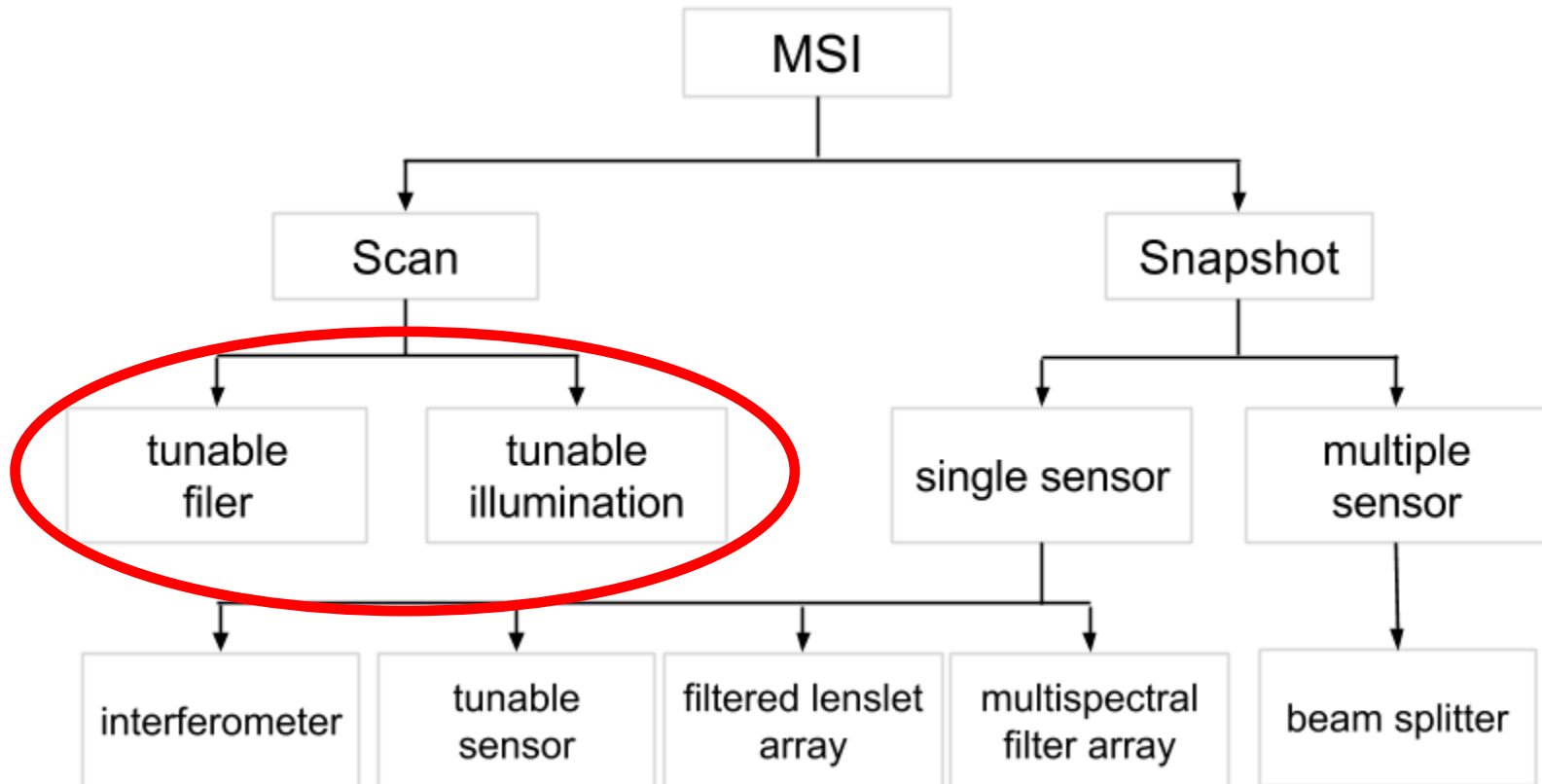
Park et al., ICCV2007

Medical imaging



Hashimoto et al., Opt. Exp. 2011

How?



Sequential acquisition

Time dependent



The Liquid Crystal Tunable Filter/Camera

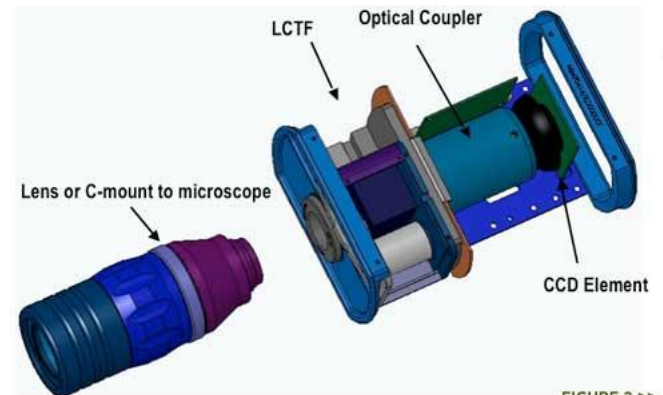
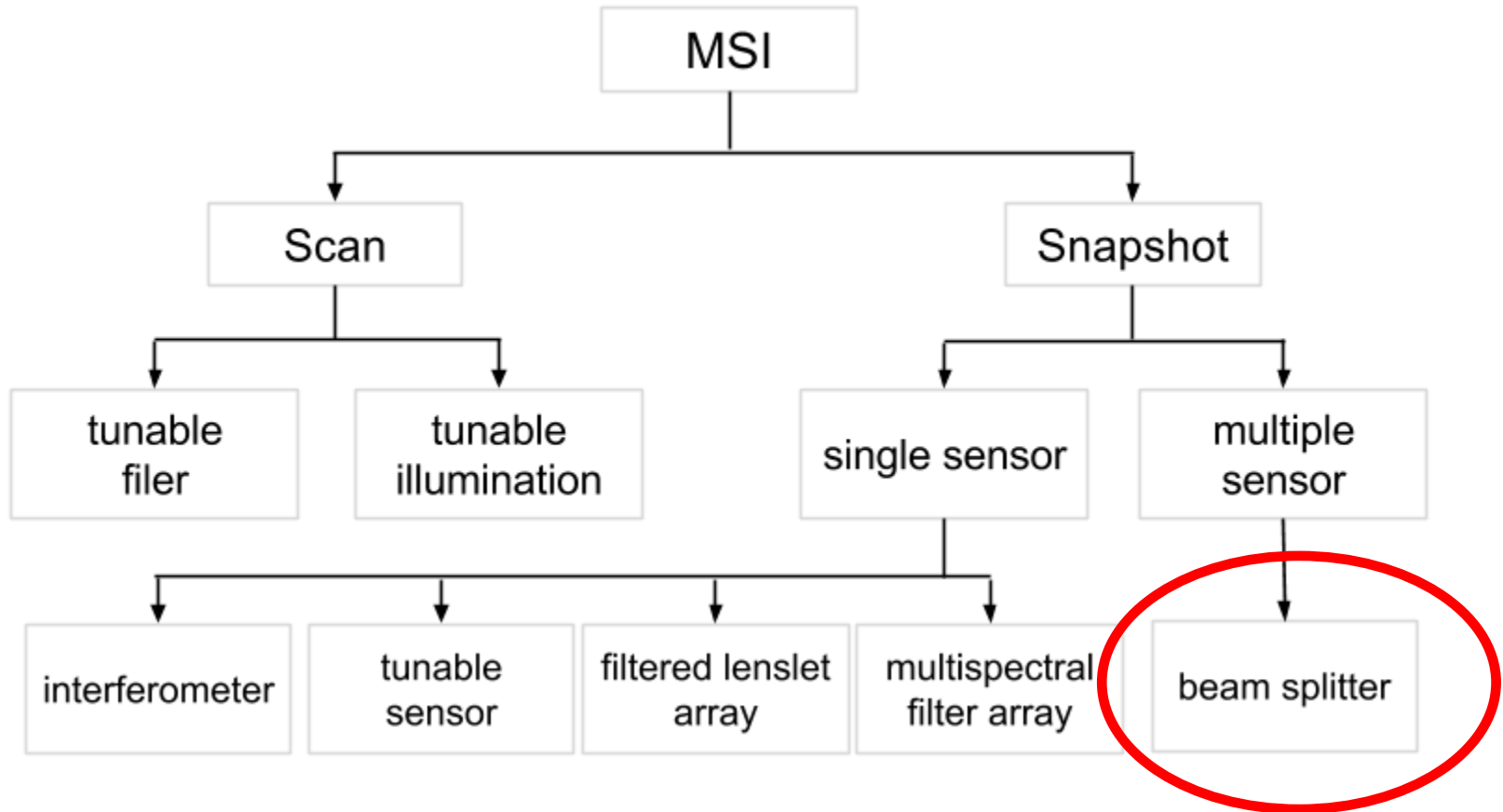


FIGURE 2 >>

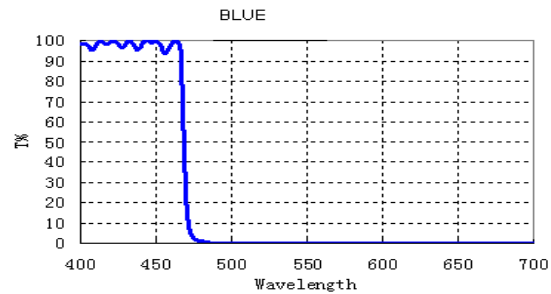
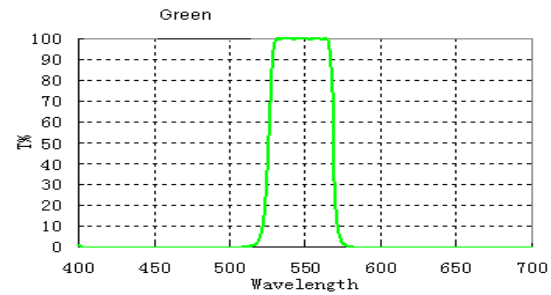
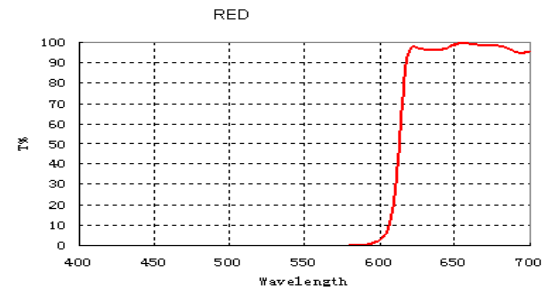
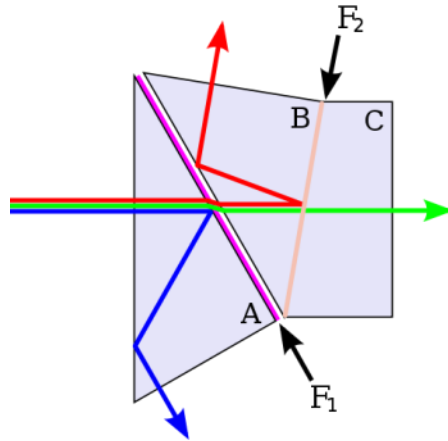
Light modulation
or
Radiance modulation

How?

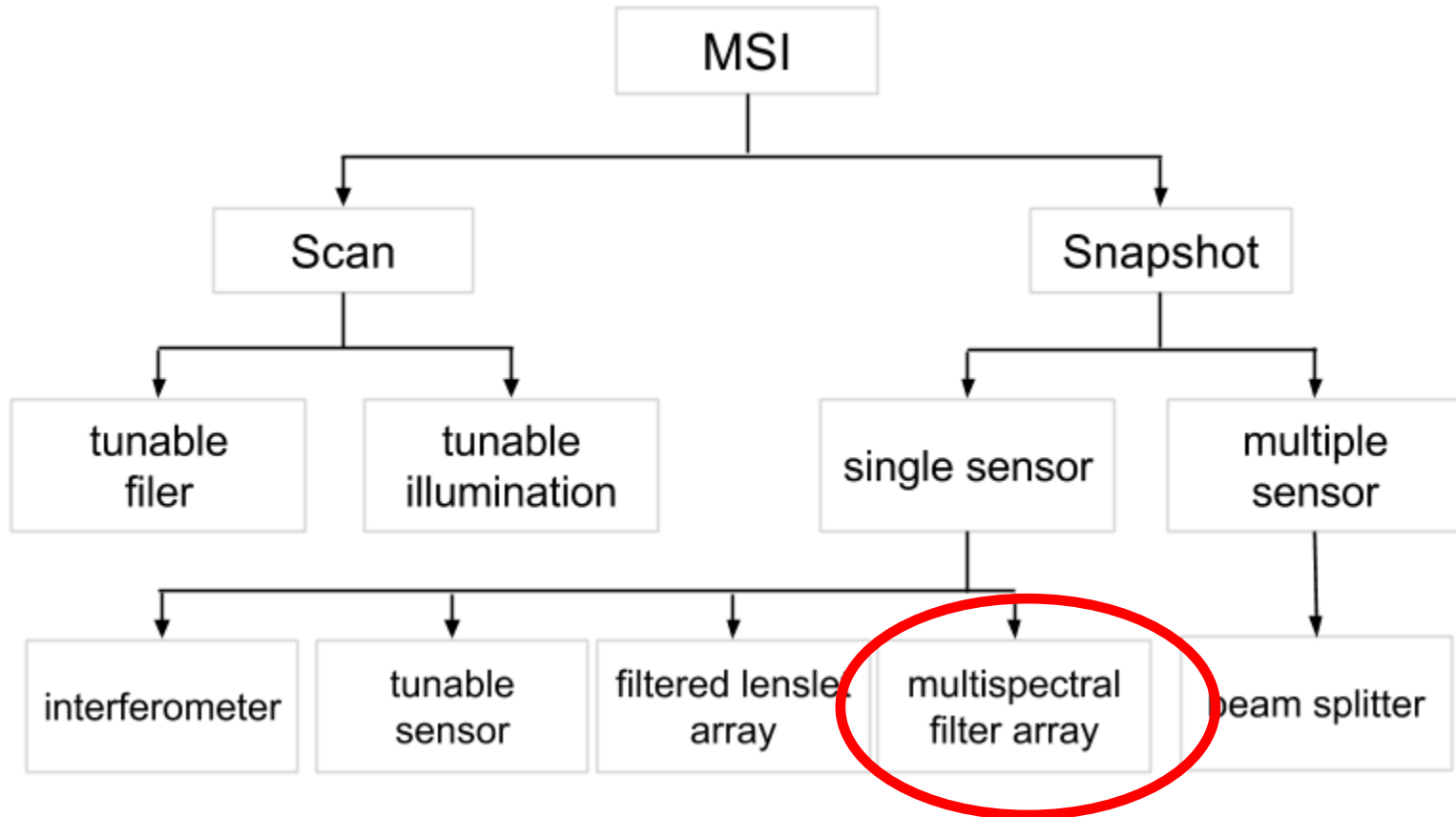


Dichroic mirrors

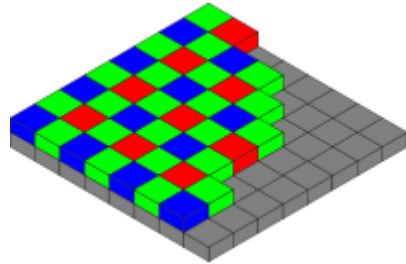
Sensitivity, noise, cost



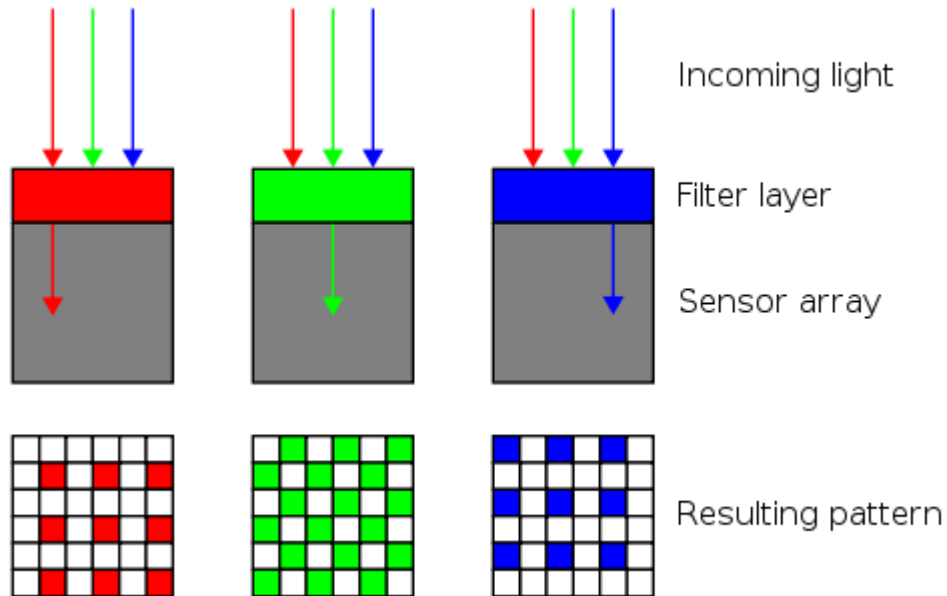
How?



Filter array for color imaging



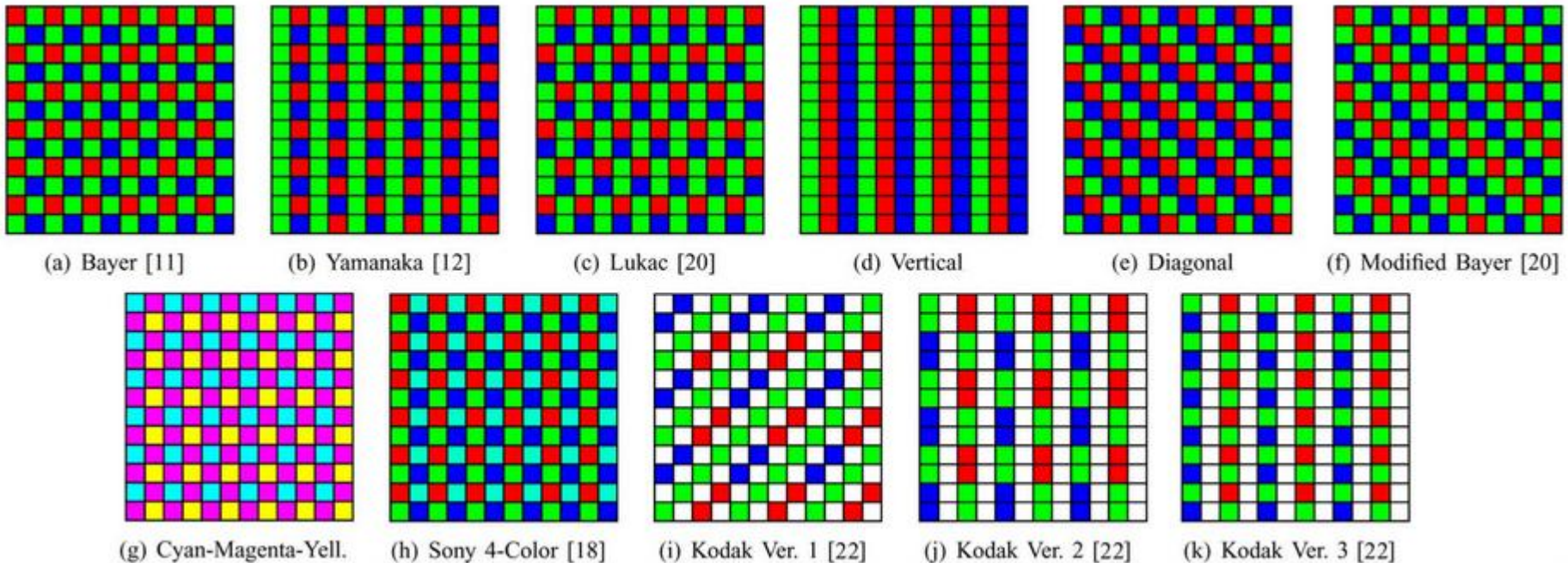
Color Filter Array (CFA)



Spatial resolution

Filter array for color imaging

- Wide range of CFA distributions



K. Hirakawa, P.J. Wolfe, "Spatio-Spectral Sampling and Color Filter Array Design," in *Single-Sensor Imaging: Methods and Applications for Digital Cameras*, ed. R. Lukac, CRC Press, 2008.

K. Hirakawa, P.J. Wolfe, "Optimal Color Filter Array Design by Spatio-Spectral Sampling," *IEEE TIP*, October 2008.

Hybrides

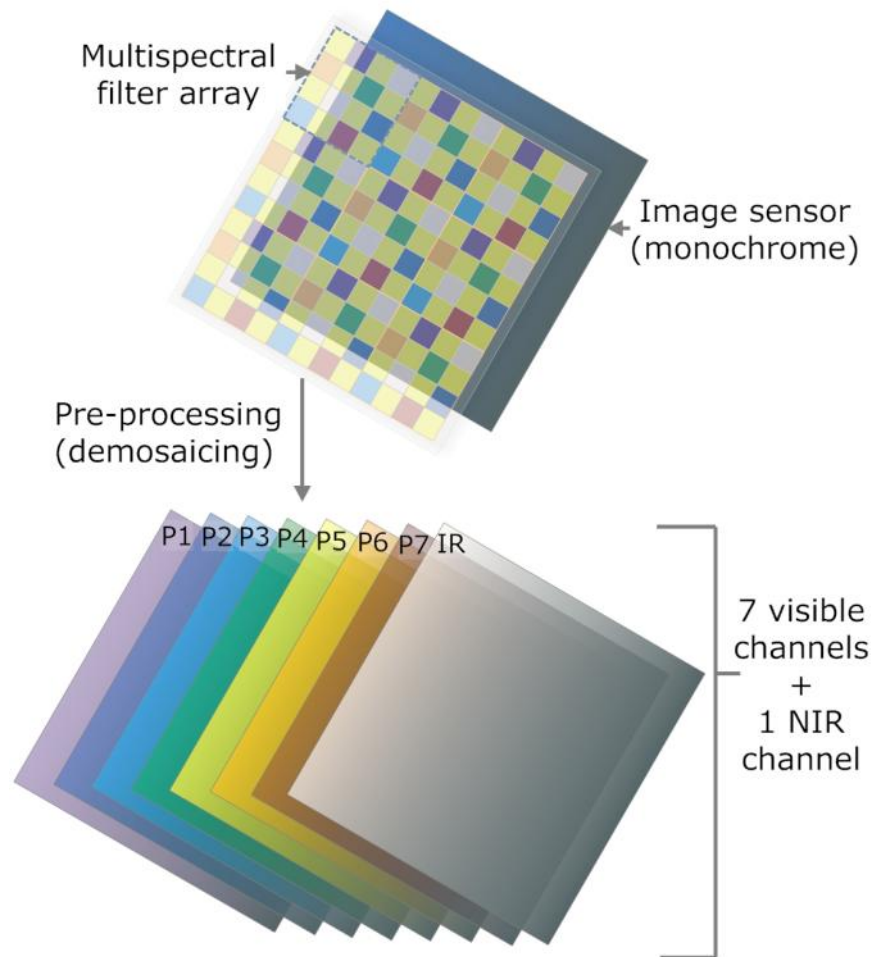
- 2-CFA sensors with complementary sensitivities + NIR sensor + Dichroic mirrors
- Any '*clever*' combination

Limits in sampling information

- Size, cost
 - time / sequential
 - Image registration
 - Spatial and spectral resolution
 - ...
-
- Interest to have a compact, cheap solution that afford real-time applications (video – CV)

Multispectral Filter Array (MSFA) or Spectral Filter Array (SFA)

- Beyond CFA, spatio-spectral sampling



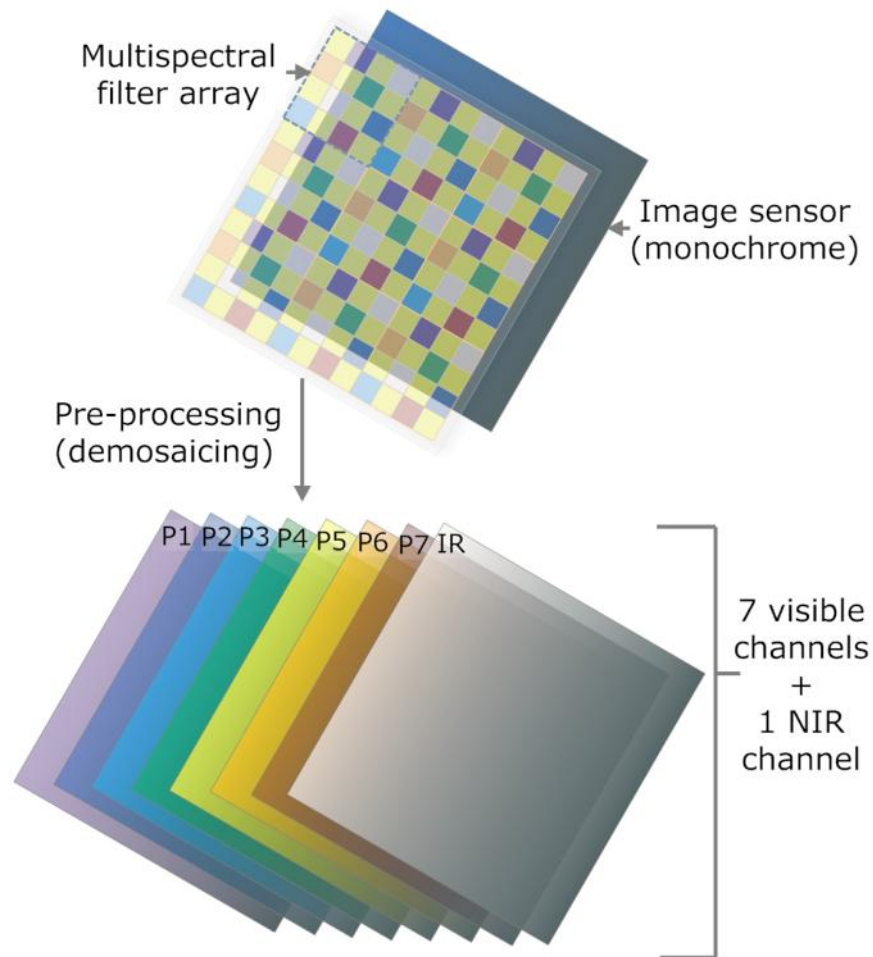
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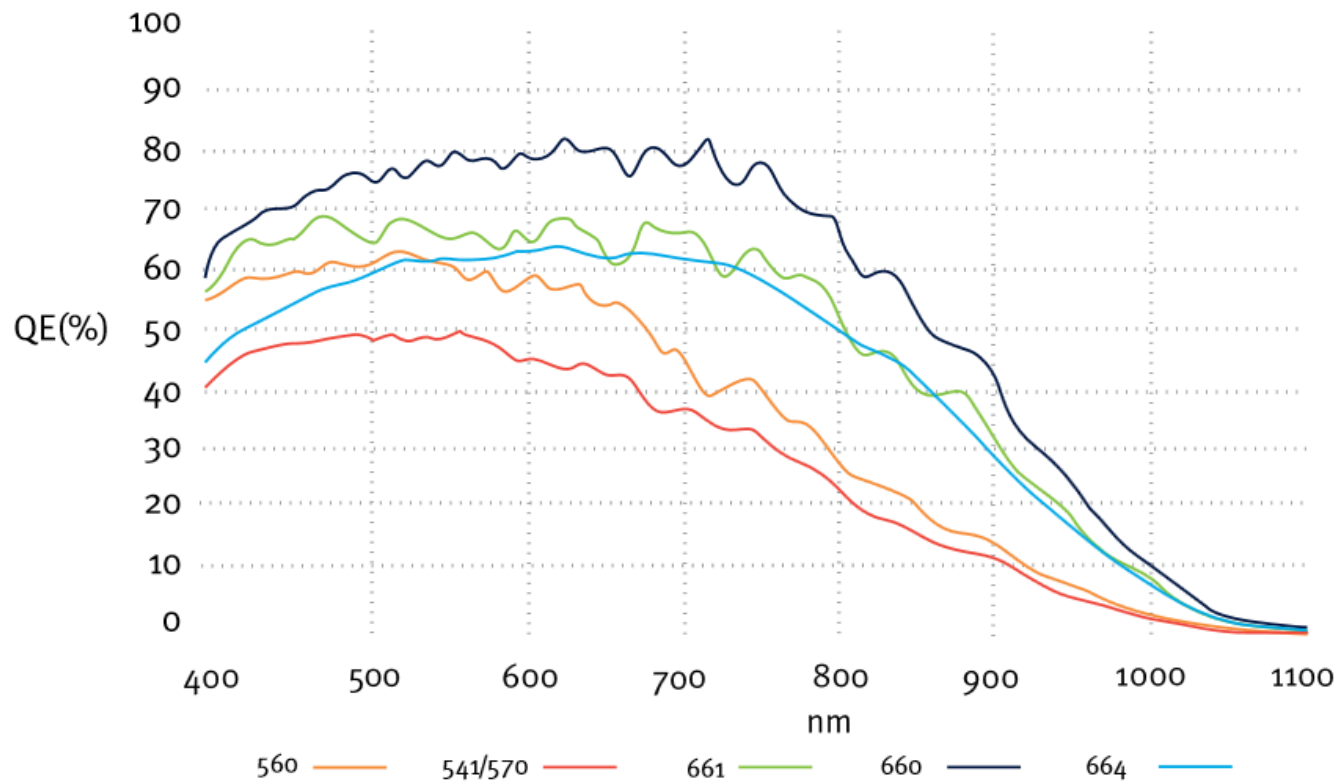
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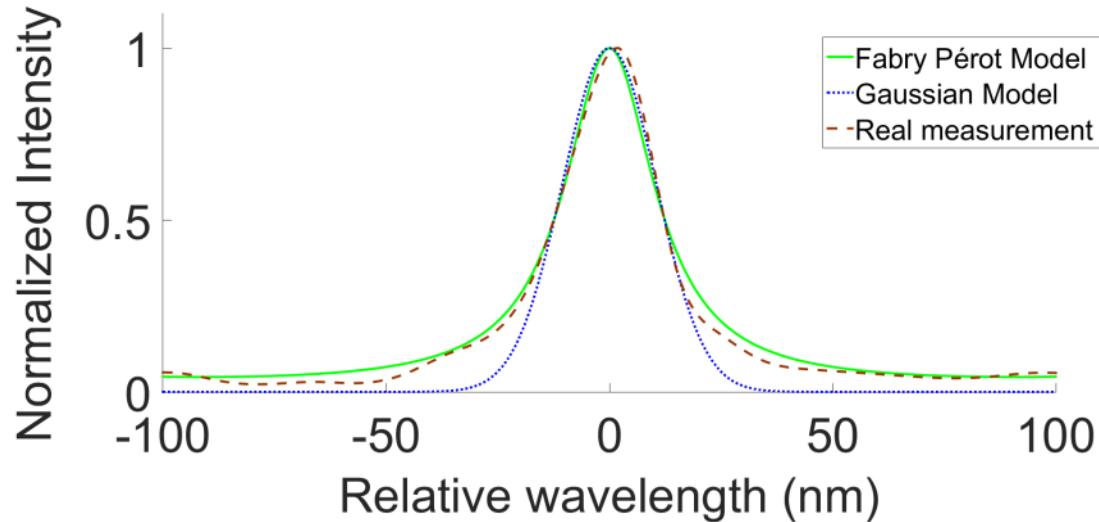
QUANTUM EFFICIENCY (QE) CURVES – CMOS SENSORS



Curves from <http://www.e2v.com/resources/account/download-literature/77>

- Fabry – Pérot type of interferometers
 - Thin film deposition (could be multilayer)
 - Nano-carving/etching
 - Transmission depends on materials, incident angle and thickness
- Nano-structure type of interferometers
 - Holes or tubes
 - Periodic or quasi-periodic structures

Gaussian simulations



Comparison between Fabry-P erot filter model, gaussian model and measure of a practical realization of a filter.

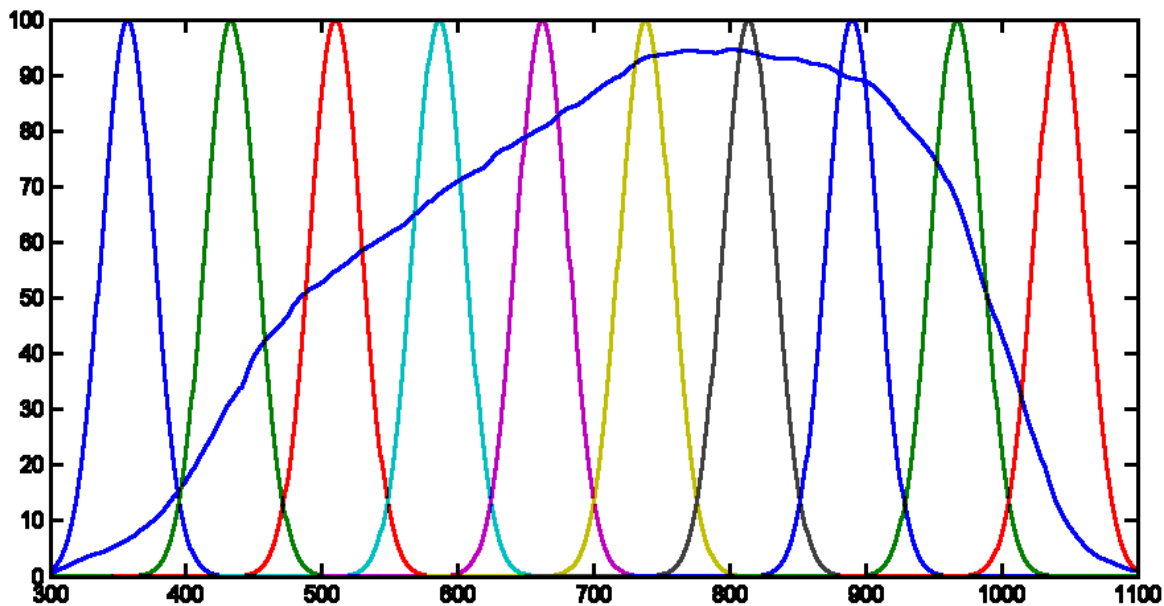
Differences between these curves as integral of function difference:

$d(F P R, G)=36.74\%$, $d(F P M, F P R)=9.96\%$ and $d(F P M, G) = 46.70\%$.

Difference at FWHM:

$d_{\sigma}(F P R, G)=-1.05\%$, $d_{\sigma}(F P M, F P R)=-1.99\%$ and $d_{\sigma}(F P M, G)=-3.04\%$

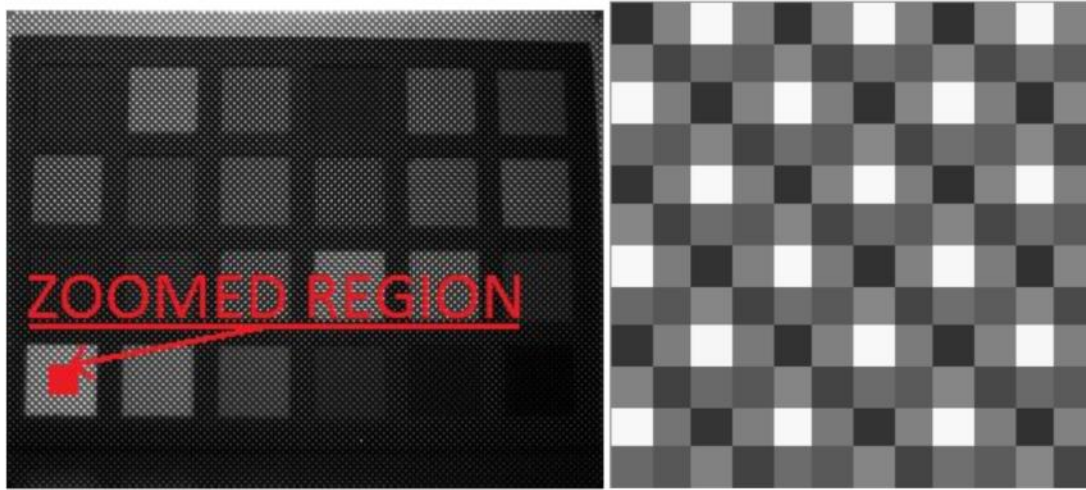
Sensor & filters



Exposure time
& Energy balance

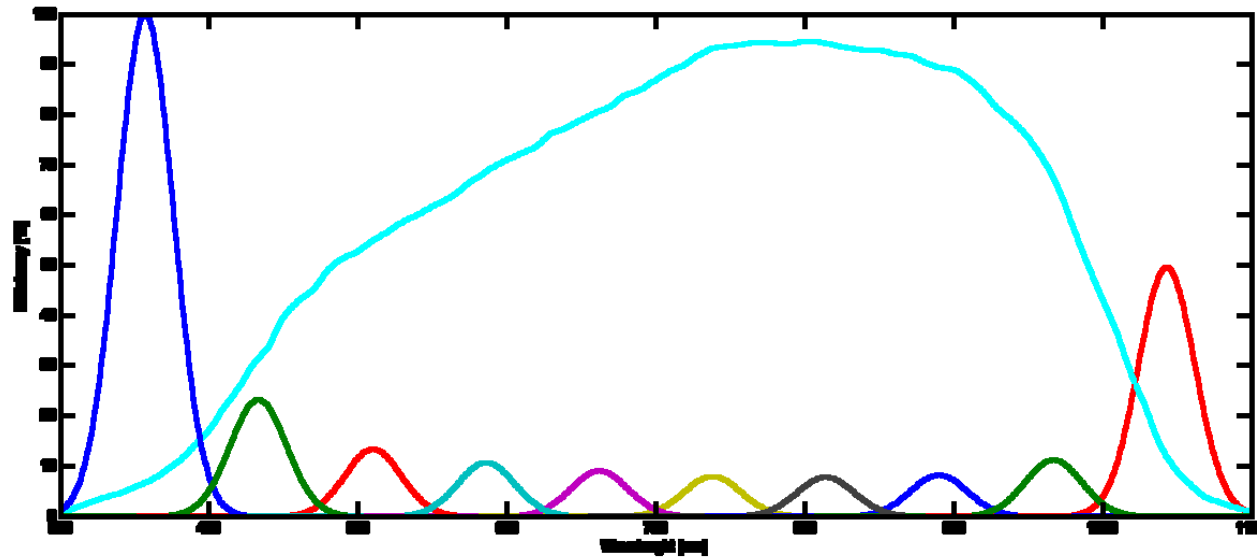
"Energy balance in single exposure multispectral sensors", Hugues PEGUILLET, Jean Baptiste THOMAS, Pierre GOUTON, Yassine RUICHEK, Colour and Visual Computing Symposium (CVCS), 2013, Gjøvik : Norvège, 2013

Sensor & filters



Single exposure time

Sensor & filters

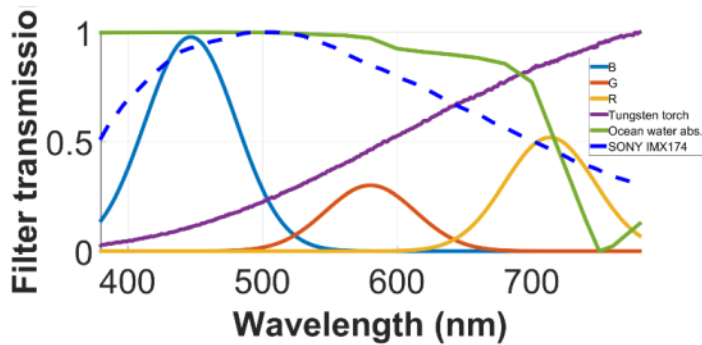


Sensitivity, noise

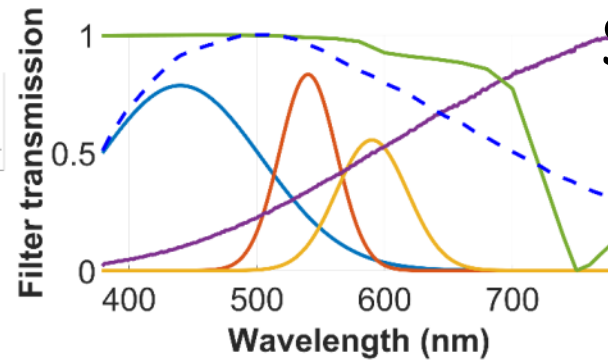
Optimized for one given illumination condition

"Energy balance in single exposure multispectral sensors", Hugues PEGUILLET, Jean Baptiste THOMAS, Pierre GOUTON, Yassine RUICHEK, Colour and Visual Computing Symposium (CVCS), 2013, Gjøvik : Norvège, 2013

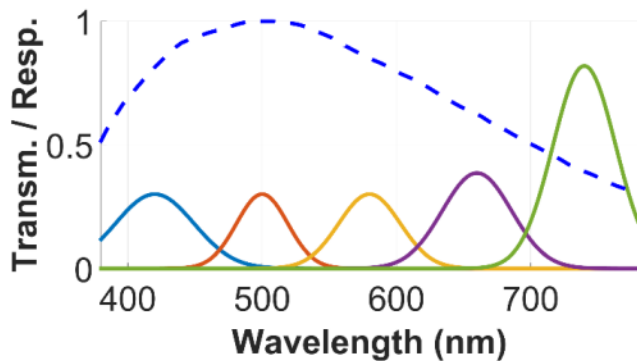
Sensor & filters



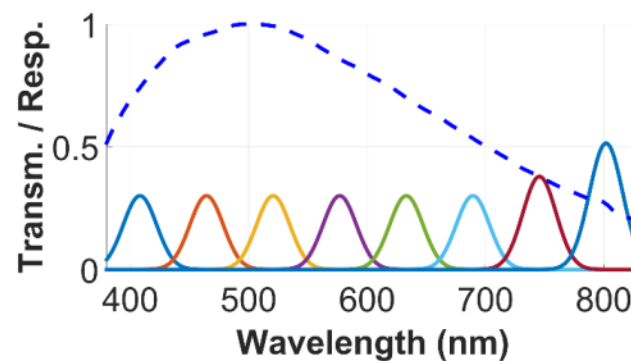
(a)



(b)



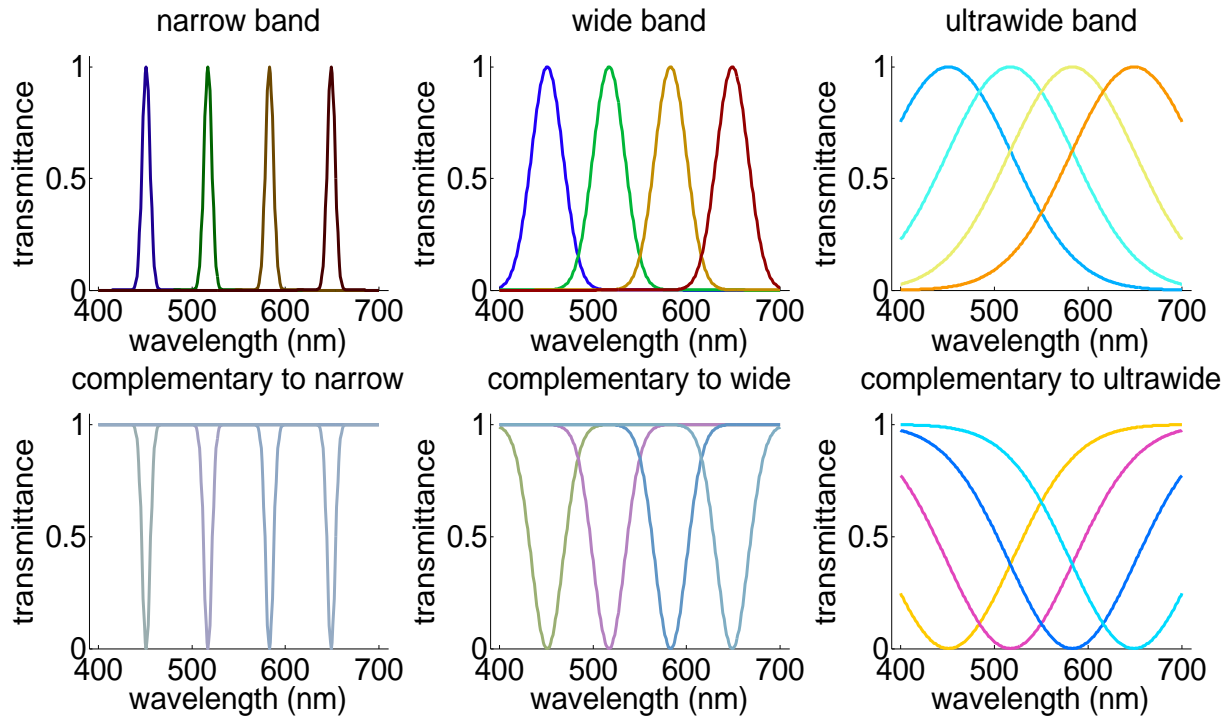
(c)



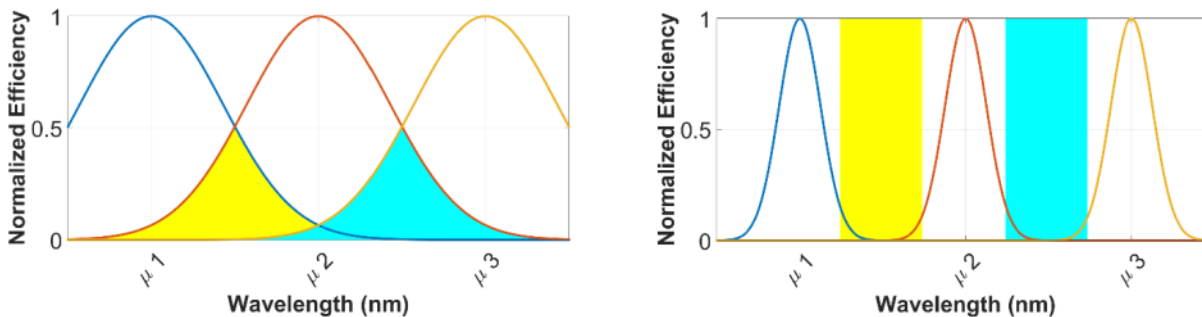
(d)

Filters optimized for specific scenarios. **a**, **b** Underwater typical environment. **c** Typical colorimetric camera setup for color imaging. **d** Typical multispectral camera for computer vision.

Sensitivities

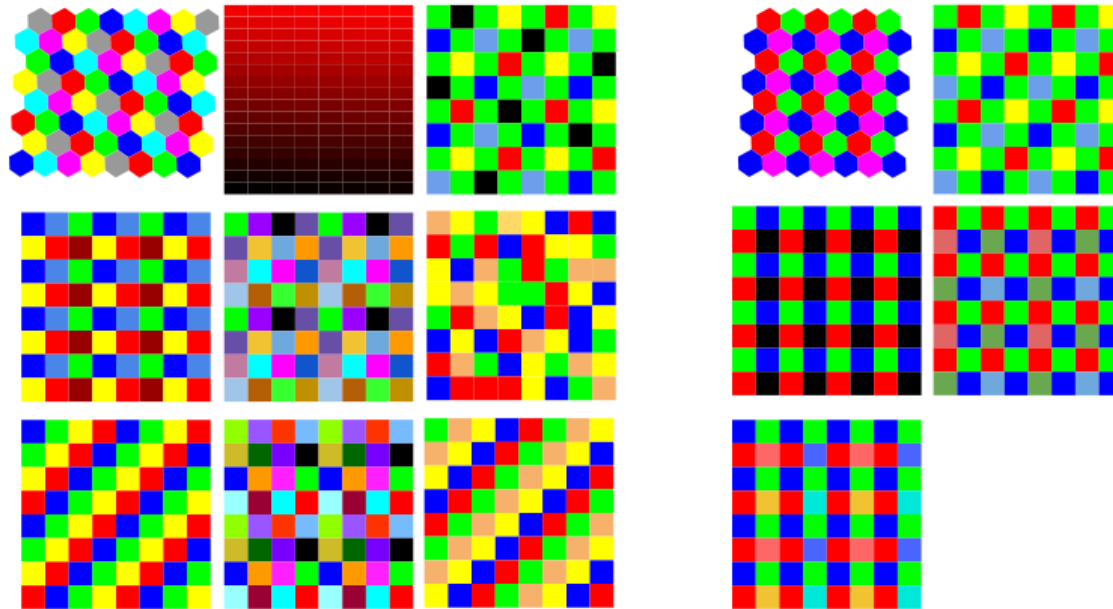


What is the best?
For which purpose?



What is possible?

Spatial distribution



a	d	g
b	e	h
c	f	i

non-compliant with
Miao *et al.*'s design methodology

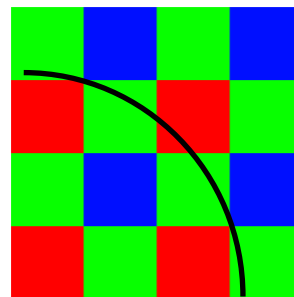
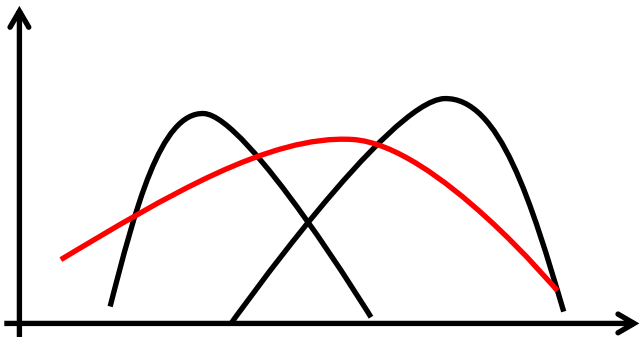
j	m
k	n
l	

compliant with
Miao *et al.*'s design methodology

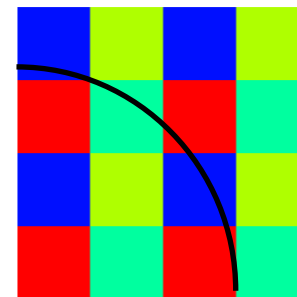
(a) Ramanath et al. ; (b) Brauers and Aach; (c) Aggarwal and Majumbar ; (d) Wang et al. ; (e) Lu et al. ; (f) Sadeghipoor et al.; (g) Kiku et al. ; (h) Aggarwal and Majumbar ; (i) Aggarwal and Majumbar ; (j) Ramanath et al. ; (k) Hershey and Zhang; (l) Yasuma et al. ; (m) Monno et al. , (n) Shrestha and Hardeberg.

Demosaicing

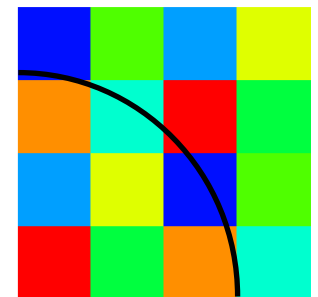
- Interpolation problem
- Might take advantage of some correlations
 - Spatial
 - One object has homogeneous properties
 - Spectral
 - Between channel sensitivity
 - Accross channel sensitivity



(a) Bayer CFA



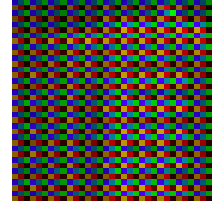
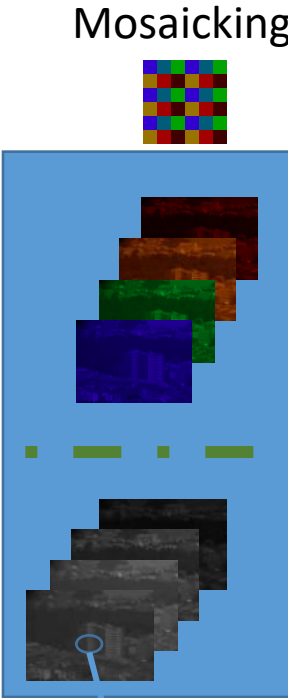
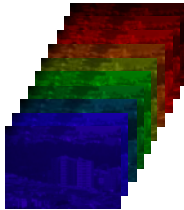
(b) 4-band SFA



(c) 8-band SFA

Demosaicing - simulation

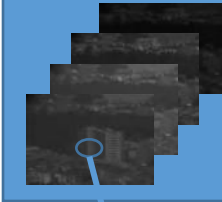
Hyperspectral
image
database



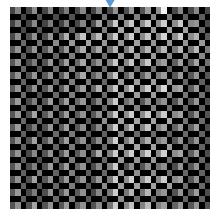
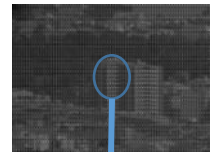
Sensing



PSNR,
SSIM



Demosaicking

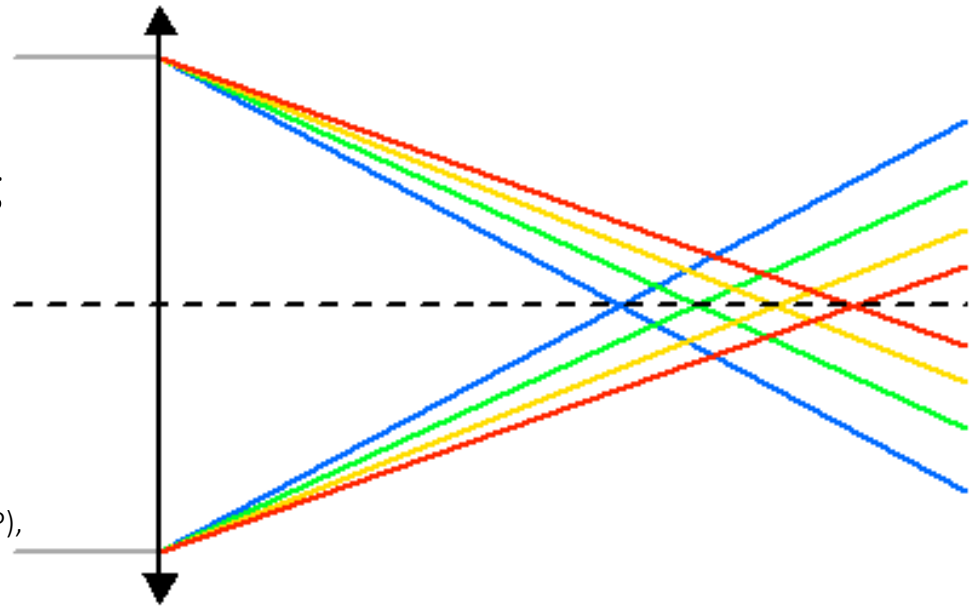


Chromatic aberrations

- Where do we focus? Impact?

- Influence spatio-spectral correlation

- Improves demosaicing
 - Reduces the overall image quality



“The influence of chromatic aberration on demosaicing”,
Xingbo WANG, Marius Pedersen, Jean Baptiste THOMAS, 5th
European Workshop on Visual Information Processing (EUVIP),
Paris, France, 2014

- Provides extra information on depth
 - Can be used to correct for out of focus area

Gradient-based correction of chromatic aberration in the joint acquisition of color and near-infrared images Z Sadeghipoor Kermani, Y Lu, S Süssstrunk - Digital Photography Xi, 2015

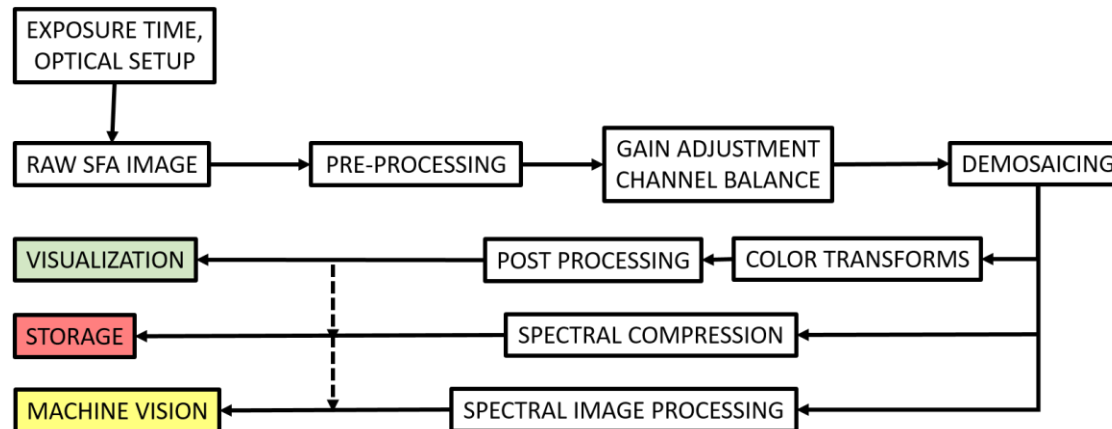
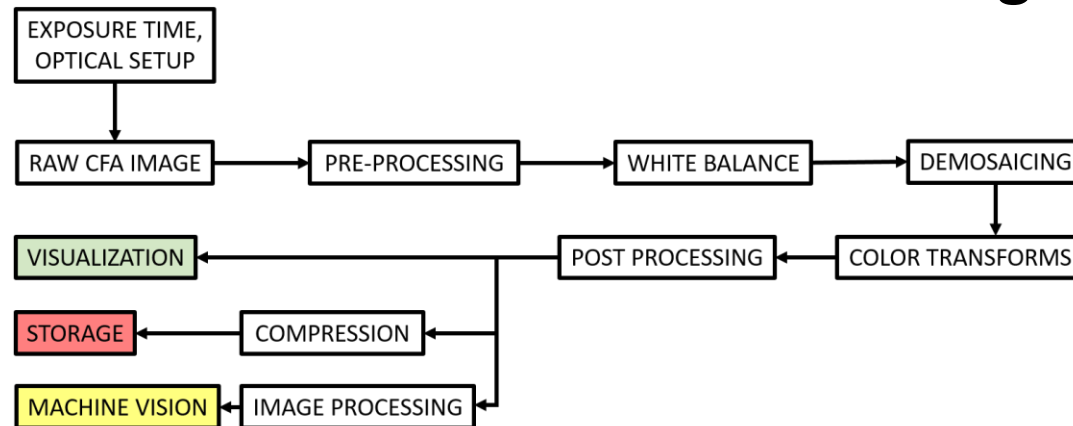
Multiscale guided deblurring: chromatic aberration correction in color and near-infrared imaging Z Sadeghipoor, YM Lu, E Mendez, S Süssstrunk - Signal Processing Conference (EUSIPCO), 2015 23rd ..., 2015

Multiscale guided deblurring: Chromatic aberration correction in color and Near-Infrared imaging Z Sadeghipoor Kermani, Y Lu, E Mendez, S Süssstrunk - European Conference on Signal Processing, 2015

Outlines

- 1-Generalities (20 min) (JB)
 - Intro on multispectral imaging
 - SFA definition and components
 - Imaging pipeline definition
- 2-Practical instantiations, databases and applications (40 min) (all of us)
 - Incl. a topo on architecture (PJ)
 - Five-bands camera in the visible domain (Y)
 - RGB-NIR camera (Y)
 - Eight-bands camera visible-NIR (JB/PJ)
 - Other state-of-the art
- 3-Demosaicing, pattern and data processing (30 min) (Yusuke)
 - Incl. color or spectral correction when NIR/visible overlap.
- 4-Insight on image quality (20 min)(PJ)
 - Incl. HDR
 - Incl. no-reference metrics tentative
- 5-Wrap up, future directions and questions (20 min) (all of us)

Imaging pipeline

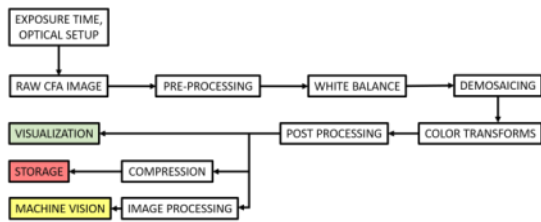


Lapray, P.-J.; Thomas, J.-B.; Gouton, P. High Dynamic Range Spectral Imaging Pipeline For Multispectral Filter Array Cameras. *Sensors* 2017, 17, 1281

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Camera architecture



SFA acquisition/processing

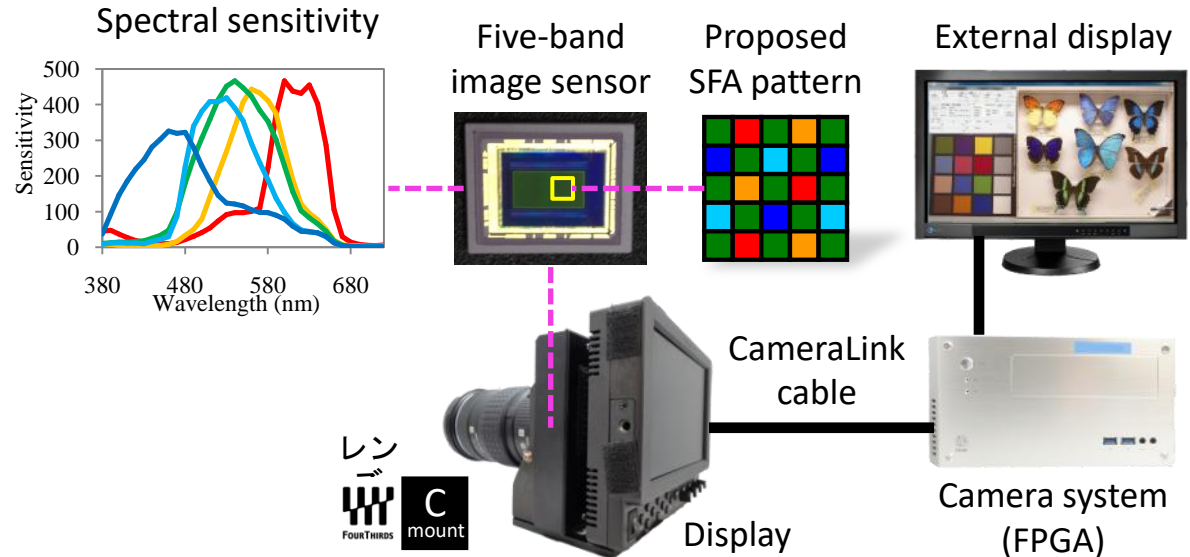
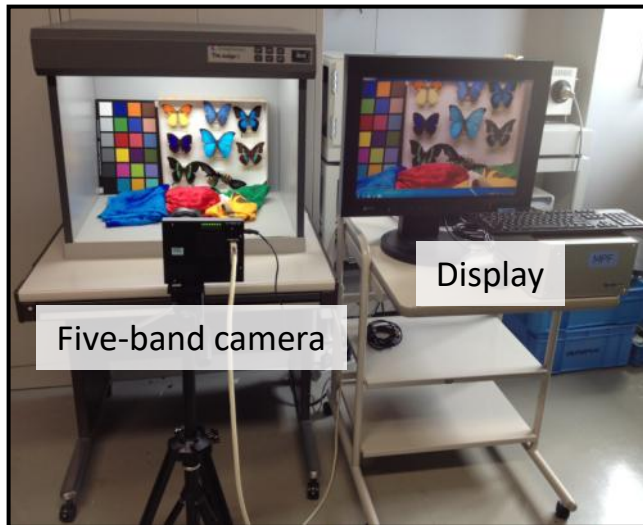
- How to process the data for snapshot real-time imaging ?
 - A lot of data to digitize/process/communicate
 - SFA are compatible with actual resolution/framerate of commercial cameras (4K, 8K, high speed cameras, etc.)
 - A good demosaicing method seems to be the most consuming process -> need a study of complexity
 - Need for a suitable computing architecture to process all the block of the pipeline
 - GPU (not embeddable, consume a lot of power, need a PC archi)
 - DSP (embeddable but processing is limited)
 - FPGA (ok, but time to market not optimal)
 - Example of efficient hardware to use: Zynq, Ultrascale, Altera SOC FPGAs...

Five-band Camera

Prototype five-band camera

- Real-time five-band imaging in the visible domain.

Overview of the prototype

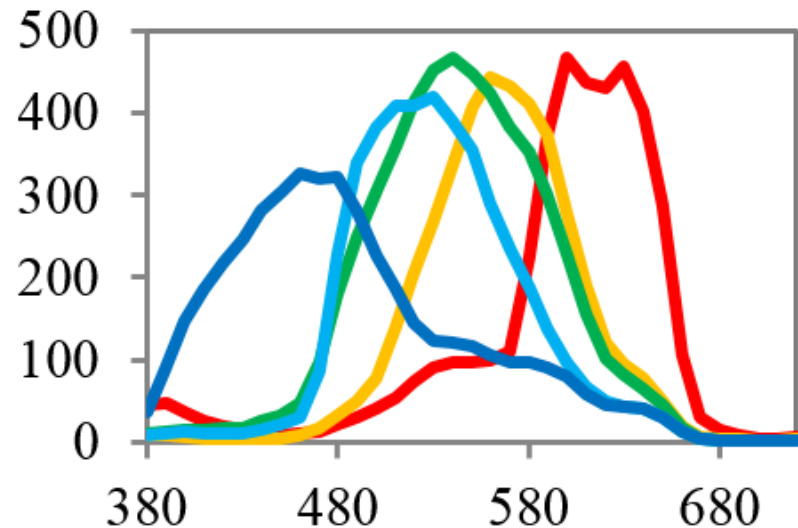


<http://www.ok.ctrl.titech.ac.jp/res/MSI/TIP-MSI.html>

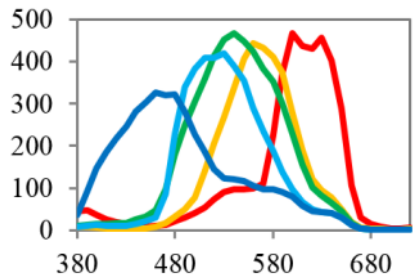
Prototype five-band camera

- SFA pattern and spectral sensitivity.

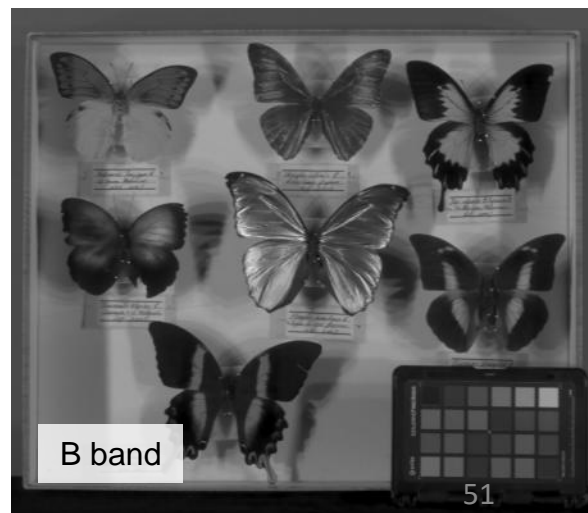
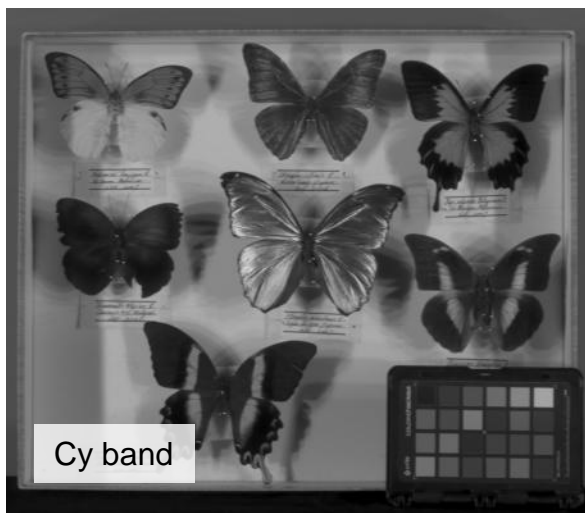
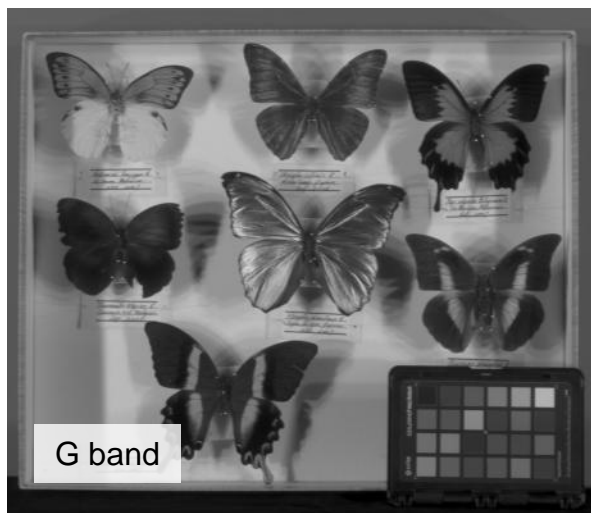
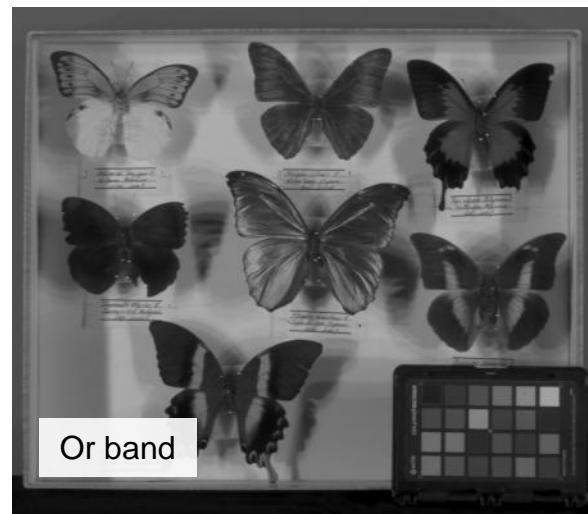
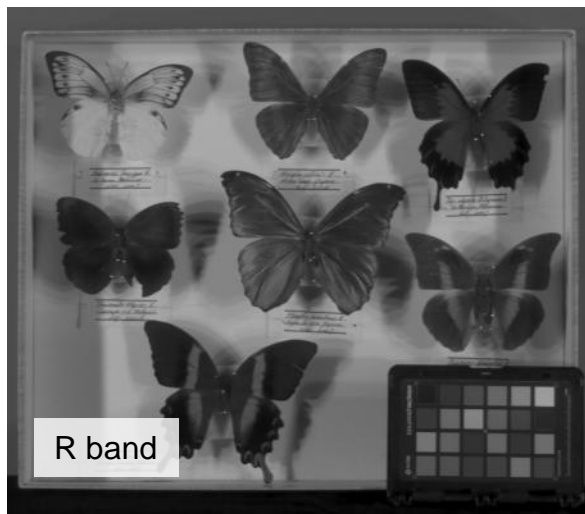
G	R	G	Or	G
B	G	Cy	G	B
G	Or	G	R	G
Cy	G	B	G	Cy
G	R	G	Or	G

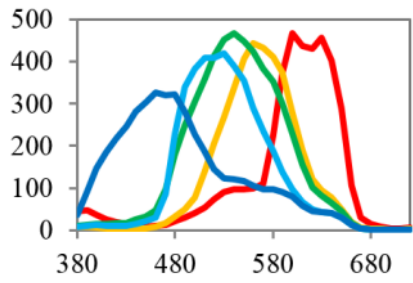


We will discuss the design of the SFA pattern and demosaicing algorithm later.

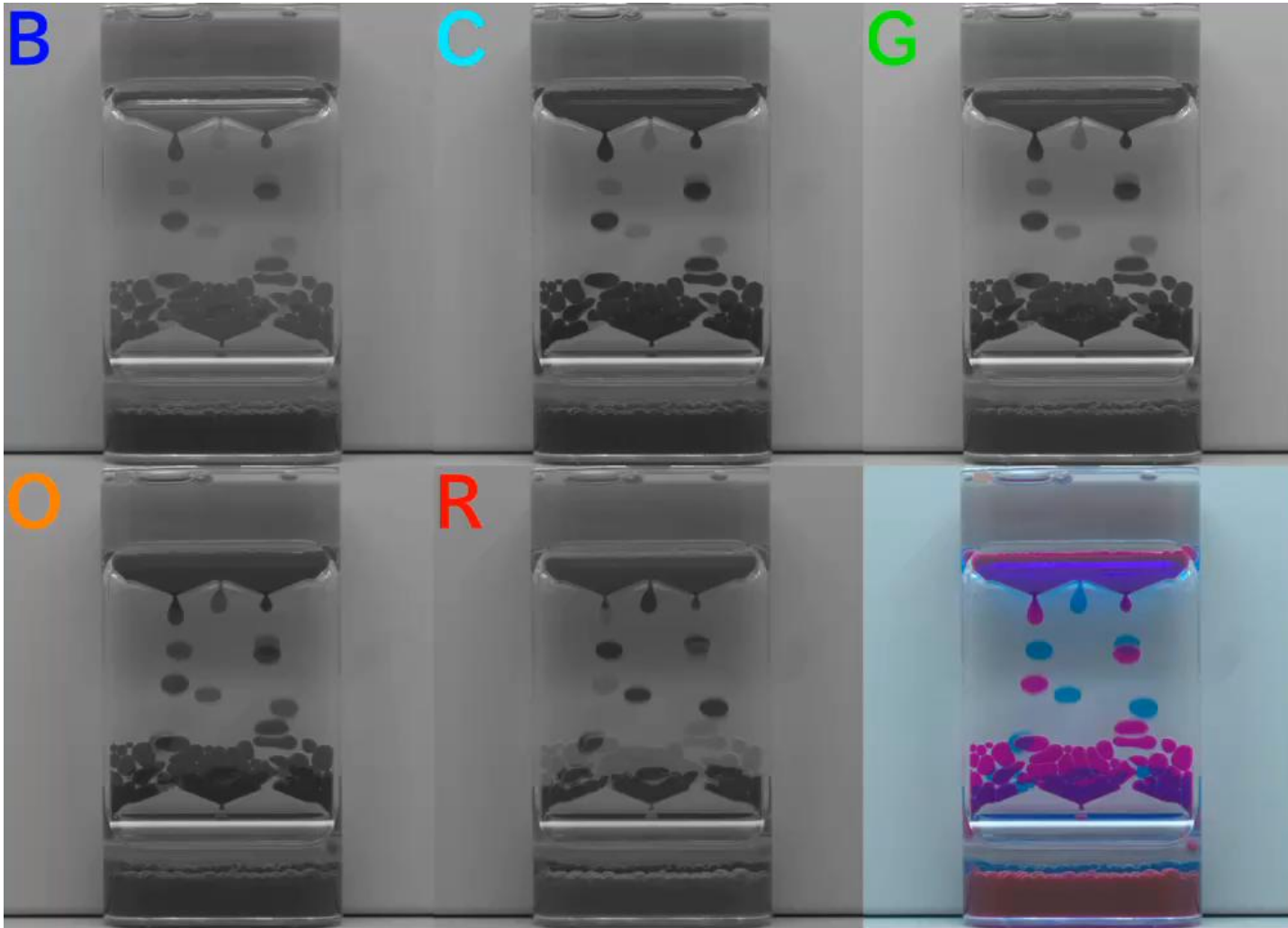


Example five-band image

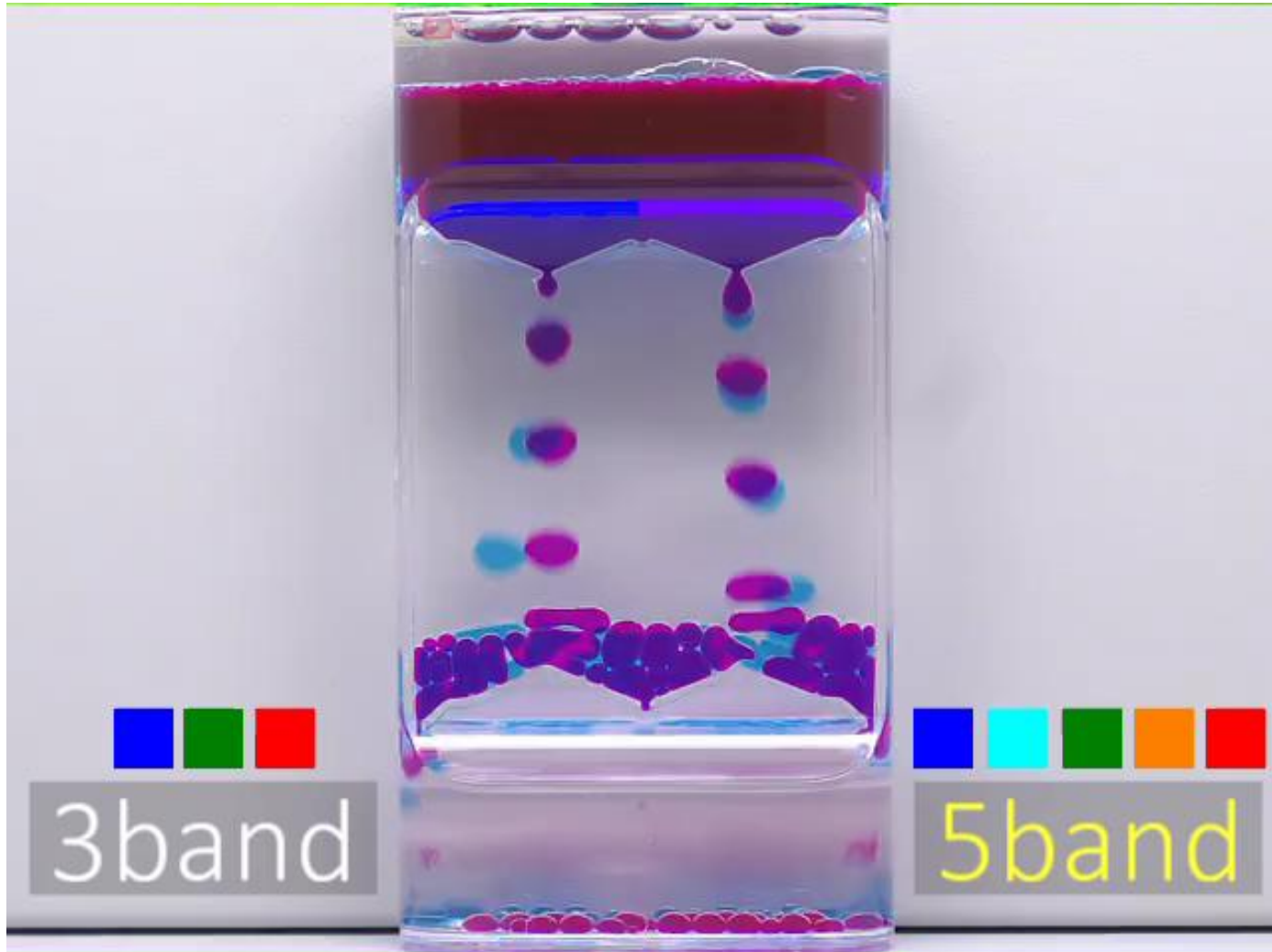
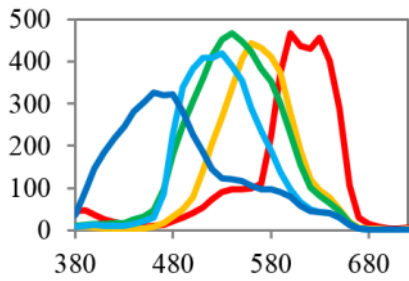




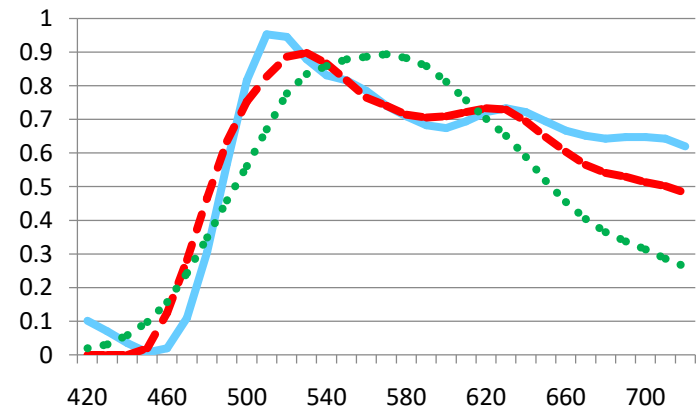
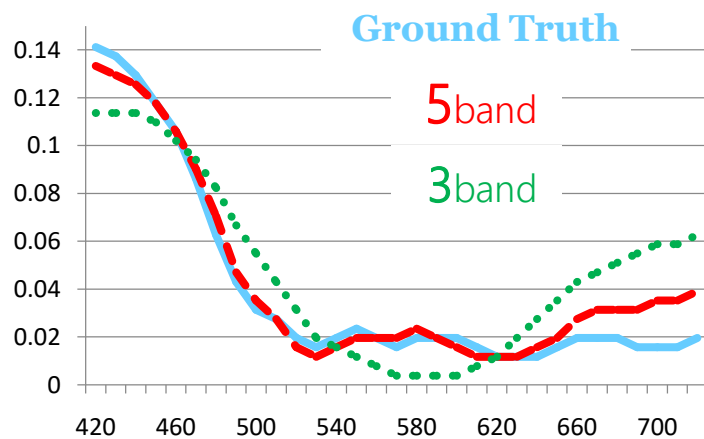
Example five-band image



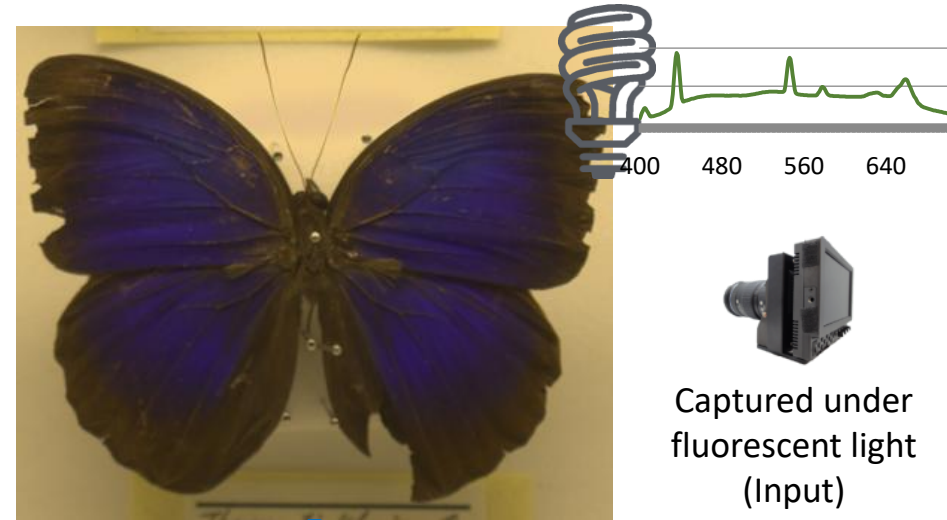
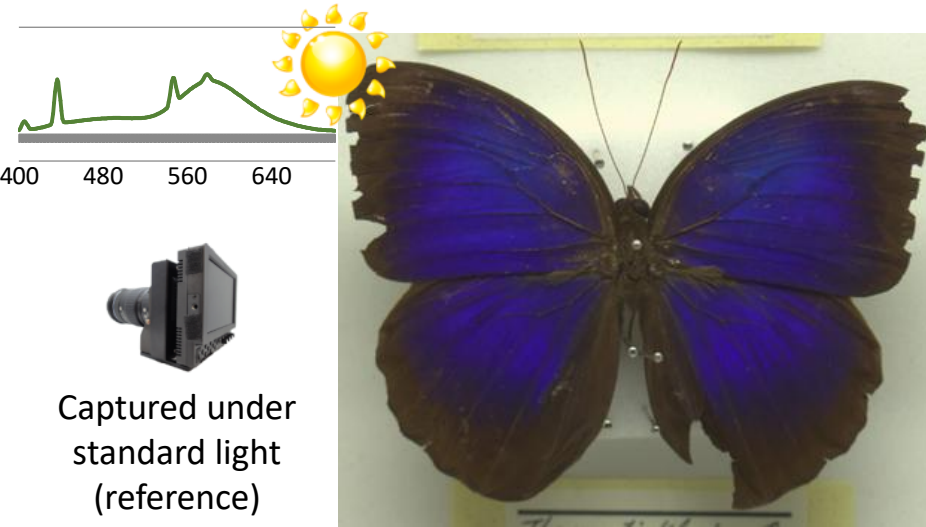
RGB vs. five-bands



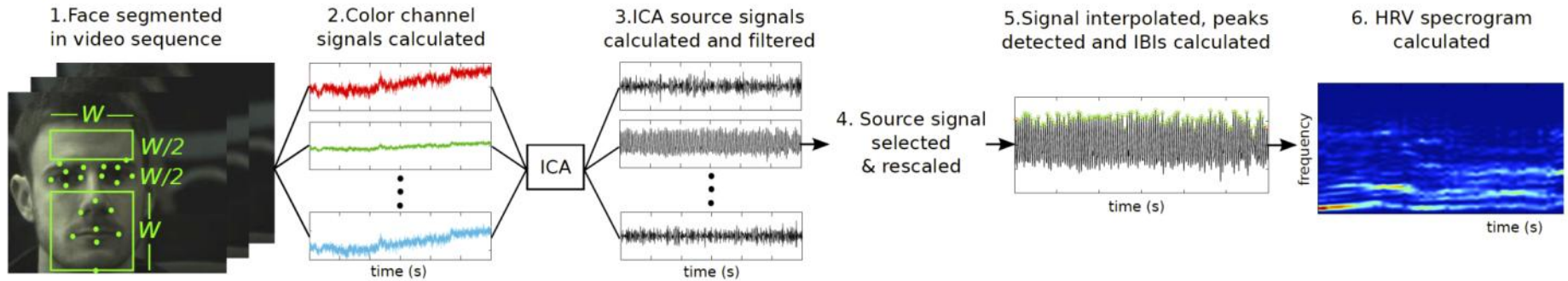
Applications: Spectral reflectance estimation



Applications: Relighting



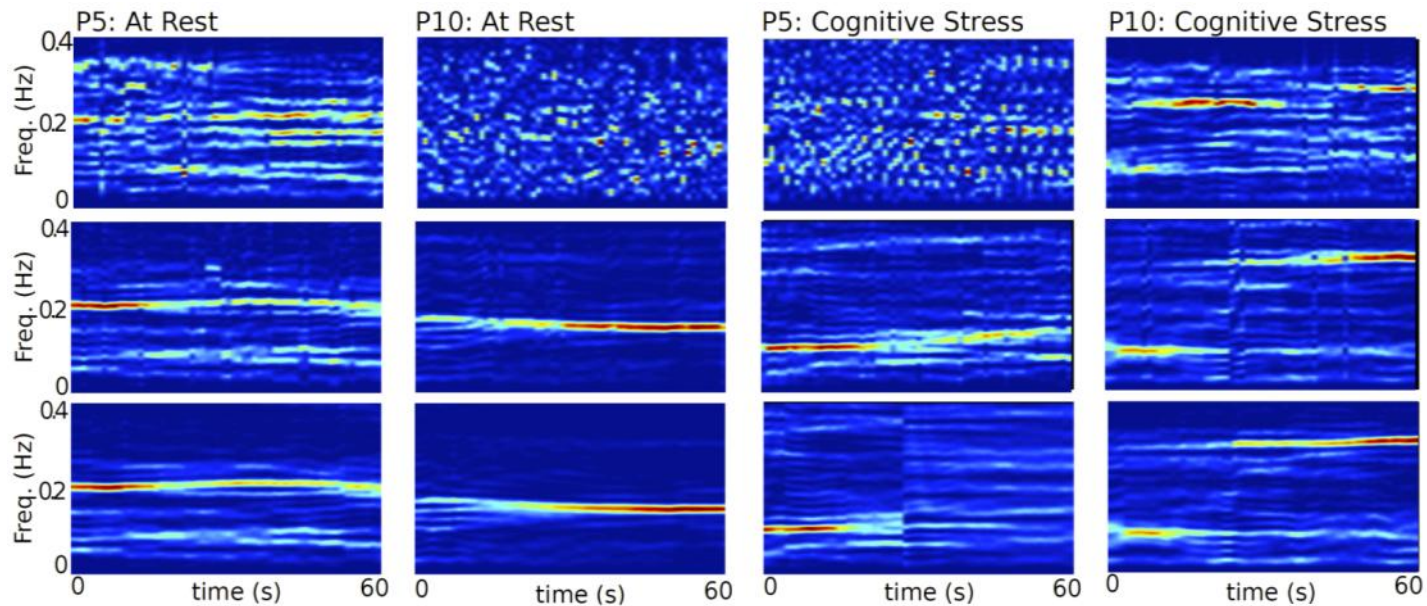
Applications: Heart Rate Measurements



Standard
RGB channels

GCO channels
among the five-bands

Contact sensor
(reference)

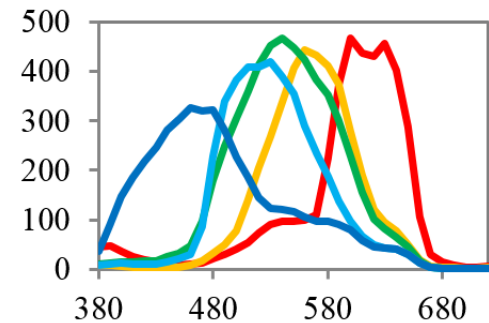


Applications: Heart Rate Measurements

	HR	BR	LF	HF	LF/HF
R	0.99	0.95	0.60	0.60	0.57
G	0.99	0.91	0.63	0.63	0.63
B	0.99	0.93	0.68	0.68	0.70
C	0.85	0.44	0.64	0.64	0.64
O	0.83	-0.02	0.43	0.43	0.34
RG	0.97	0.66	0.72	0.72	0.74
RB	0.95	0.89	0.47	0.47	0.47
RC	0.99	0.67	0.69	0.69	0.73
RO	1.00	0.93	0.88	0.88	0.89
GB	0.89	0.75	0.44	0.44	0.44
GC	0.99	0.83	0.82	0.82	0.82
GO	1.00	0.98	0.88	0.88	0.88
BC	0.99	0.68	0.61	0.61	0.65
BO	1.00	0.92	0.87	0.87	0.87
CO	0.99	0.67	0.40	0.40	0.48
RGB	0.85	0.67	0.45	0.45	0.46
RGC	0.99	0.75	0.67	0.67	0.71
RGO	1.00	0.92	0.83	0.83	0.86
RBC	0.99	0.69	0.71	0.71	0.68
RBO	1.00	0.92	0.83	0.83	0.83
RCO	1.00	0.90	0.91	0.91	0.89
GBC	0.99	0.77	0.80	0.80	0.78
GBO	1.00	0.93	0.84	0.84	0.83
GCO	1.00	0.93	0.93	0.93	0.93
BCO	0.99	0.84	0.69	0.69	0.77
RGBC	0.99	0.89	0.72	0.72	0.68
RGBO	1.00	0.81	0.79	0.79	0.81
RGCO	1.00	0.90	0.87	0.87	0.86
RBCO	1.00	0.90	0.81	0.81	0.77
GBCO	1.00	0.72	0.83	0.83	0.80
RGBCO	1.00	0.74	0.81	0.81	0.79

Lowest \bar{r}
O
RGB
CO
GB
C
RB
BC
R
RC
RBC
G
RGC
RG
BCO
B
RGBC
GBC
RGBCO
GBCO
RGBO
GC
RBCO
RBO
GBO
RGO
RGCO
BO
RO
RCO
GO
GCO

Standard RGB channels

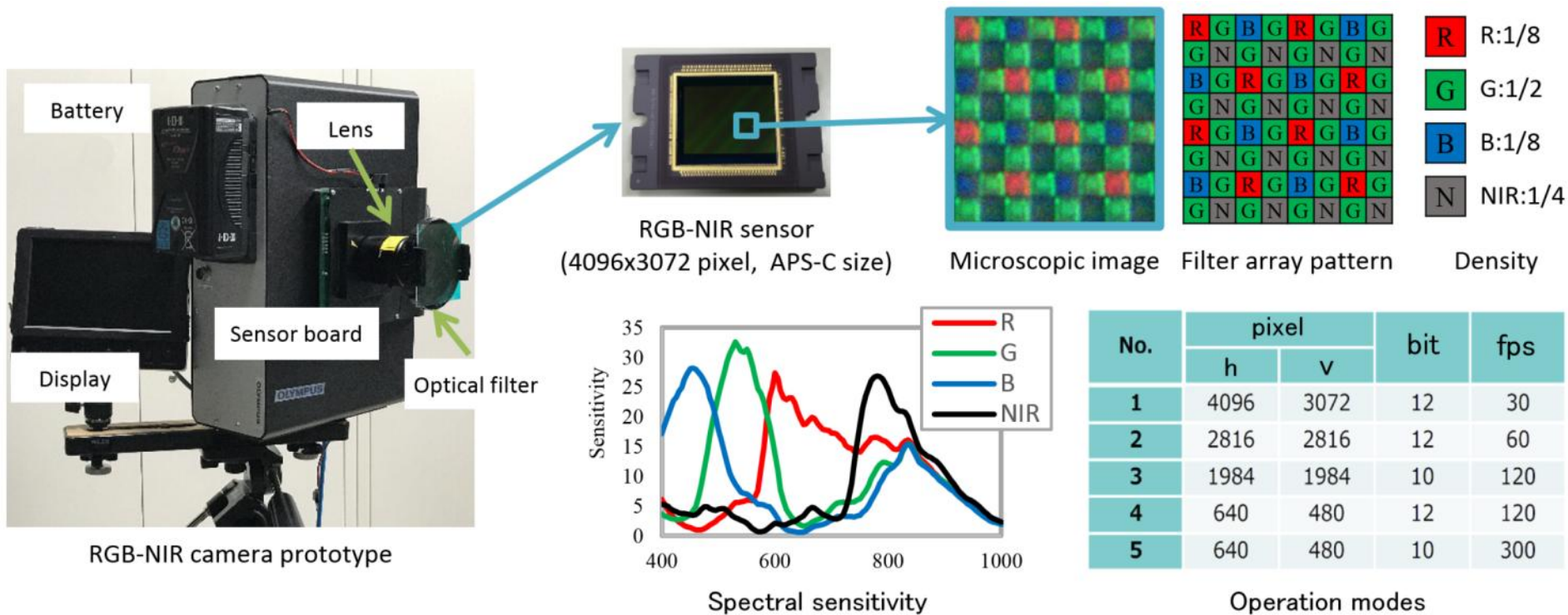


Generally, the Or band is effective for heart rate measurements

RGB-NIR Camera

Prototype RGB-NIR camera

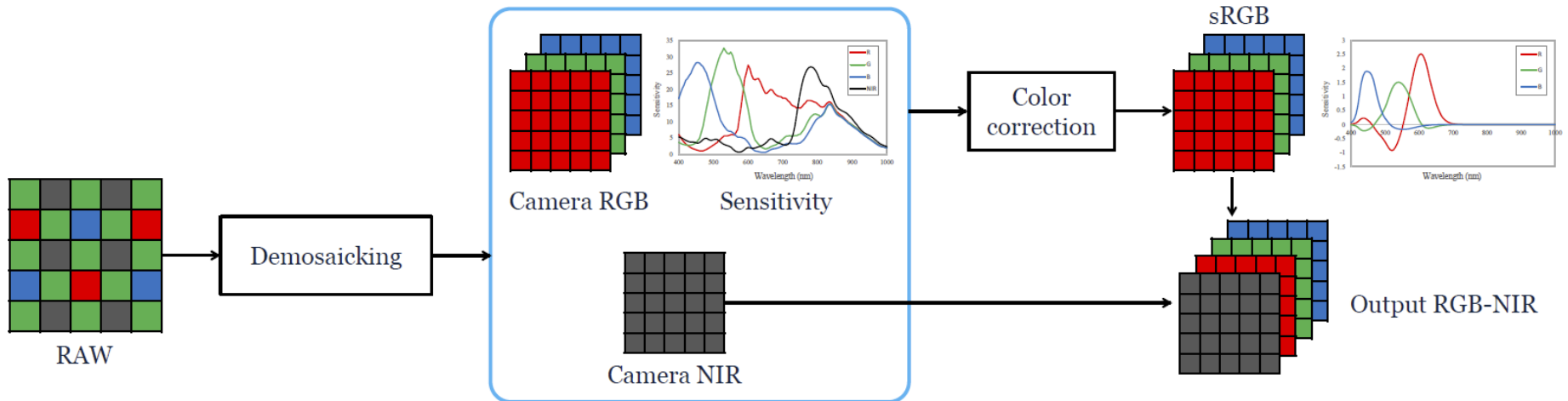
- Can capture RGB and NIR images in real time.



<http://www.ok.ctrl.titech.ac.jp/res/MSI/RGB-NIR.html>

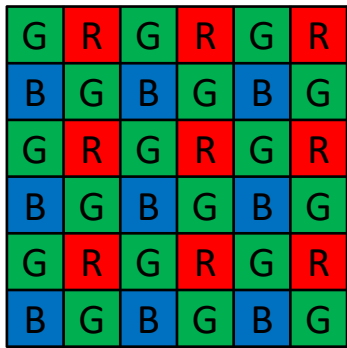
Image processing pipeline

- Demosaicing + color correction.



Filter array comparison

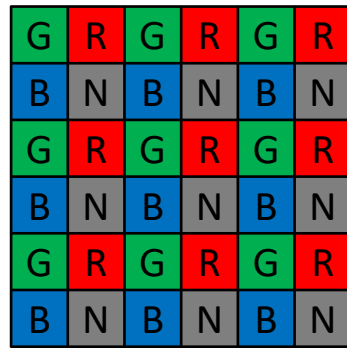
- We considered three array patterns.



Bayer pattern
(RGB)

Sampling density

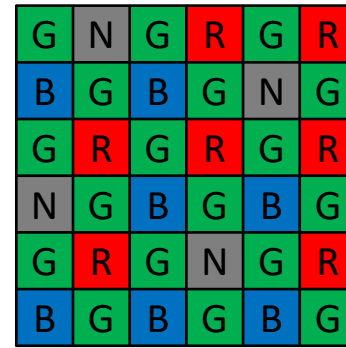
R	G	B	NIR
1/4	1/2	1/4	-



Uniform

Sampling density

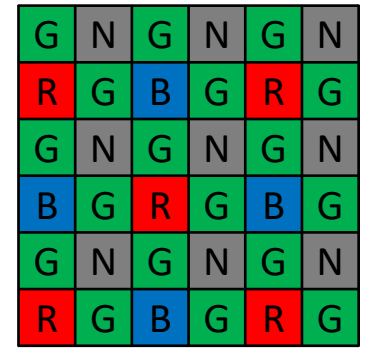
R	G	B	NIR
1/4	1/4	1/4	1/4



Proposed 1

Sampling density

R	G	B	NIR
1/5	1/2	1/5	1/10



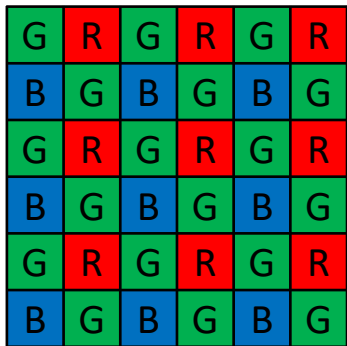
Proposed 2

Sampling density

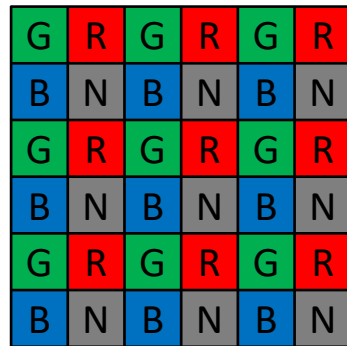
R	G	B	NIR
1/8	1/2	1/8	1/4

Filter array comparison

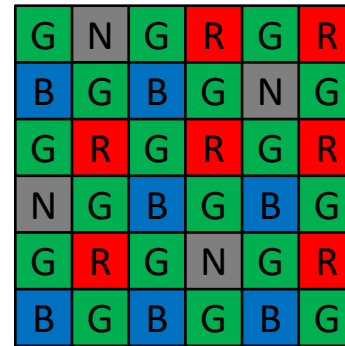
- We considered three array patterns.



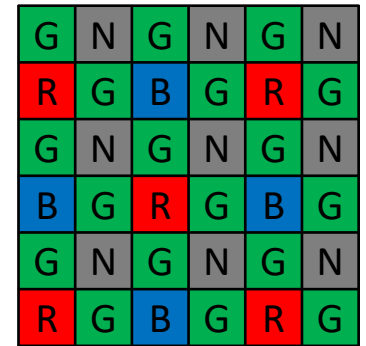
Bayer pattern
(RGB)



Uniform



Proposed 1

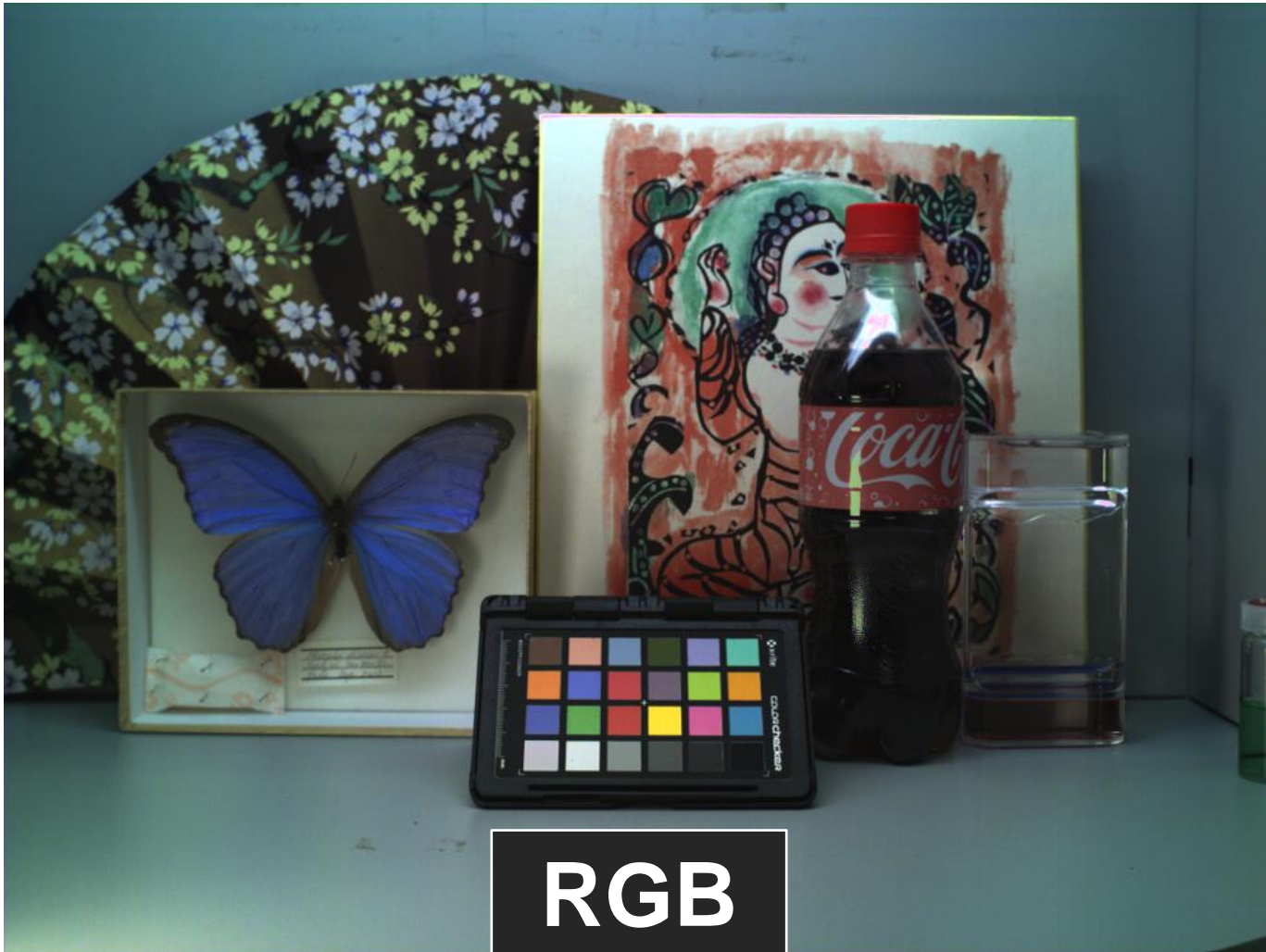


Proposed 2

Average PSNR results
for 20 scenes

	Uniform	Proposed 1	Proposed 2
Color PSNR (sRGB)	32.25	34.48	34.02
PSNR (NIR)	33.87	38.37	40.22
Average	33.06	36.43	37.12

Example images



RGB

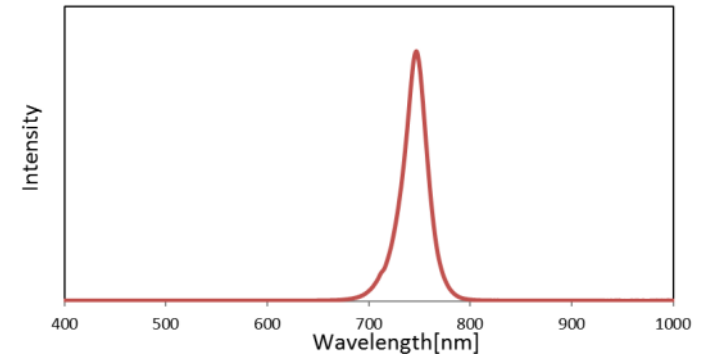
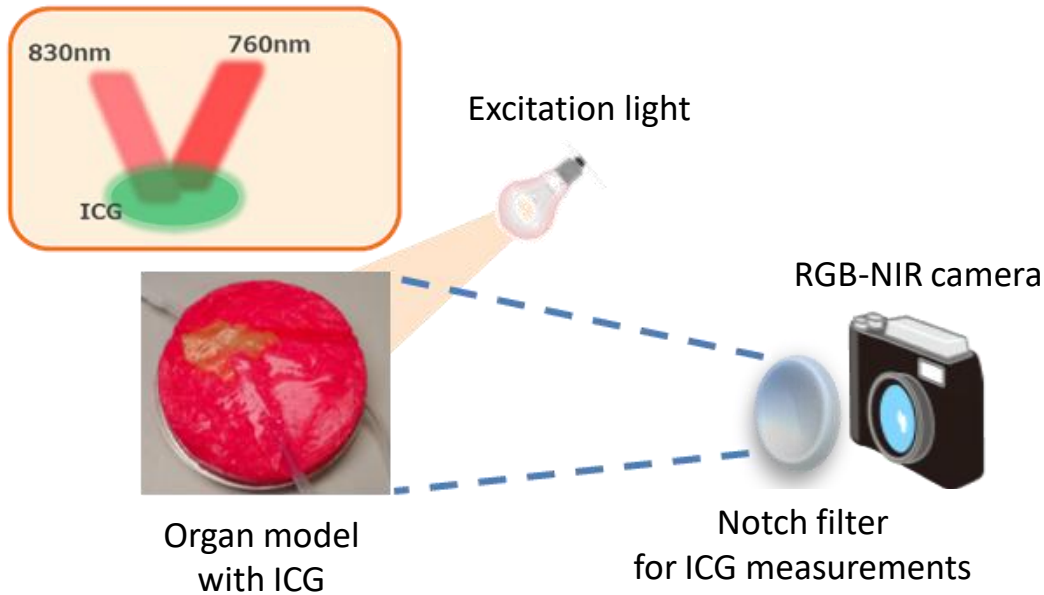
Example images



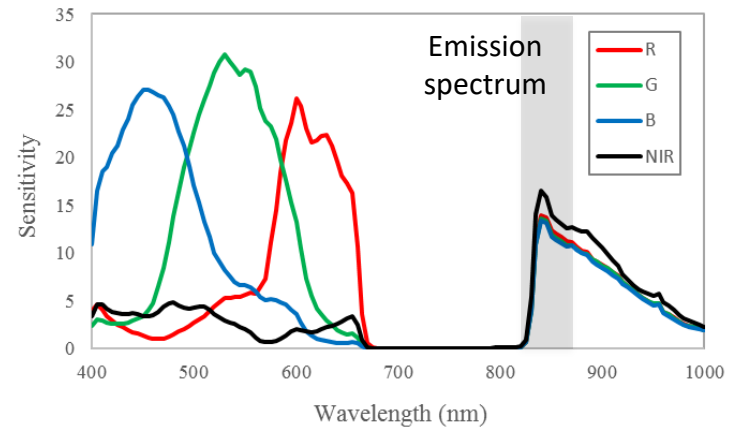
NIR

Applications: ICG fluorescent imaging

Imaging system (ICG: IndoCyanine Green)

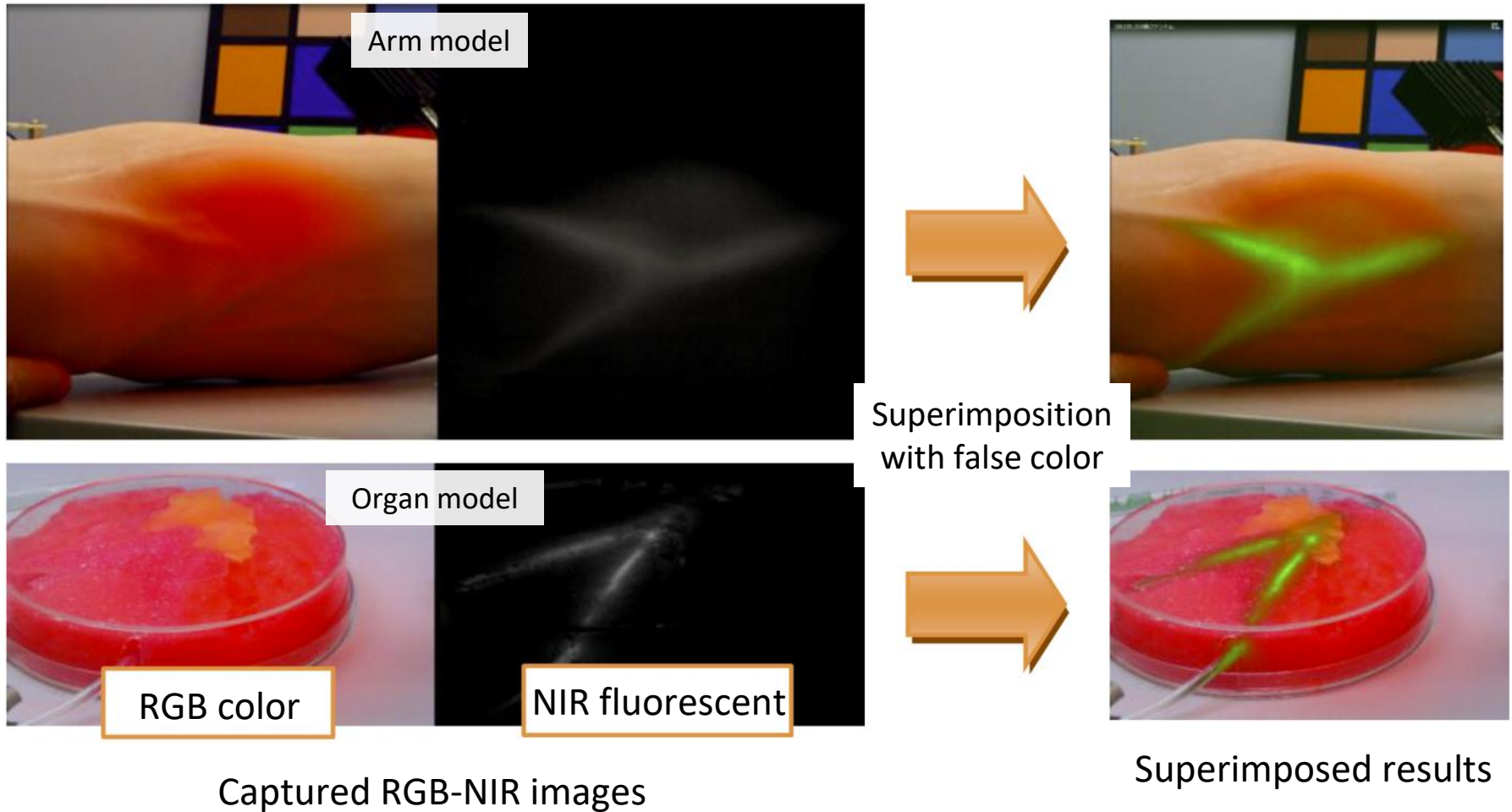


Excitation light



Camera sensitivity

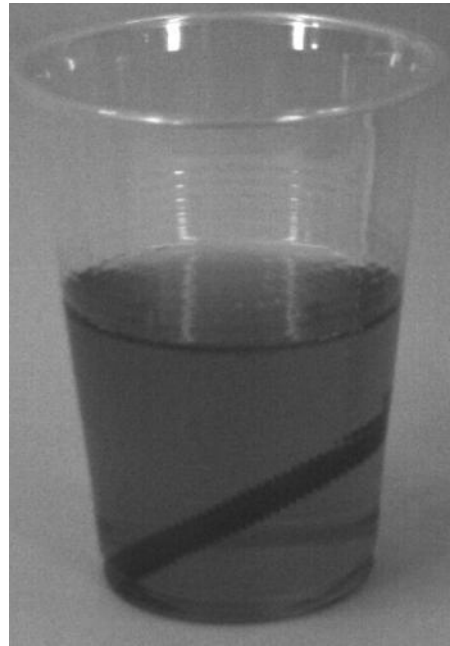
Superimposed representation



Applications: Food inspection



RGB



NIR



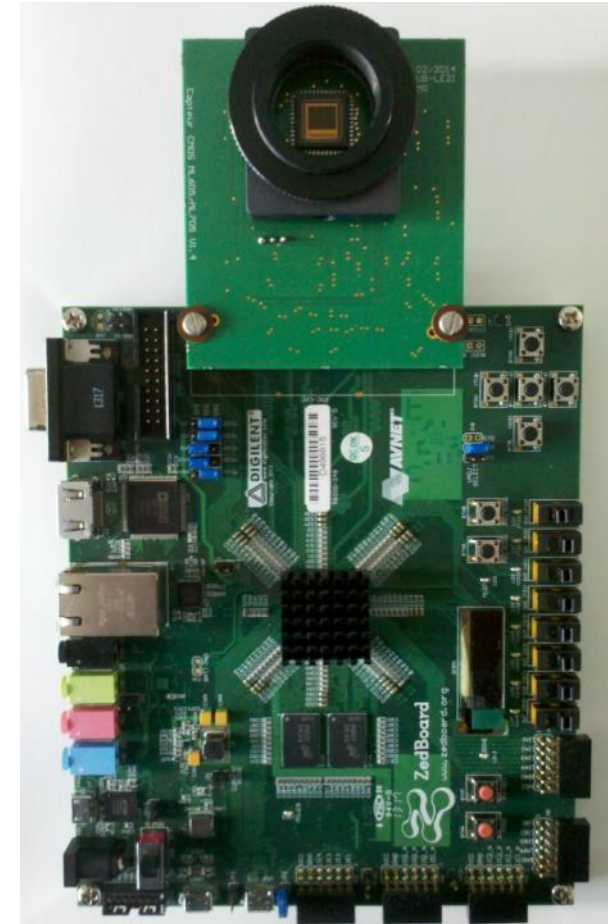
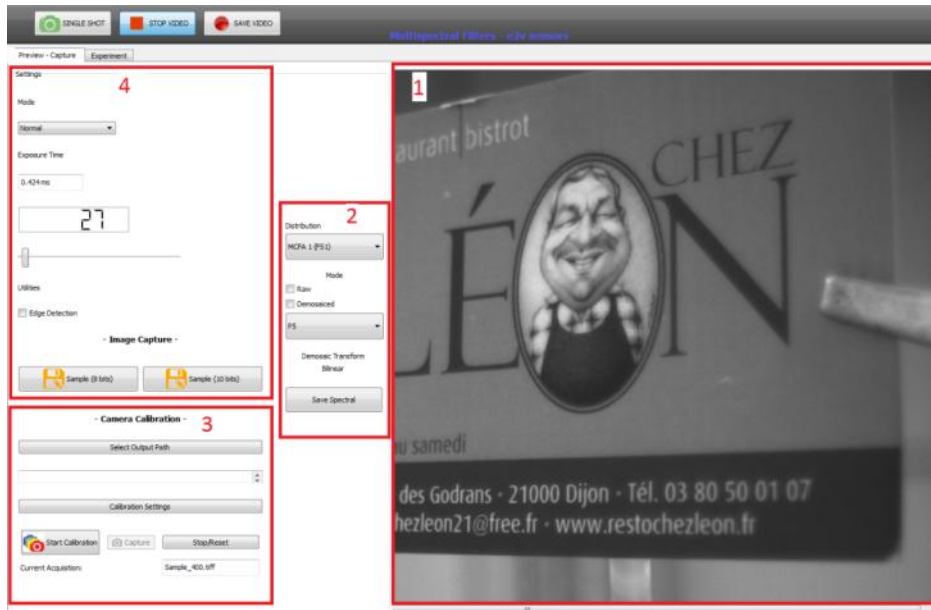
Superimposition
with false color



RGB + NIR

Eight band Camera Visible + NIR

Prototype



P5	P1	P5	IR
P6	P5	P4	P5
P5	IR	P5	P2
P3	P5	P7	P5

(a) FS1

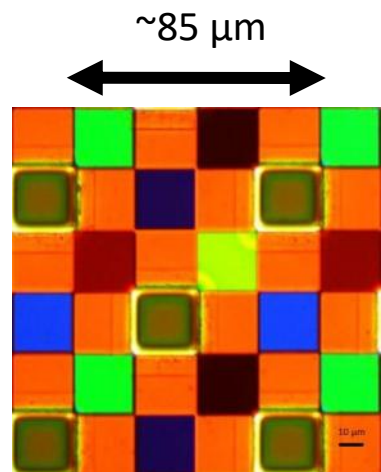
P1	P5	P2	P6
P7	P3	IR	P4
P2	P6	P1	P5
IR	P4	P7	P3

(b) FS2

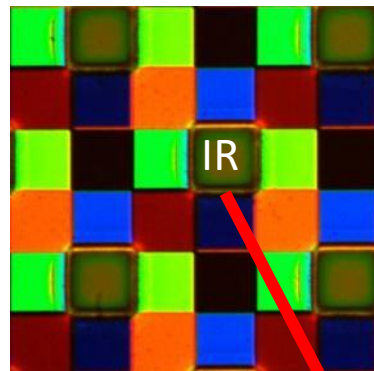
Lapray, P.-J.; Wang, X.; Thomas, J.-B.; Gouton, P. Multispectral Filter Arrays: Recent Advances and Practical Implementation. *Sensors* **2014**, *14*, 21626-21659.

Thomas, J.-B.; Lapray, P.-J.; Gouton, P.; Clerc, C. Spectral Characterization of a Prototype SFA Camera for Joint Visible and NIR₆₉ Acquisition. *Sensors* **2016**, *16*, 993.

Prototype



First arrangement



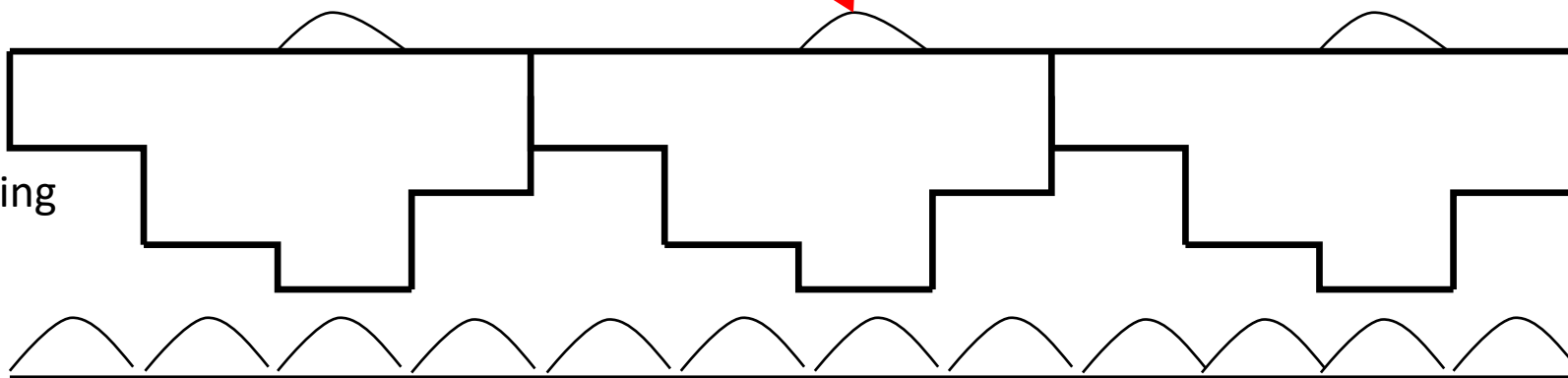
Second arrangement

Dynamic process

Thin layer
NIR

Glass
nano-etching
VIS
Glue

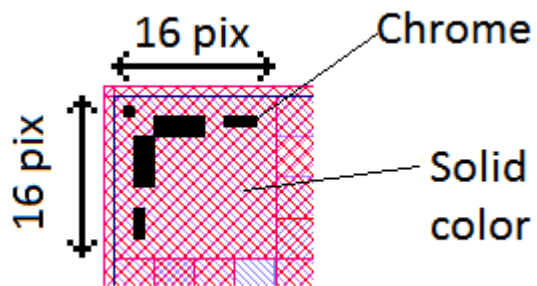
Sensor



Pre-processing

Sensor: $5.3 \mu\text{m}^2$ (1280*1024)

Filter: $21.2 \mu\text{m}^2$



P5	P5	P5	P5	P1	P1	P1	P1	P5	P5	P5	P5	IR	IR	IR	IR
P5	P5	P5	P5	P1	P1	P1	P1	P5	P5	P5	P5	IR	IR	IR	IR
P5	P5	P5	P5	P1	P1	P1	P1	P5	P5	P5	P5	IR	IR	IR	IR
P5	P5	P5	P5	P1	P1	P1	P1	P5	P5	P5	P5	IR	IR	IR	IR
P6	P6	P6	P6	P5	P5	P5	P5	P4	P4	P4	P4	P5	P5	P5	P5
P6	P6	P6	P6	P5	P5	P5	P5	P4	P4	P4	P4	P5	P5	P5	P5
P6	P6	P6	P6	P5	P5	P5	P5	P4	P4	P4	P4	P5	P5	P5	P5
P6	P6	P6	P6	P5	P5	P5	P5	P4	P4	P4	P4	P5	P5	P5	P5
P5	P5	P5	P5	IR	IR	IR	IR	P5	P5	P5	P5	P2	P2	P2	P2
P5	P5	P5	P5	IR	IR	IR	IR	P5	P5	P5	P5	P2	P2	P2	P2
P5	P5	P5	P5	IR	IR	IR	IR	P5	P5	P5	P5	P2	P2	P2	P2
P5	P5	P5	P5	IR	IR	IR	IR	P5	P5	P5	P5	P2	P2	P2	P2
P3	P3	P3	P3	P5	P5	P5	P5	P7	P7	P7	P7	P5	P5	P5	P5
P3	P3	P3	P3	P5	P5	P5	P5	P7	P7	P7	P7	P5	P5	P5	P5
P3	P3	P3	P3	P5	P5	P5	P5	P7	P7	P7	P7	P5	P5	P5	P5
P3	P3	P3	P3	P5	P5	P5	P5	P7	P7	P7	P7	P5	P5	P5	P5

Pre-processing

P1	P1	P1	P1	P5	P5	P5	P5	P2	P2	P2	P2	P6	P6	P6	P6
P1	P1	P1	P1	P5	P5	P5	P5	P2	P2	P2	P2	P6	P6	P6	P6
P1	P1	P1	P1	P5	P5	P5	P5	P2	P2	P2	P2	P6	P6	P6	P6
P1	P1	P1	P1	P5	P5	P5	P5	P2	P2	P2	P2	P6	P6	P6	P6
P7	P7	P7	P7	P3	P3	P3	P3	IR	IR	IR	IR	P4	P4	P4	P4
P7	P7	P7	P7	P3	P3	P3	P3	IR	IR	IR	IR	P4	P4	P4	P4
P7	P7	P7	P7	P3	P3	P3	P3	IR	IR	IR	IR	P4	P4	P4	P4
P7	P7	P7	P7	P3	P3	P3	P3	IR	IR	IR	IR	P4	P4	P4	P4
P2	P2	P2	P2	P6	P6	P6	P6	P1	P1	P1	P1	P5	P5	P5	P5
P2	P2	P2	P2	P6	P6	P6	P6	P1	P1	P1	P1	P5	P5	P5	P5
P2	P2	P2	P2	P6	P6	P6	P6	P1	P1	P1	P1	P5	P5	P5	P5
P2	P2	P2	P2	P6	P6	P6	P6	P1	P1	P1	P1	P5	P5	P5	P5
IR	IR	IR	IR	P4	P4	P4	P4	P7	P7	P7	P7	P3	P3	P3	P3
IR	IR	IR	IR	P4	P4	P4	P4	P7	P7	P7	P7	P3	P3	P3	P3
IR	IR	IR	IR	P4	P4	P4	P4	P7	P7	P7	P7	P3	P3	P3	P3
IR	IR	IR	IR	P4	P4	P4	P4	P7	P7	P7	P7	P3	P3	P3	P3

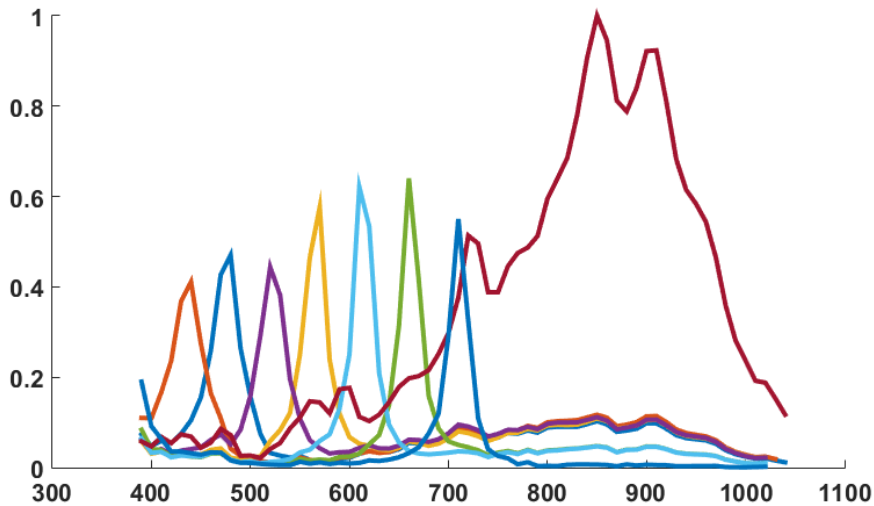
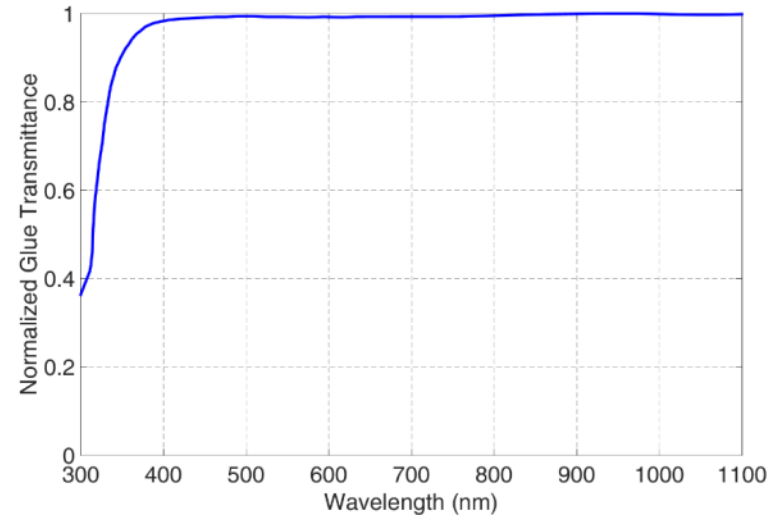
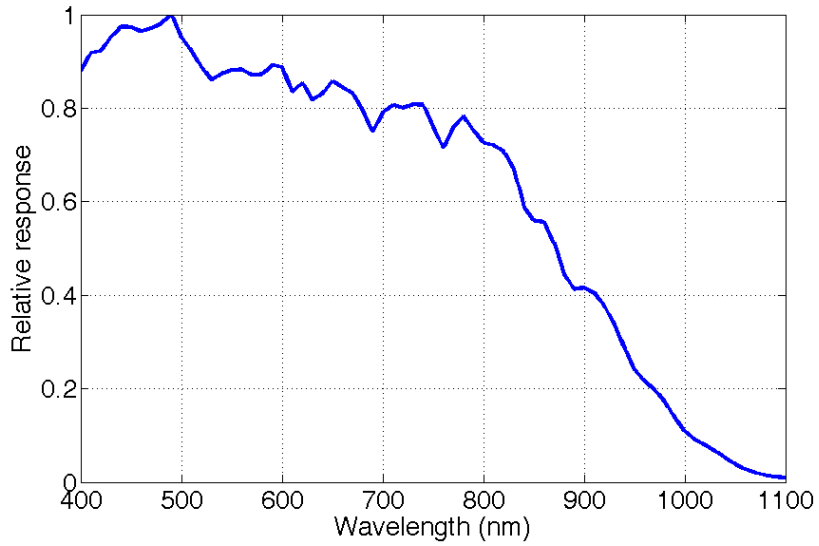
(1280*1024)=>(320*256)

Moxel pre-processing

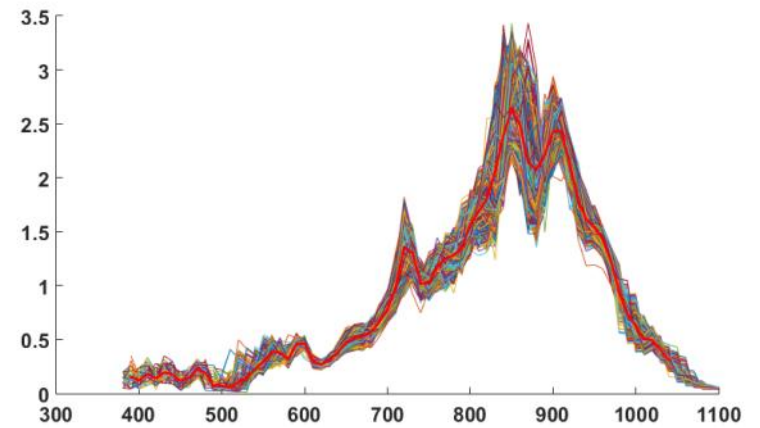
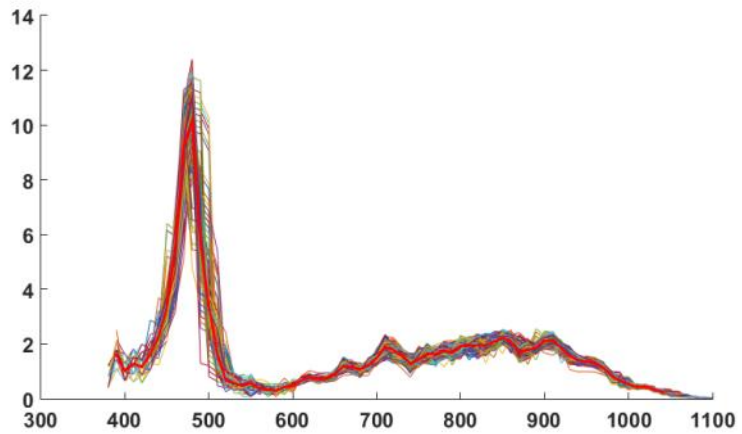
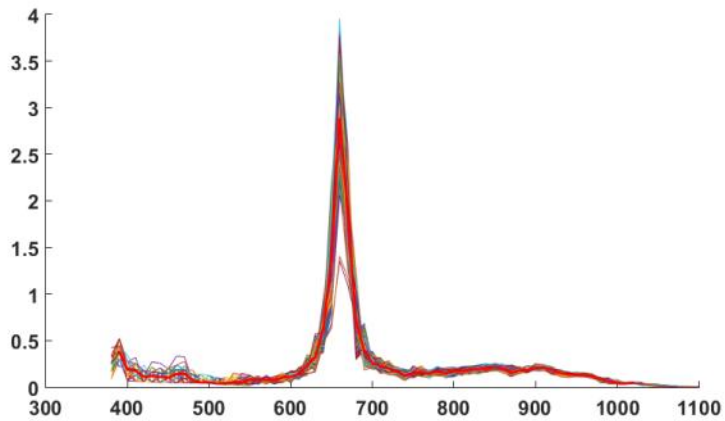
$$P_i^k = \frac{1}{4} \sum_{j=1}^{j=4} P_i^j$$

P1	P5	P2	P6
P7	P3	IR	P4
P2	P6	P1	P5
IR	P4	P7	P3

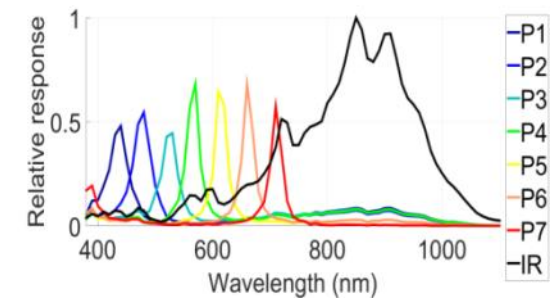
Sensitivities of the elements



Spatial uniformity



Eight-bands camera visible-NIR

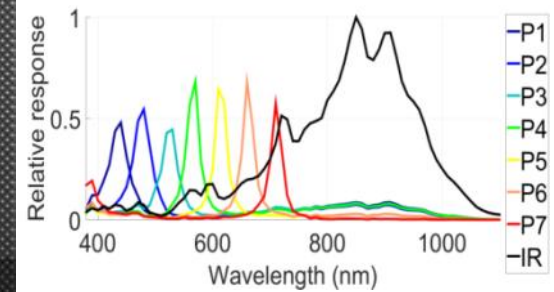
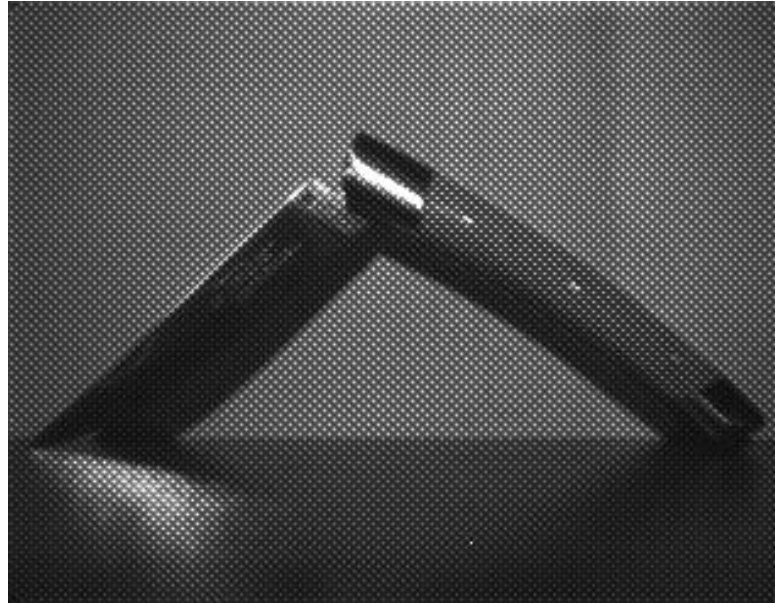


DEMOSAICING

Channels 1-7, NIR

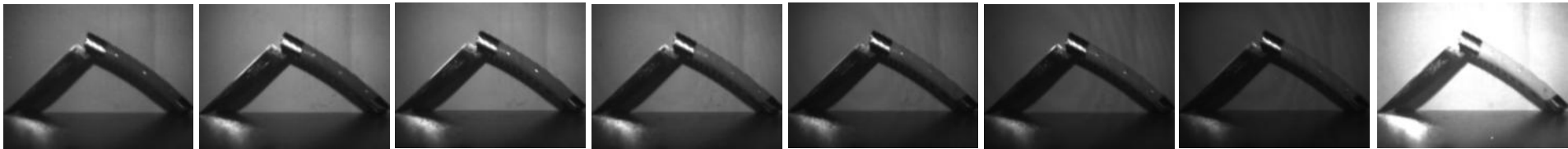


Eight-bands camera visible-NIR



DEMOSAICING

Channels 1-7, NIR



Eight-bands camera visible-NIR



Database available at: <http://chic.u-bourgogne.fr/> (select SFA LDR)

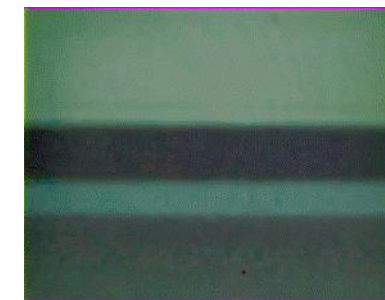
Video acquisition



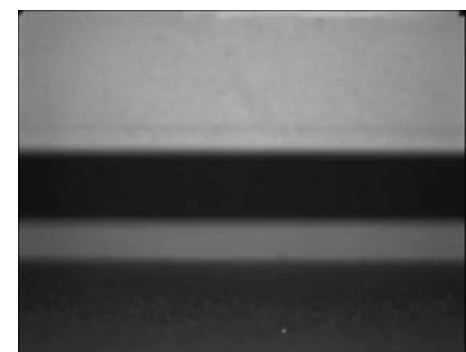
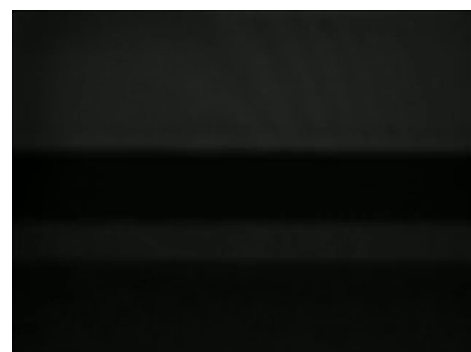
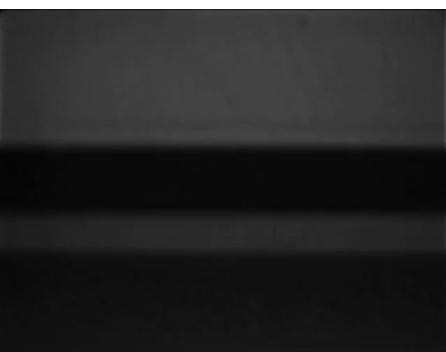
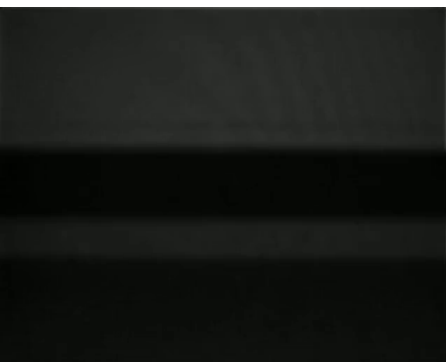
Raw SFA Video Acquisition

Video acquisition

Raw video



sRGB representation



8 Demosaiced videos from the raw video

Application: Background subtraction with MS video

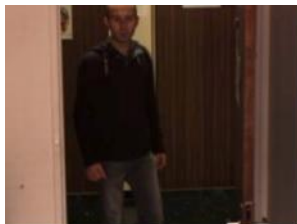
- Change detection is one of the most important low-level tasks in video analytics



Yannick Benezeth, Sidibé, D.; Thomas, J.B. *Background subtraction with multispectral video sequences*. In Proceedings of IEEE International Conference on Robotics and Automation Workshop on Non-Classical Cameras, Camera Networks and Omnidirectional Vision (OMNIVIS), Hong Kong, China, 31 May–7 June 2014.

Database

- Videos with various challenges
 - gradual illumination changes, shadows, camouflage effects
- 7 bands: 6 visibles, 1 NIR
 - Plus a version of RGB sequences
- 5 annotated videos
 - Static, moving, shadows, out of ROI, unknown
- 3 not annotated



Video 1



Video 2



Video 3



Video 4



Video 5

Publicly available dataset of MS videos

<http://ilt.u-bourgogne.fr/benezeth/>

- F-measures on 5 video sequences

Video sequence	Mahalanobis distance (RGB)	Mahalanobis distance (MS)	Pooling	Spectral distances	
				d_{θ}	d_{SID}
Video #1	0.65	0.81	0.80	0.90	0.90
Video #2	0.87	0.89	0.88	0.96	0.97
Video #3	0.66	0.69	0.65	0.90	0.90
Video #4	0.82	0.83	0.83	0.67	0.69
Video #5	0.75	0.77	0.77	0.74	0.76

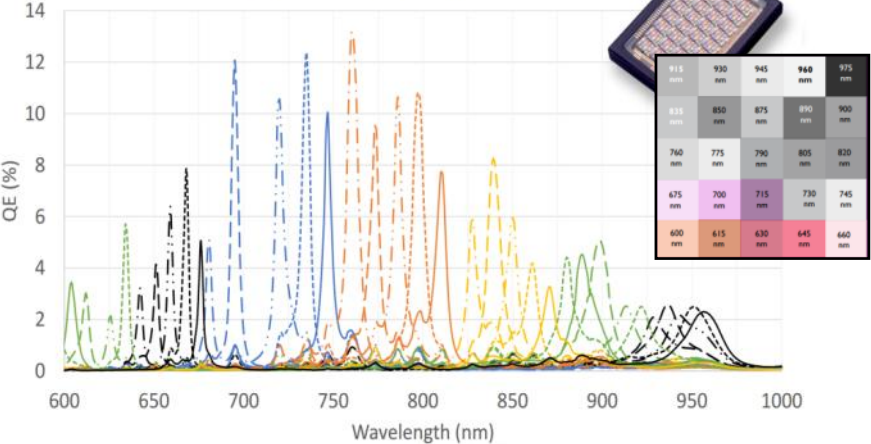
- Improved performances with MS videos
- The 2 spectral distances have very close results
- Performances are highly dependent on the video

Other State-of-the-art

Multispectral sensor products

IMEC hyperspectral sensor

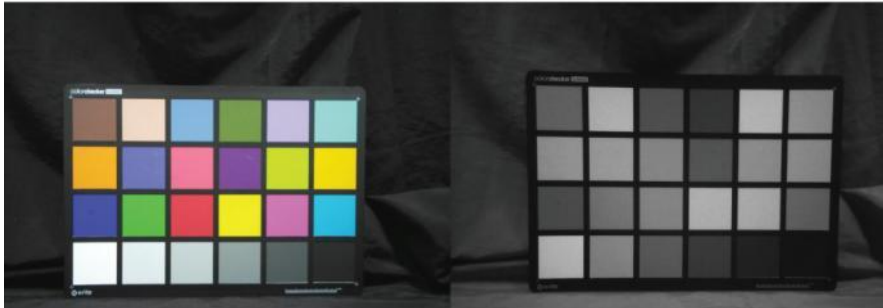
Snapshot 5x5 mosaic NIR 25bands sensor
(from CMOSIS CMV2000 - without microlenses)



OmniVision RGB-NIR sensor



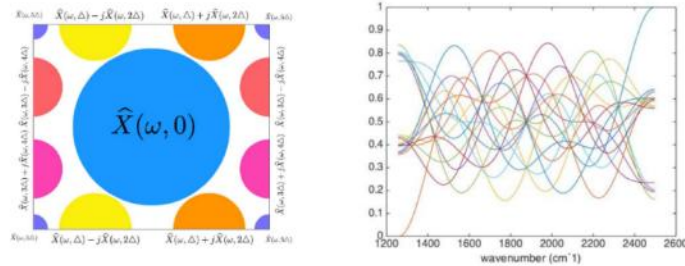
OV4682 4MP product brief



<http://www2.imec.be/content/user/File/Brochures/2015/HSI%20activity.pdf>

<https://www.e-consystems.com/OV4682-RGB-IR-USB3-camera.asp>
<http://www.ovt.com/products/sensor.php?id=145>

Multispectral sensor research



$$(a) \hat{Y}(\omega) = \{\hat{S} \star \hat{X}_Q\}(\omega, 0)$$

$$(b) \tilde{S}(\mathbf{n}, \sigma)$$

Fig. 11. Example Fourier SFA design. (a) Sensor data in spatial frequency domain. (b) Spectral transmittance $\tilde{S}(\mathbf{n}, \sigma)$. A visualization of Fourier SFA is shown in Figure 14(a).

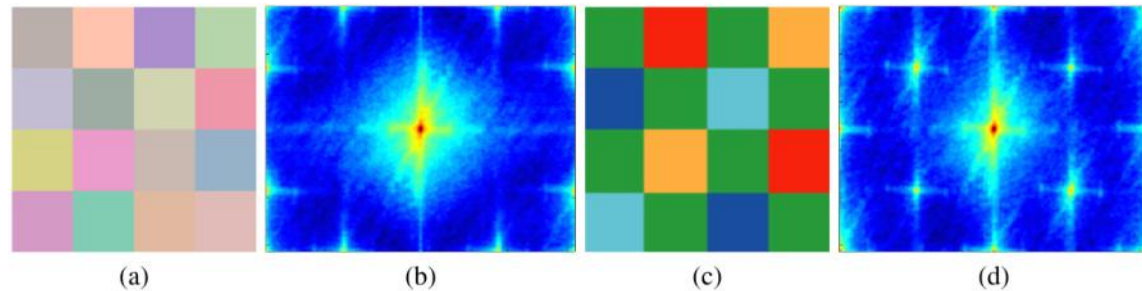


Fig. 13. SFA patterns and the spatial frequency response of the simulated sensor data. (a) Proposed Fourier SFA pattern. (b) Log Fourier magnitude of simulated Fourier SFA sensor data of (a). (c) Narrowband SFA pattern of [22]. (d) Log Fourier magnitude of simulated Fourier SFA sensor data of (c). Simulated from hyperspectral image data acquired by Surface Optics SOC730 sensor, shown in Figure 6(a).

J. Jia, K. J. Barnard and K. Hirakawa, "Fourier Spectral Filter Array for Optimal Multispectral Imaging," in *IEEE Transactions on Image Processing*, vol. 25, no. 4, pp. 1530-1543, April 2016.

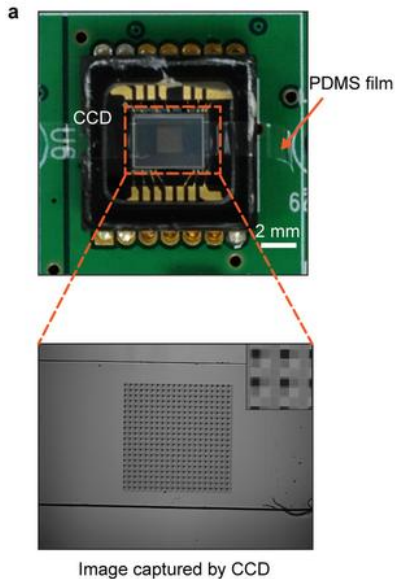
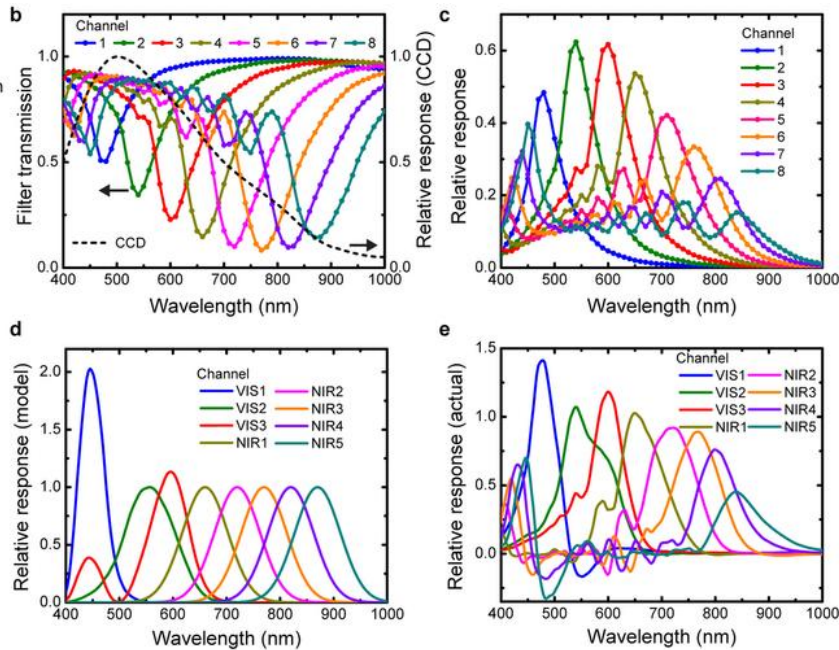
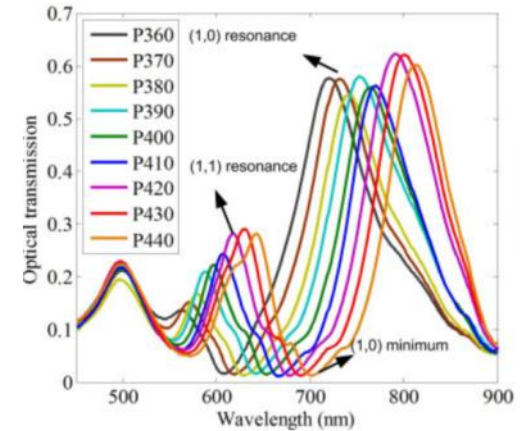


Image captured by CCD

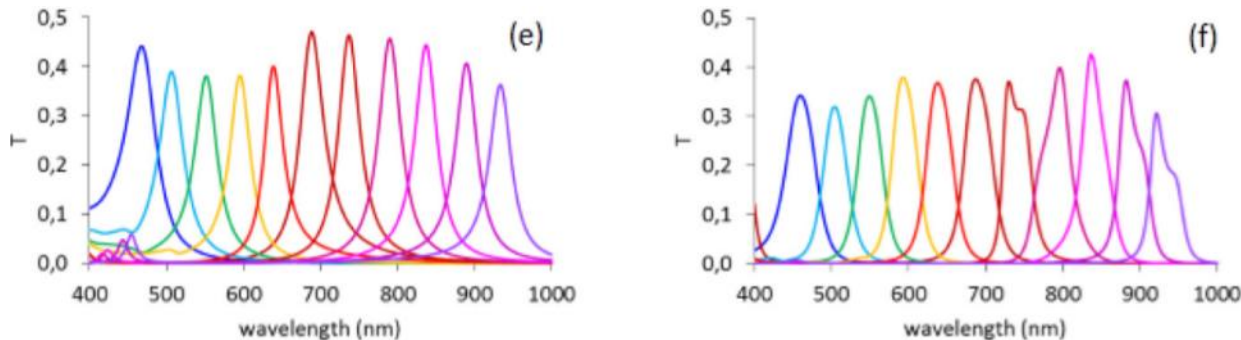


Park, H.; Crozier, K.B. Multispectral imaging with vertical silicon nanowires. Scientific reports 2013, 3.

Research on filters



Najiminaini, M.; Vasefi, F.; Kaminska, B.; Carson, J.J.L. Nanohole-array-based device for 2D snapshot multispectral imaging. Scientific Reports 2013, 3, 2589–.



Frey, L.; Masarotto, L.; Armand, M.; Charles, M.L.; Lartigue, O. Multispectral interference filter arrays with compensation of angular dependence or extended spectral range. Opt. Express 2015, 23, 11799–11812.

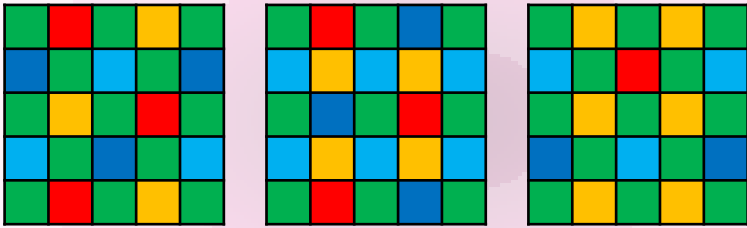
This presentation is intended for pedagogical purpose.
If you see borrowed material that is not properly acknowledged,
please inform us, we will give credits or modify the content!

Outlines

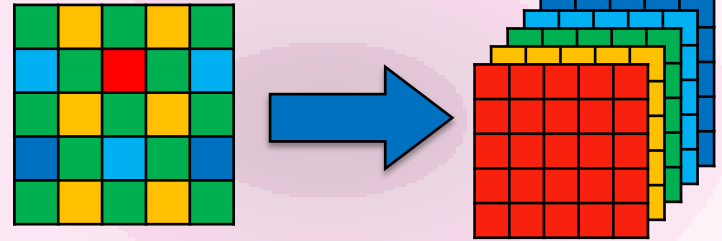
- 1-Generalities (20 min) (JB)
 - Intro on multispectral imaging
 - SFA definition and components
 - Imaging pipeline definition
- 2-Practical instantiations, databases and applications (40 min) (all of us)
 - Incl. a topo on architecture (PJ)
 - Five-bands camera in the visible domain (Y)
 - RGB-NIR camera (Y)
 - Eight-bands camera visible-NIR (JB/PJ)
 - Other state-of-the art
- 3-Demosaicing, pattern and data processing (30 min) (Yusuke)
 - Incl. color or spectral correction when NIR/visible overlap.
- 4-Insight on image quality (20 min)(PJ)
 - Incl. HDR
 - Incl. no-reference metrics tentative
- 5-Wrap up, future directions and questions (20 min) (all of us)

Main components of SFA camera

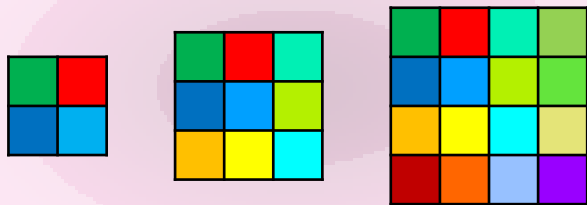
SFA pattern



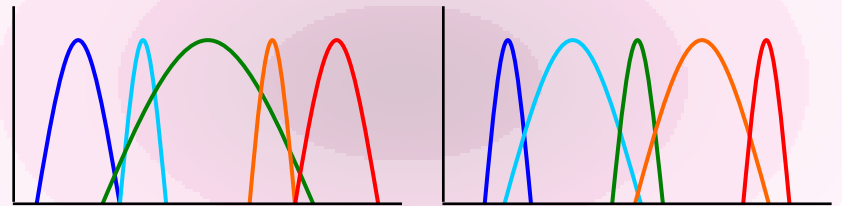
Demosaicing algorithm



Number of spectral bands



Spectral sensitivity



SFA pattern and demosaicing

- Currently, there is no de-facto SFA pattern.
- Joint design of an SFA pattern and a demosaicing algorithm is potentially effective.



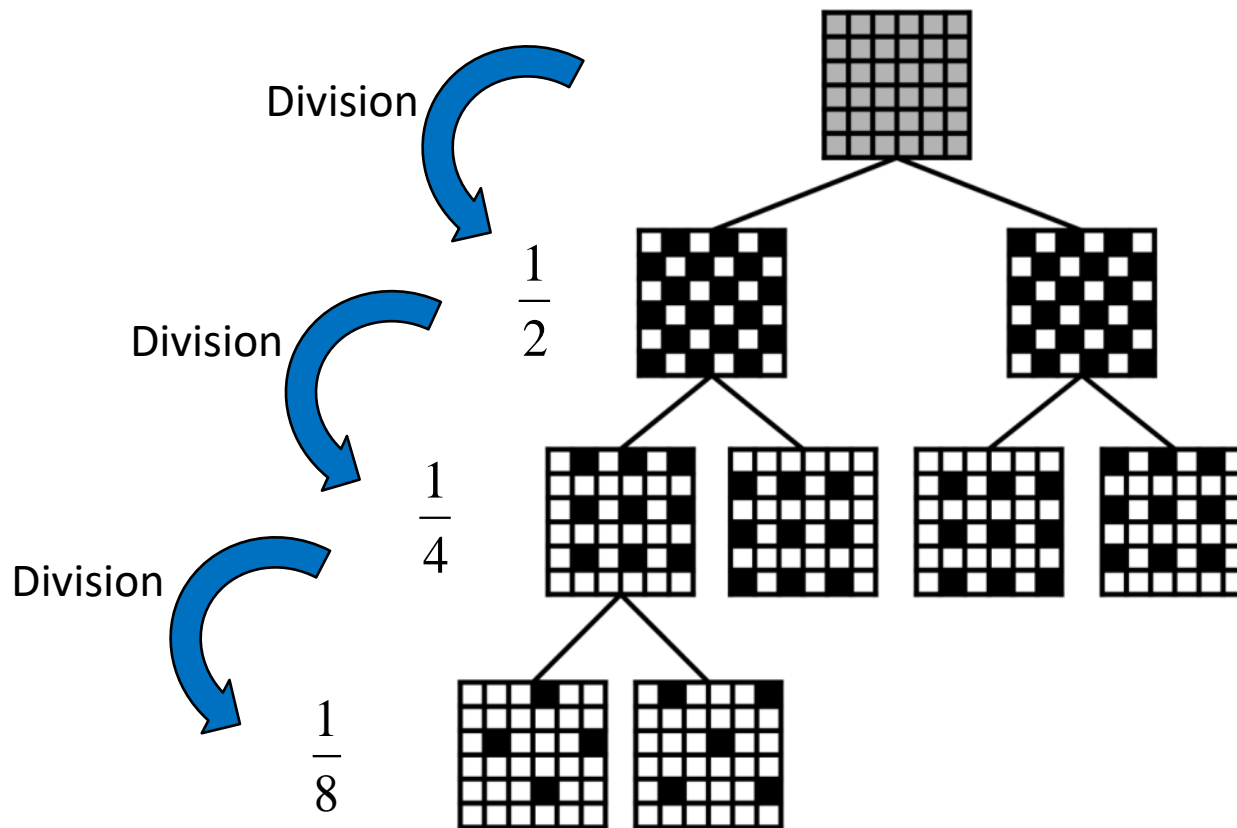
SFA pattern

Chicken-and-egg
problem

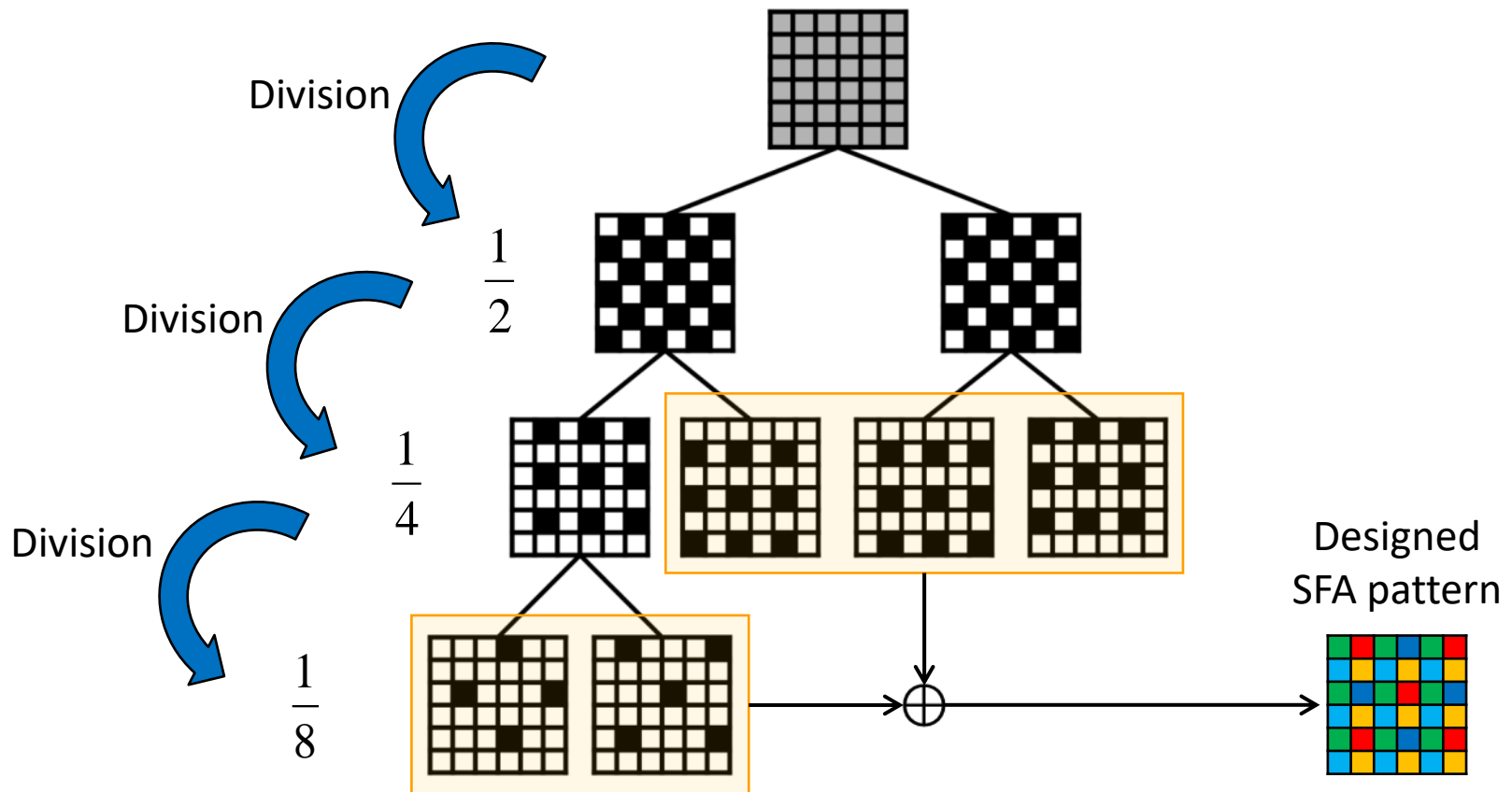


Demosaicing algorithm

- General framework for designing SFA patterns based on a **binary tree**

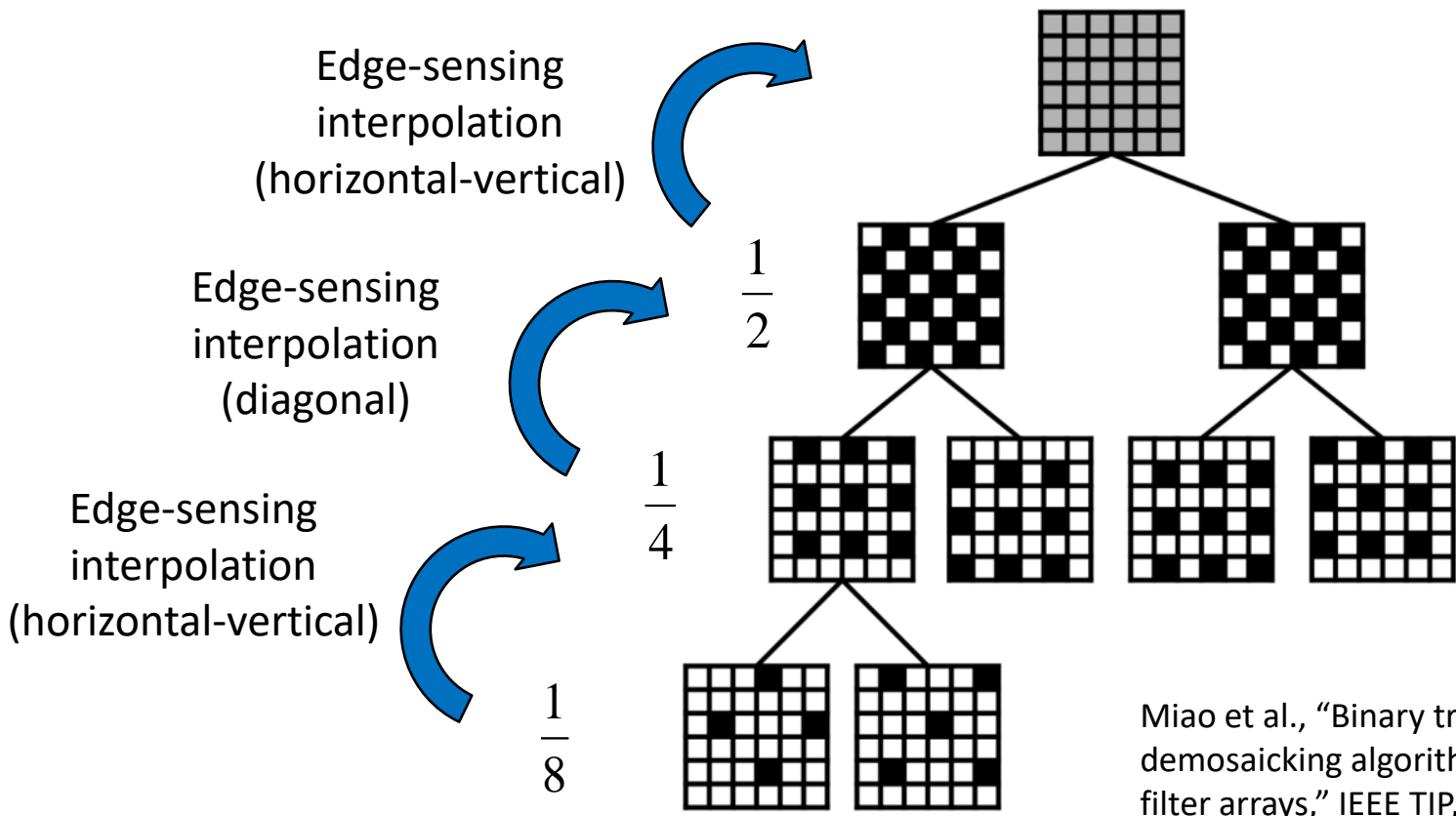


- General framework for designing SFA patterns based on a **binary tree**



Binary tree-based edge-sensing (BTES) demosaicing algorithm

- General algorithm for designed SFA patterns

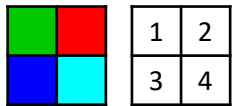


Miao et al., "Binary tree-based generic demosaicking algorithm for multispectral filter arrays," IEEE TIP, 2006.

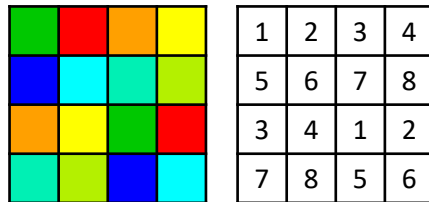
Two streams for SFA patterns

- Uniform patterns
 - Simple and intuitive

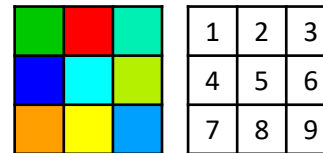
Square ones



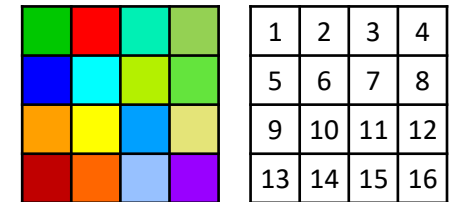
4 bands
(e.g. RGB-NIR)



8 bands



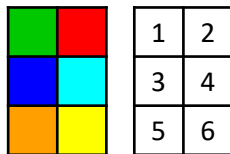
9 bands



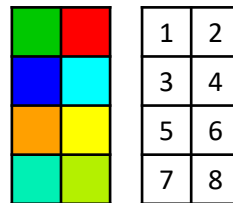
16 bands

...

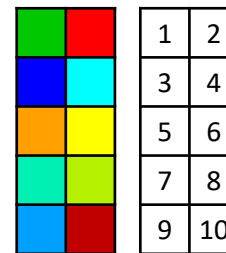
Rectangular ones



6 bands



8 bands



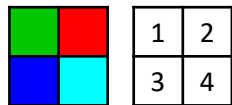
10 bands

...

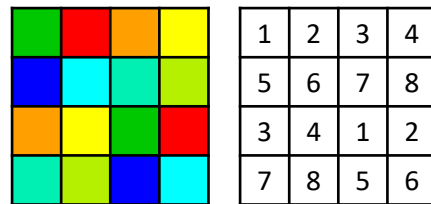
Two streams for SFA patterns

- Uniform patterns

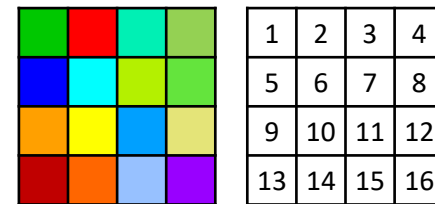
- Some patterns are instances of the generic method.



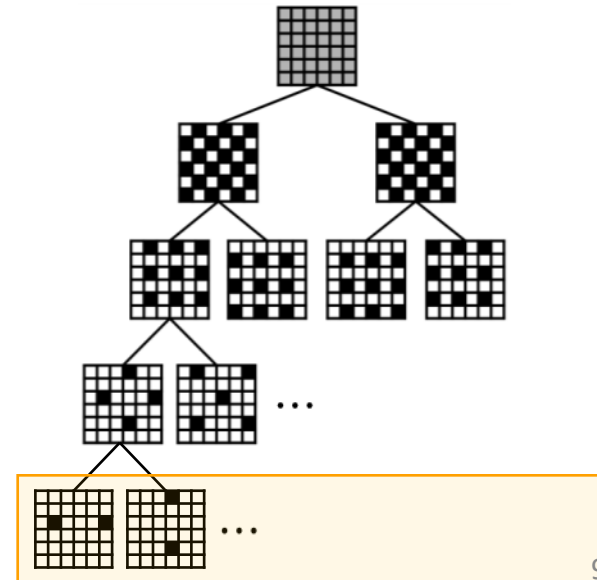
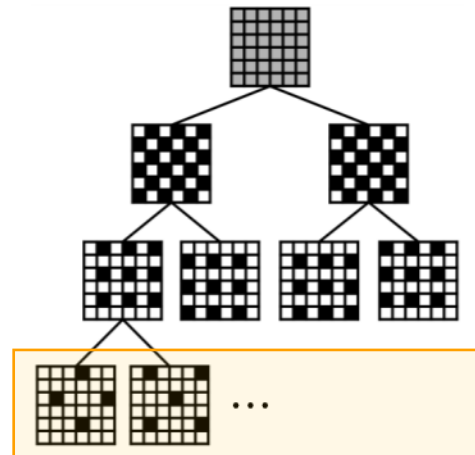
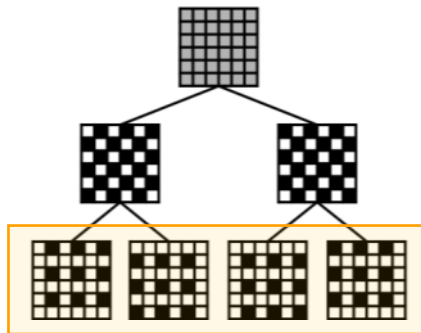
4 bands
(e.g. RGB-NIR)



8 bands

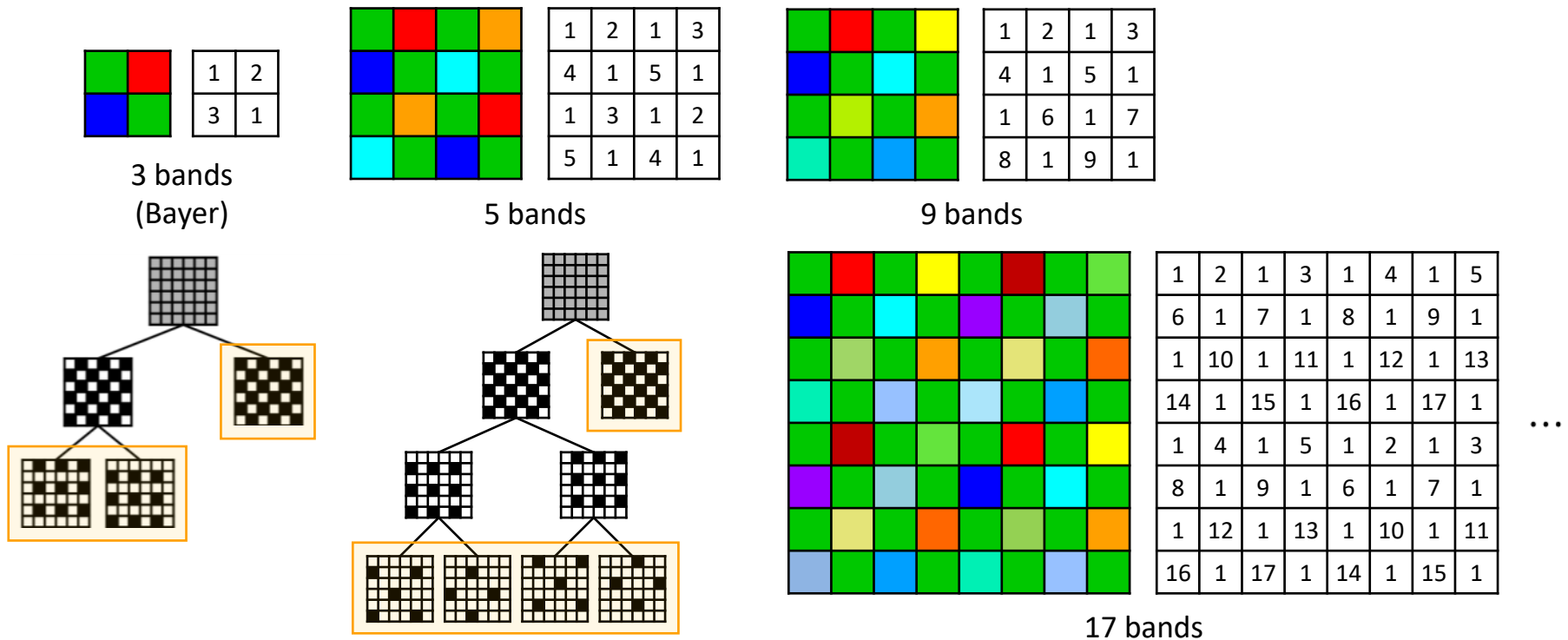


16 bands



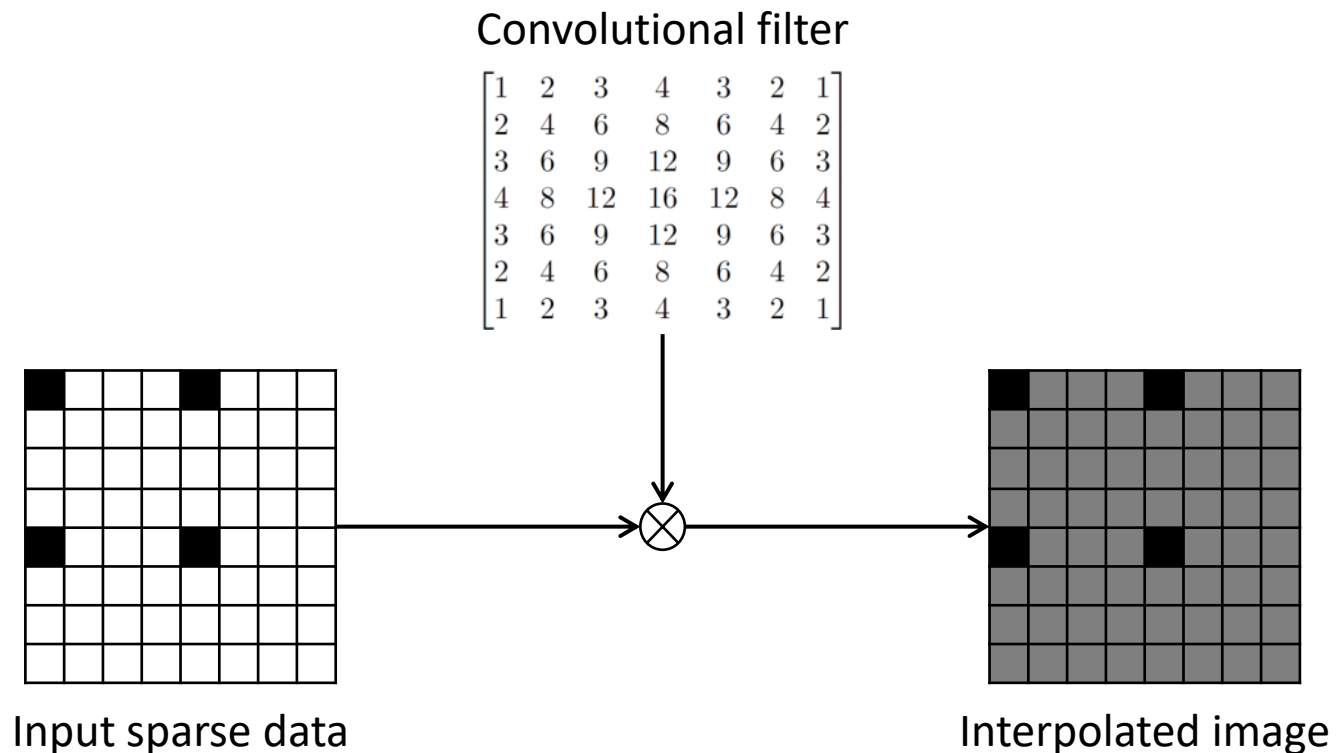
Two streams for SFA patterns

- Patterns with a dominant spectral band
 - Effective demosaicing when spectral correlations exist.



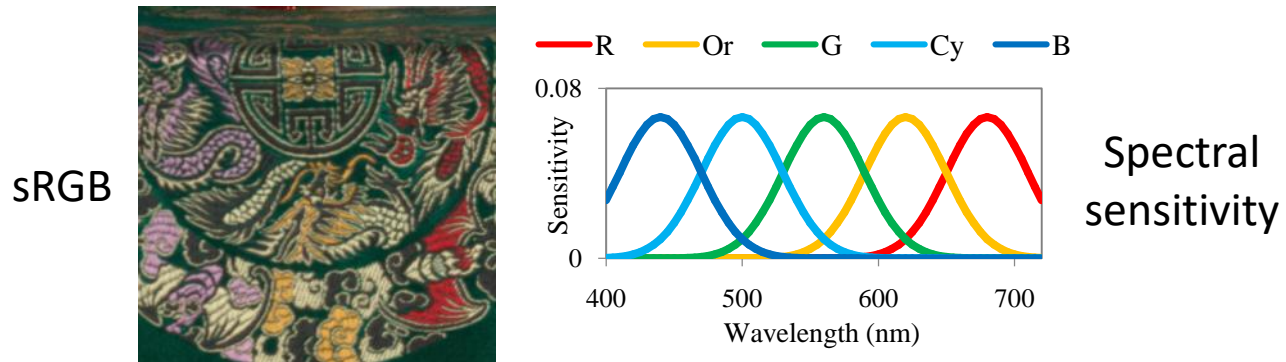
Demosaicing algorithm

- Channel-independent bilinear/bicubic interpolation
 - Only exploit spatial correlations.

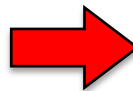


Common observation

- Spectral images generally have correlations.



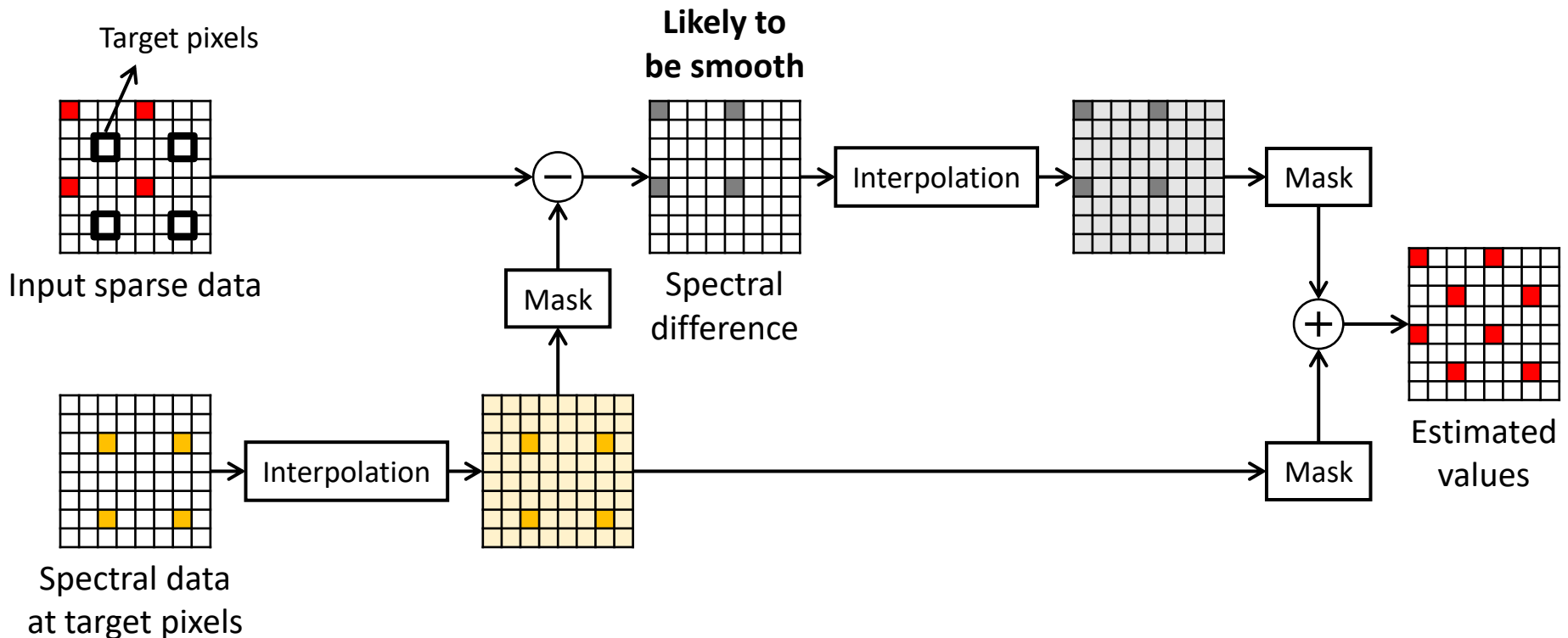
Spectral correlations



Similar textures or edges

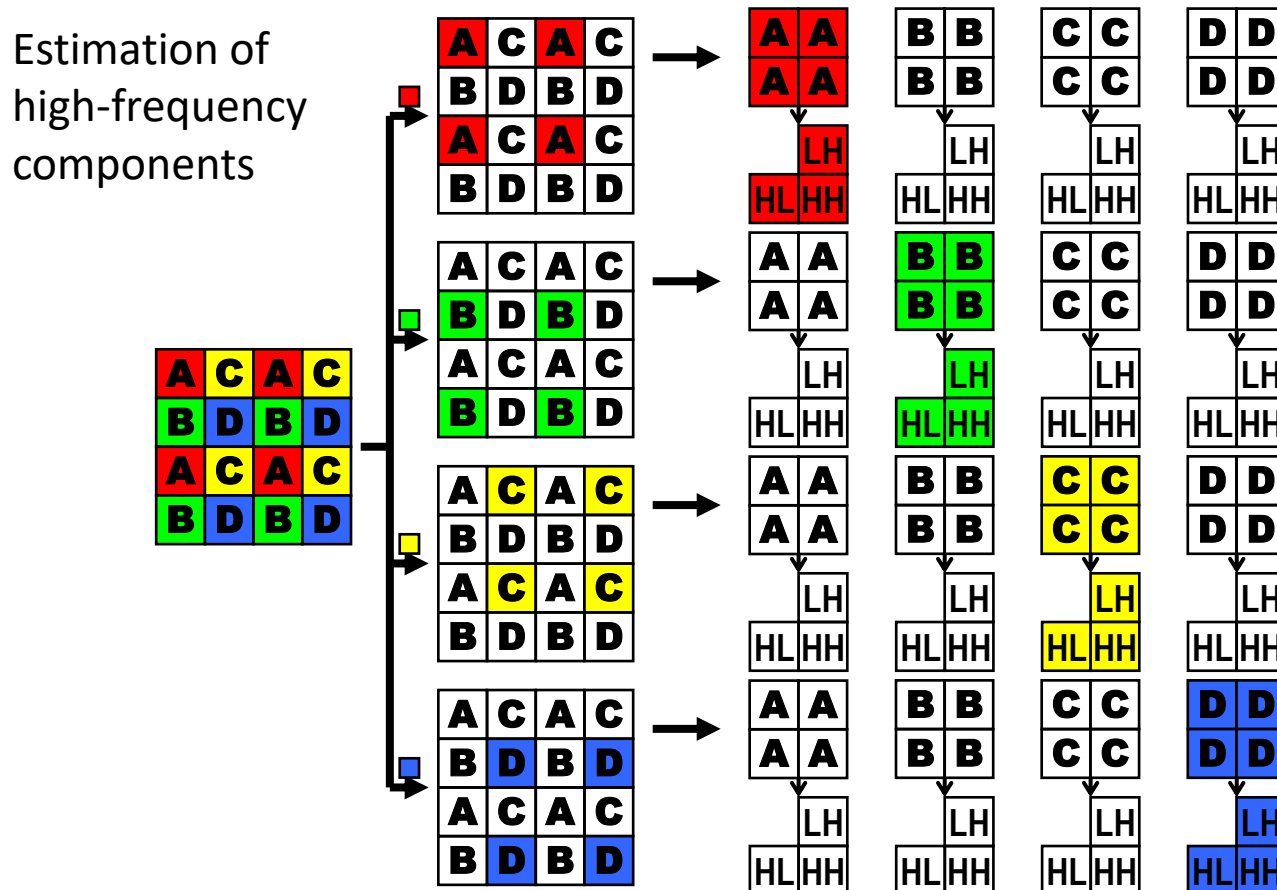
Demosaicing algorithm

- Spectral difference interpolation
 - Exploit spectral correlation as spectral difference.



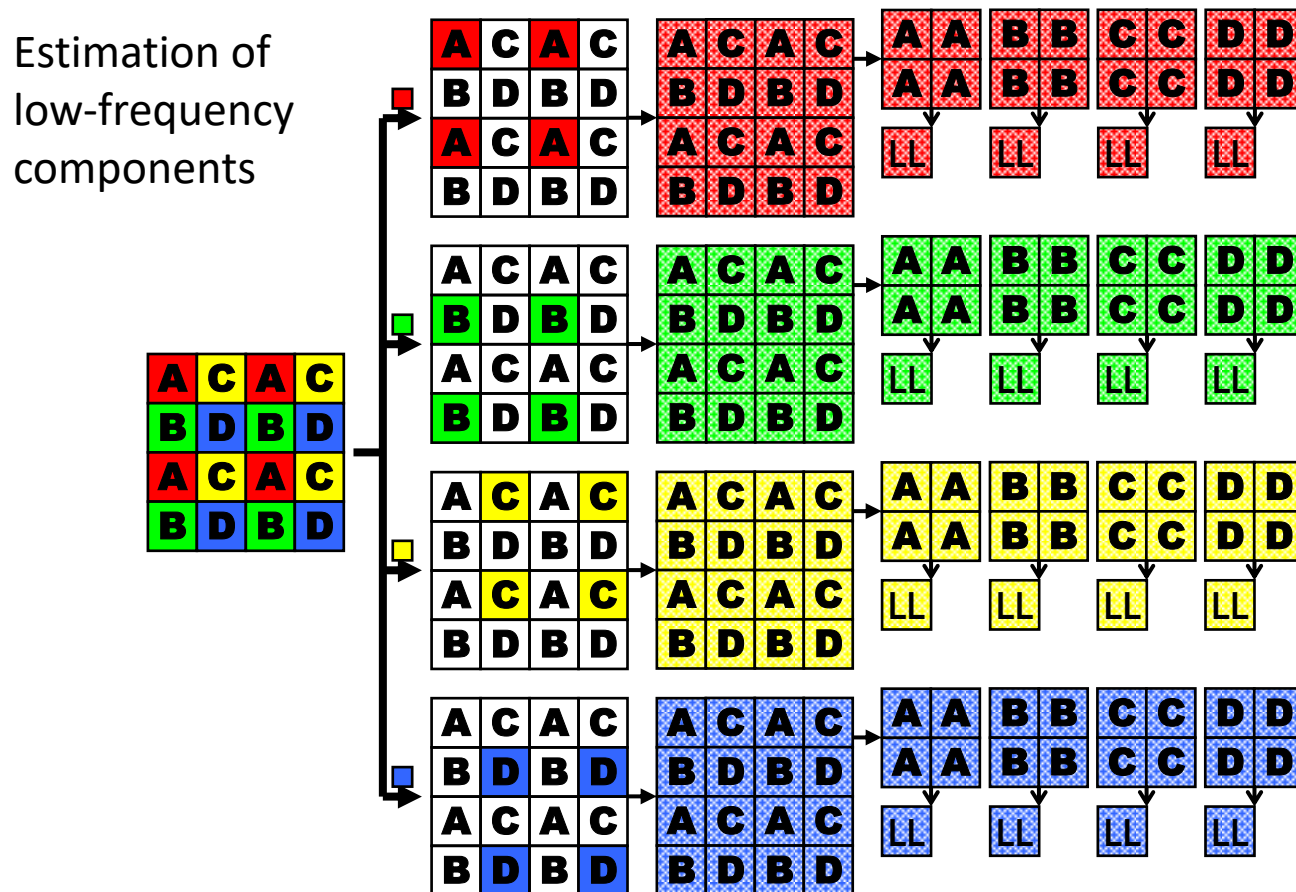
Demosaicing algorithm

- Discrete wavelet transform (DWT) based algorithm
 - Exploit spectral correlation in frequency domain



Demosaicing algorithm

- Discrete wavelet transform (DWT) based algorithm
 - Exploit spectral correlation in frequency domain

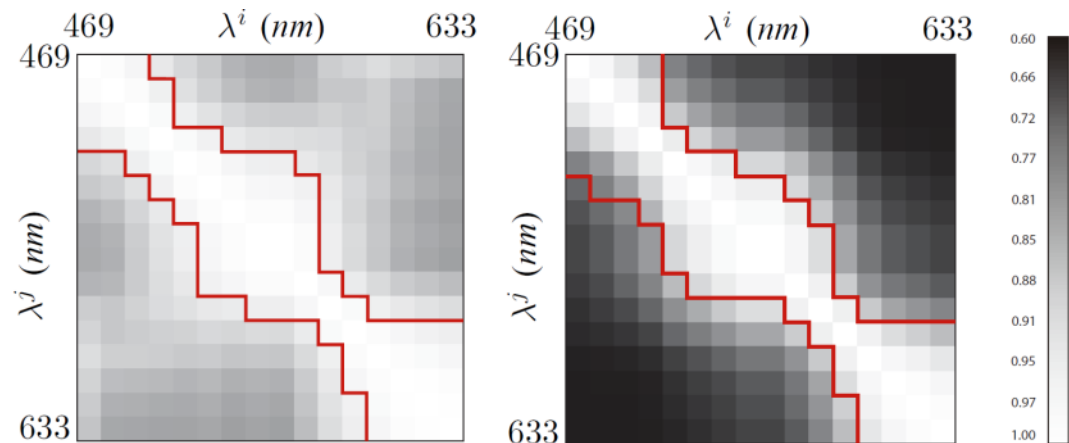


Demosaicing algorithm

- Use of a pseudo-panchromatic image
 - State-of-the-art for uniform SFA patterns

Spectral correlation analysis

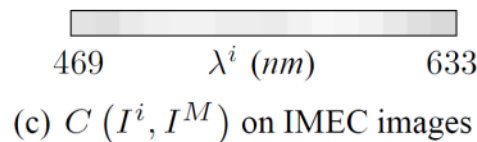
Each band
vs. each band



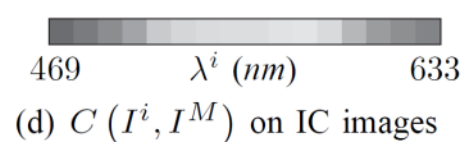
(a) $C(I^i, I^j)$ on IMEC images

(b) $C(I^i, I^j)$ on IC images

Each band
vs. panchromatic
(Luminance)



(c) $C(I^i, I^M)$ on IMEC images

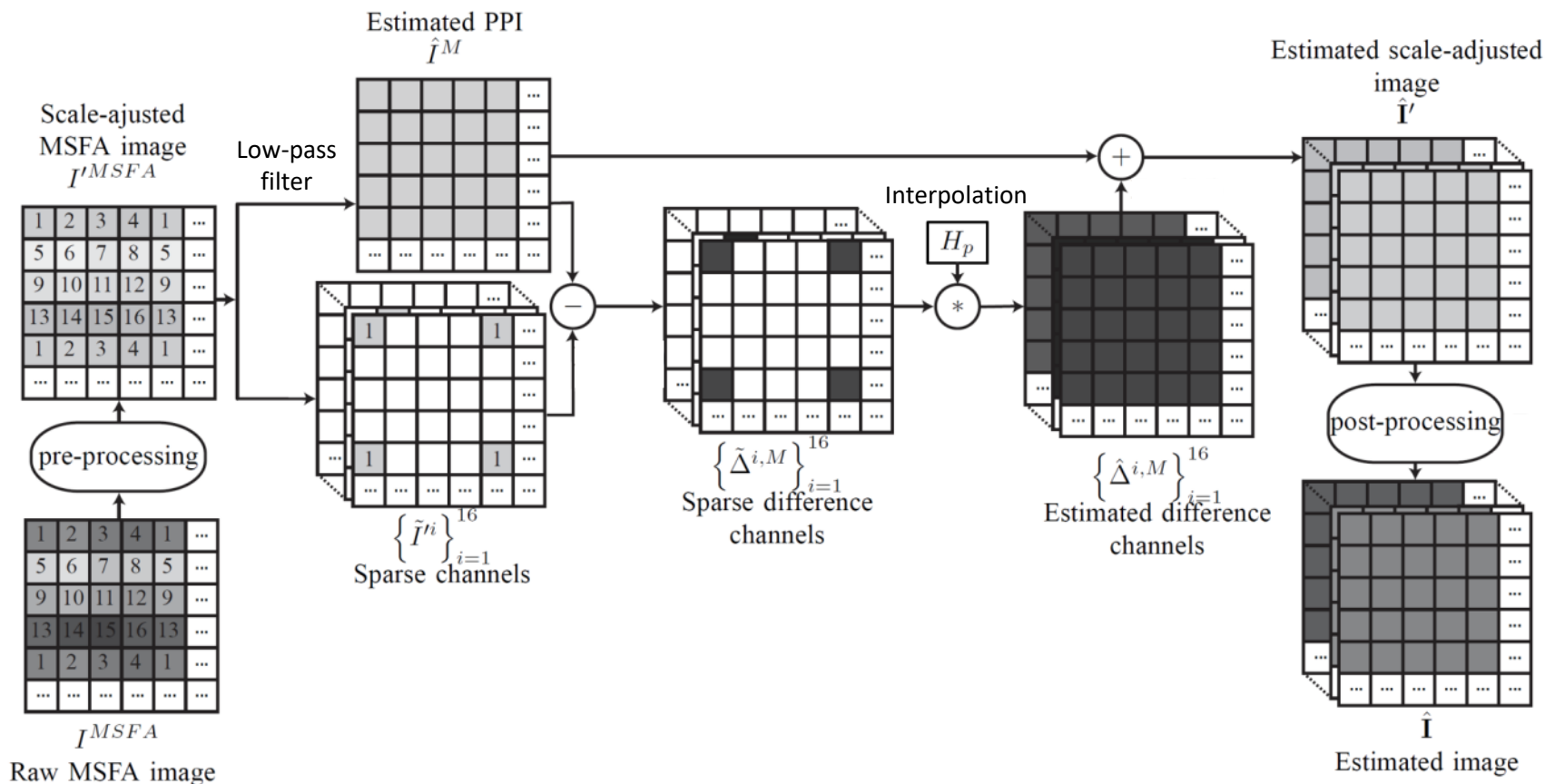


(d) $C(I^i, I^M)$ on IC images

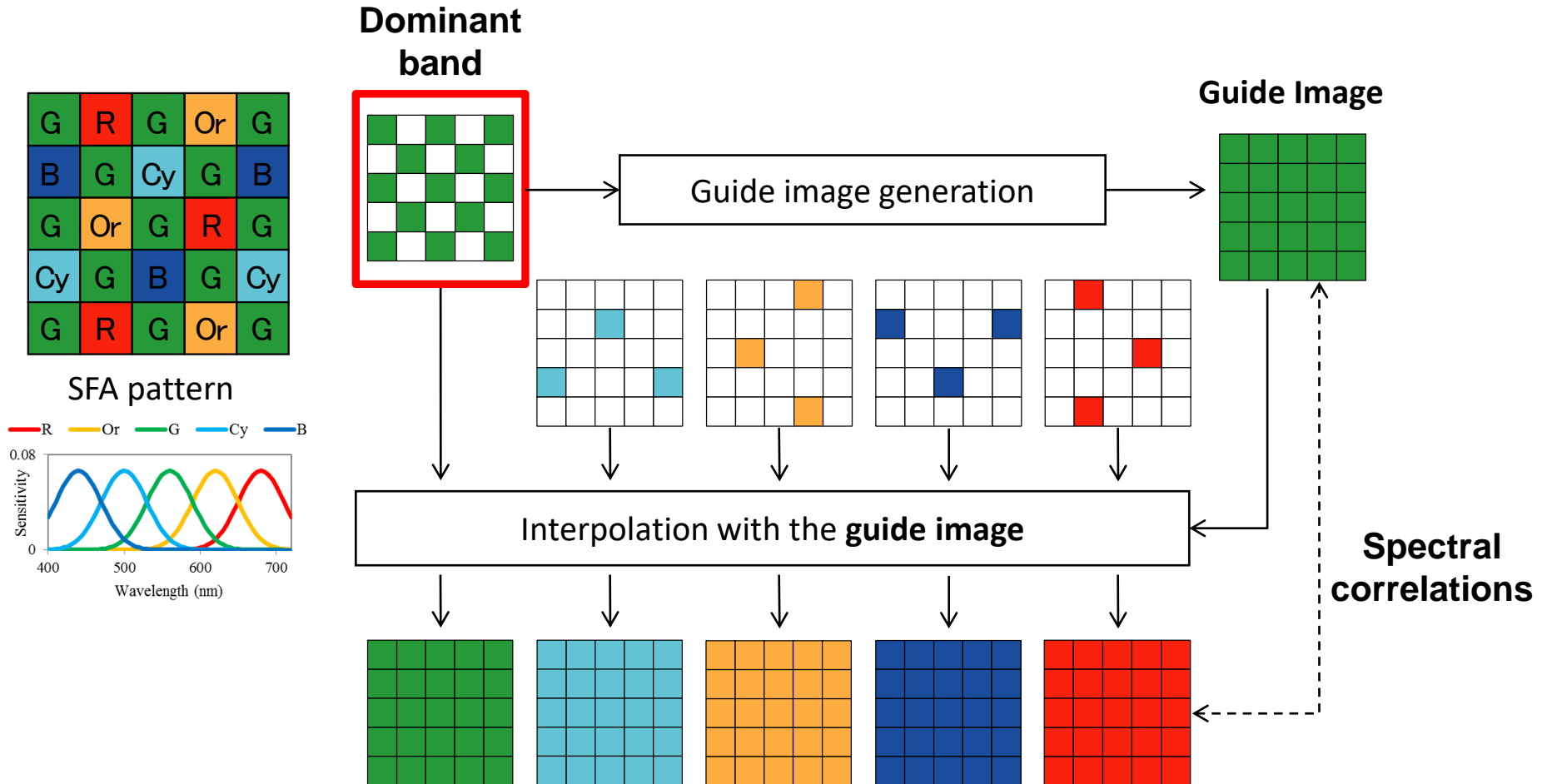
Finding: Panchromatic image has high spectral correlations with all bands

Demosaicing algorithm

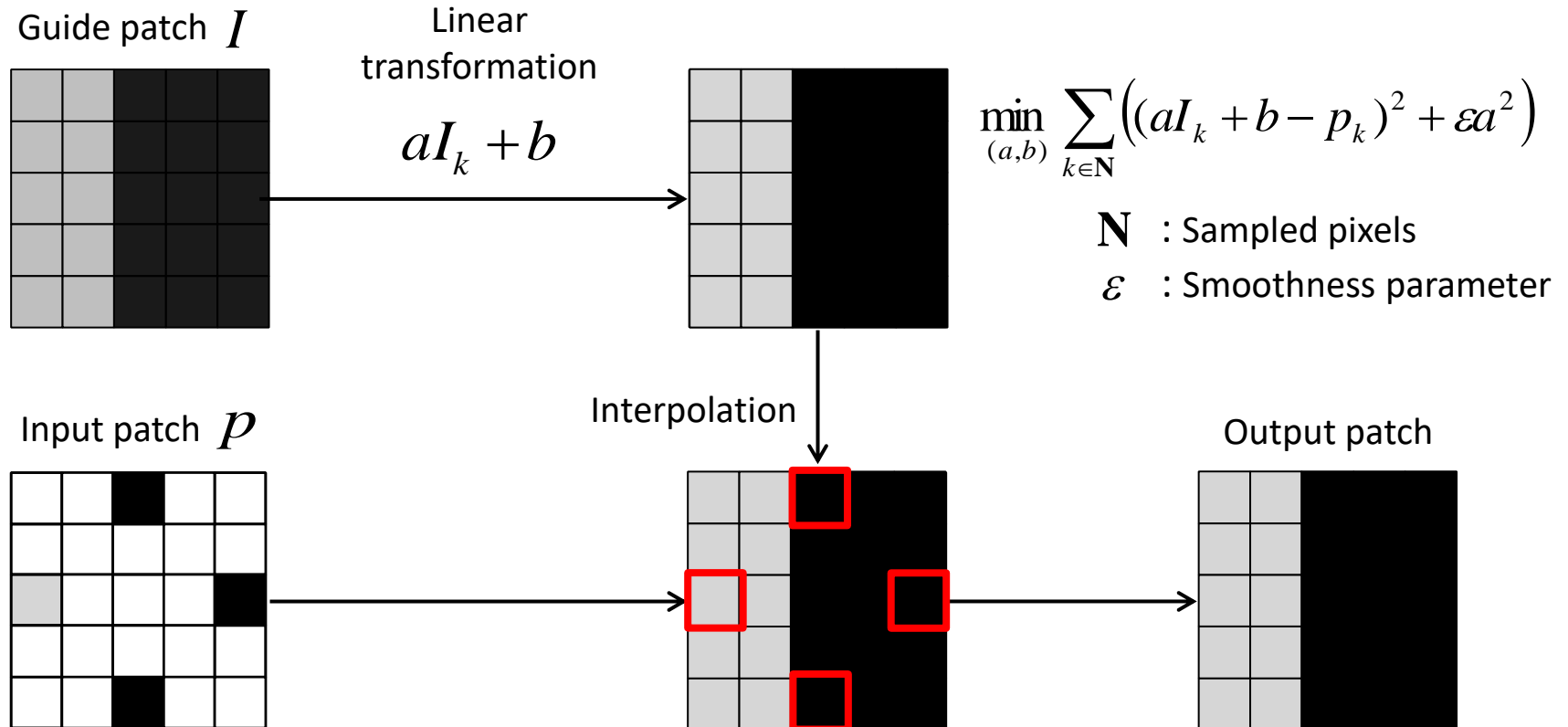
- Use of a pseudo-panchromatic image
 - State-of-the-art for uniform SFA patterns



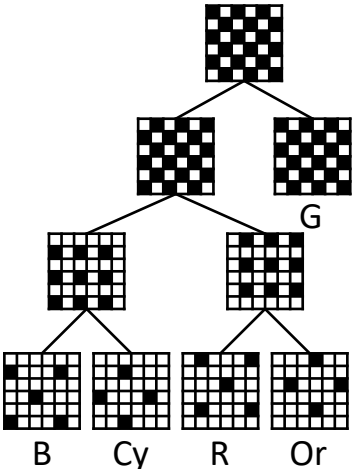
Demosaicing algorithm with a dominant spectral band



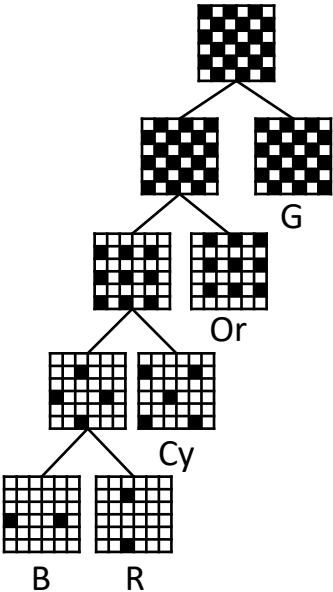
Interpolation by the guided filter



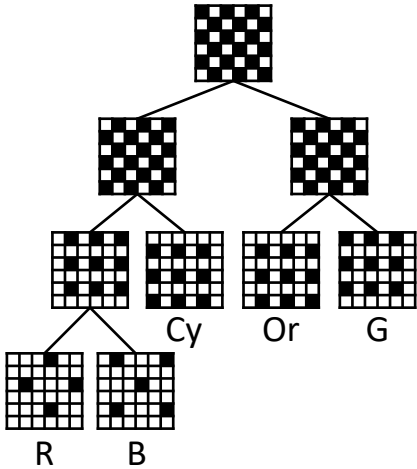
Comparison in the case of 5 bands



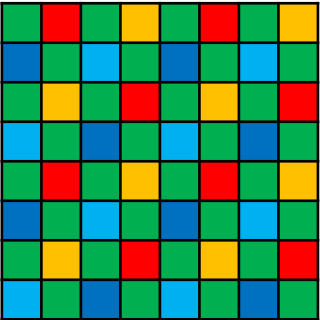
Binary tree for Monno's SFA



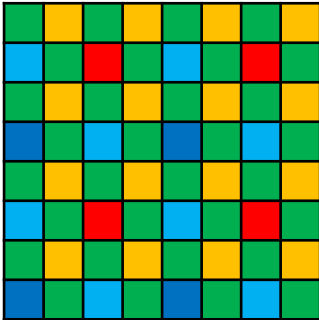
Binary tree for SFA2



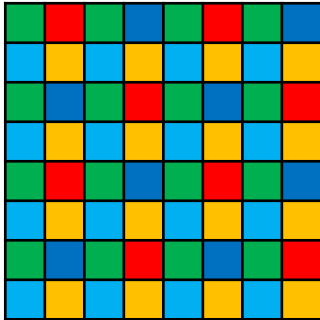
Binary tree for SFA3



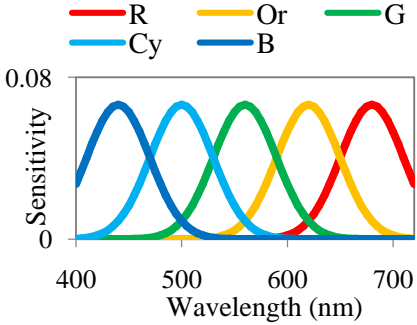
Monno's SFA



SFA2



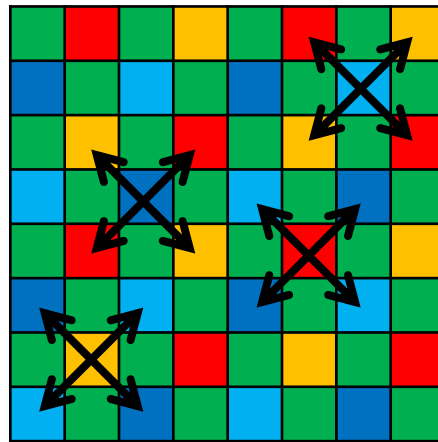
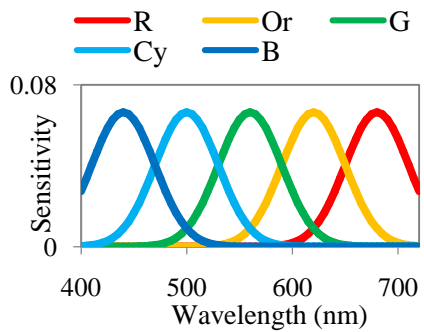
SFA3



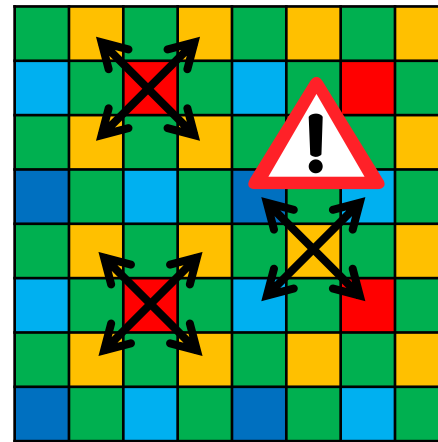
Spectral sensitivity

Properties of each SFA

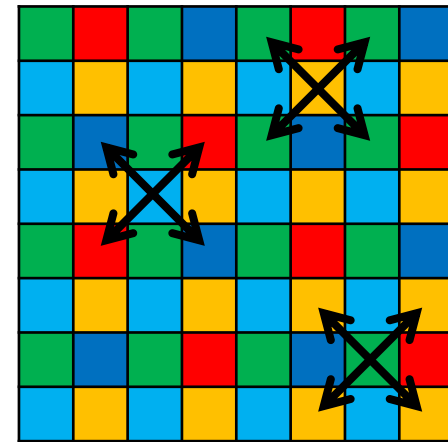
- Two design requirements



Monno's SFA



SFA2



SFA3

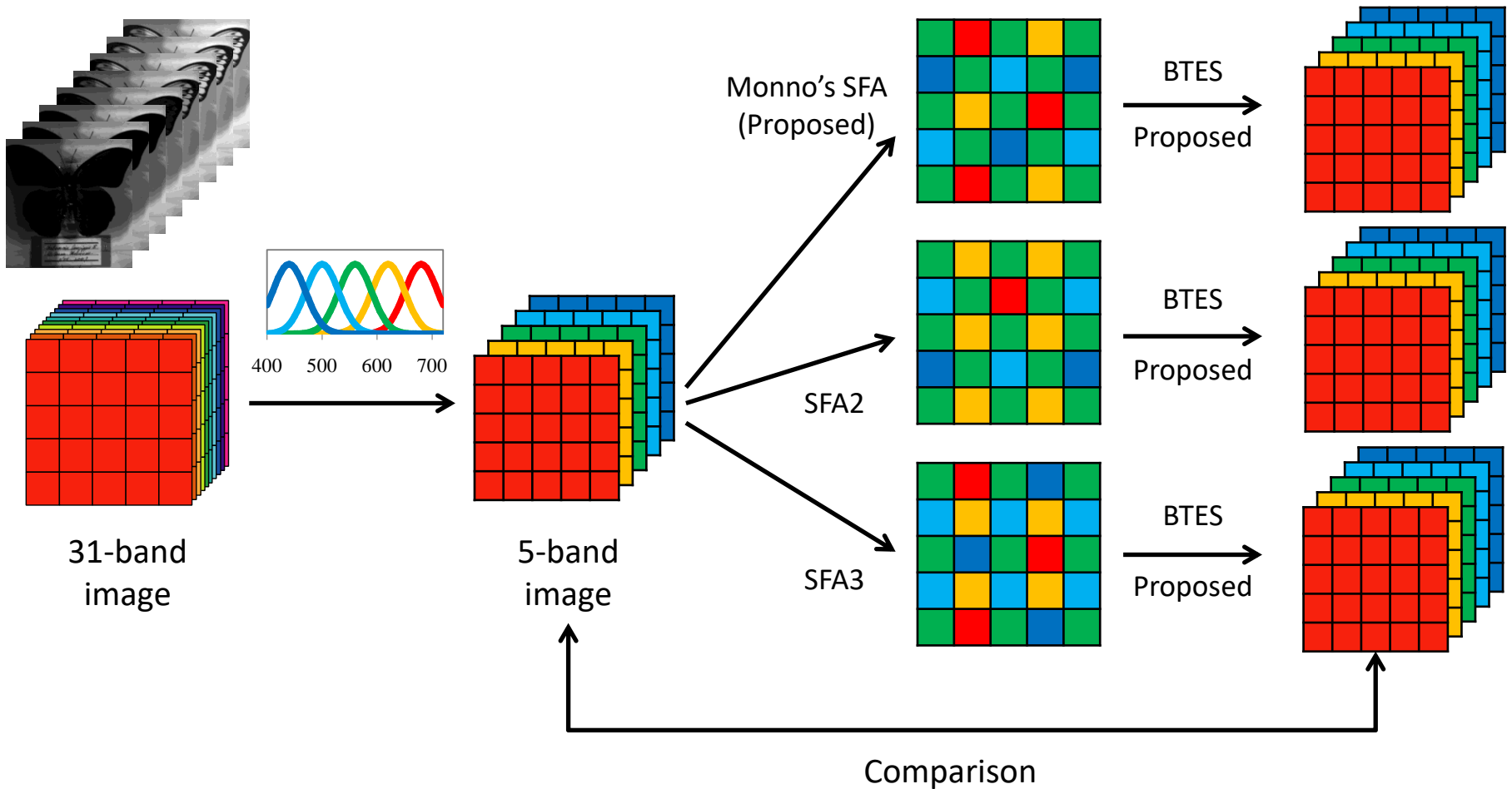
Density



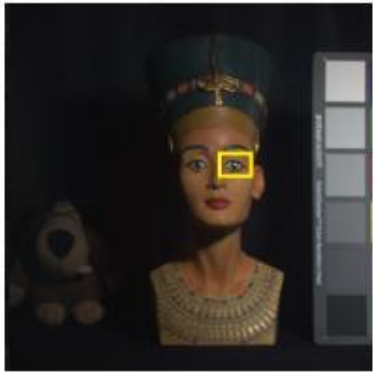
Derivative



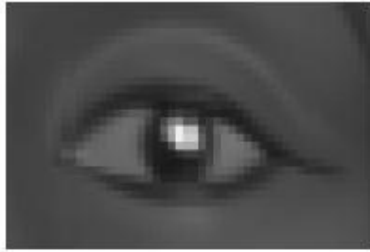
Experimental comparison



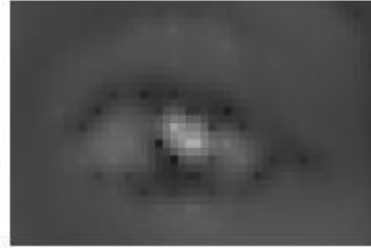
Results



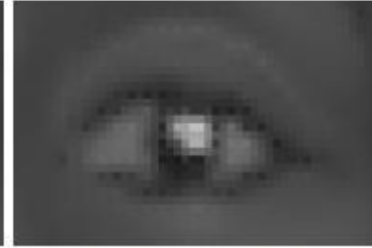
CAVE dataset:
Egyptian statue (sRGB)



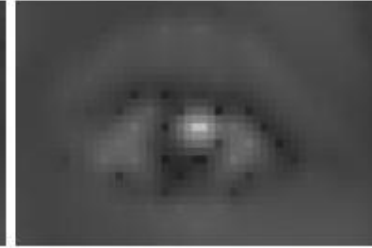
Ground truth (Cy band)



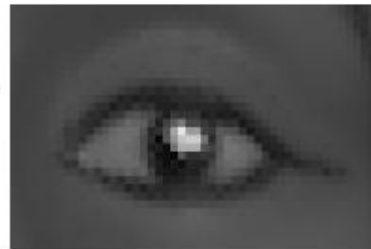
MSFA2 + BTES



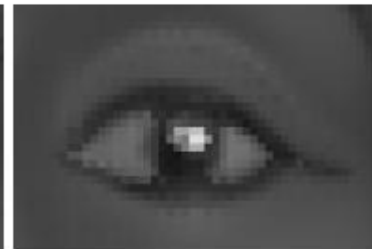
MSFA3 + BTES



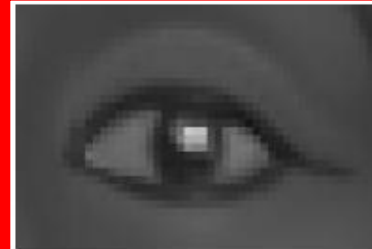
Pro. MSFA + BTES



MSFA2 + Pro. Algo.



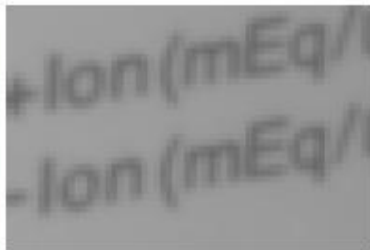
MSFA3 + Pro. Algo.



Pro. MSFA + Pro. Algo.



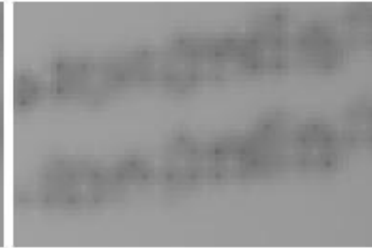
Our dataset:
Can (sRGB)



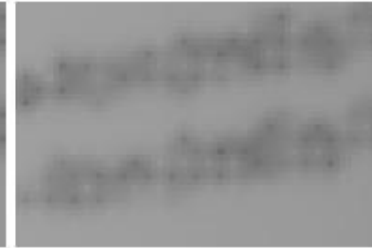
Ground truth (R band)



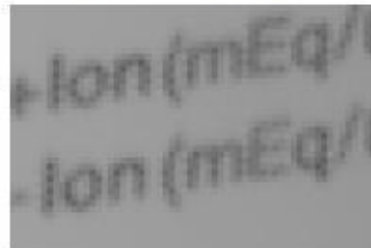
MSFA2 + BTES



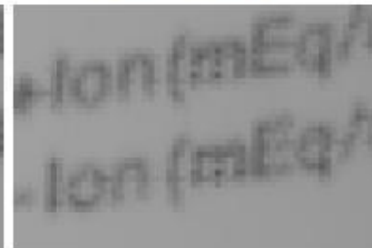
MSFA3 + BTES



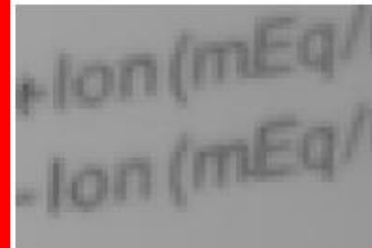
Pro. MSFA + BTES



MSFA2 + Pro. Algo.



MSFA3 + Pro. Algo.



Pro. MSFA + Pro. Algo.

Results

- Average PSNR for CAVE (32 scenes) and Our (30 scenes) datasets

Light	Data	MSFA pattern	Algo.	PSNR R	PSNR Or	PSNR G	PSNR Cy	PSNR B	5band PSNR Ave.		
D65	CAVE	Pro.	BTES	42.60	39.41	46.54	37.83	40.46	41.37		
			Pro.	45.36	44.76	48.06	44.68	43.96	45.36		
		MSFA2	BTES	39.26	42.11	46.54	37.84	37.30	40.61		
			Pro.	43.59	45.02	45.71	43.09	41.81	43.85		
		MSFA3	BTES	42.59	42.04	40.90	40.28	40.54	41.27		
			Pro.	44.70	42.92	41.43	41.27	41.78	42.42		
		D65	Our	Pro.	BTES	38.27	37.05	45.51	36.34	39.11	39.26
					Pro.	43.82	43.28	46.57	42.92	43.62	44.04
MSFA2	BTES			34.71	40.81	45.51	36.31	35.49	38.57		
	Pro.			42.28	43.83	44.63	42.03	41.99	42.95		
MSFA3	BTES			38.30	40.84	39.72	40.14	39.24	39.65		
	Pro.			42.17	41.30	40.34	40.49	42.12	41.28		

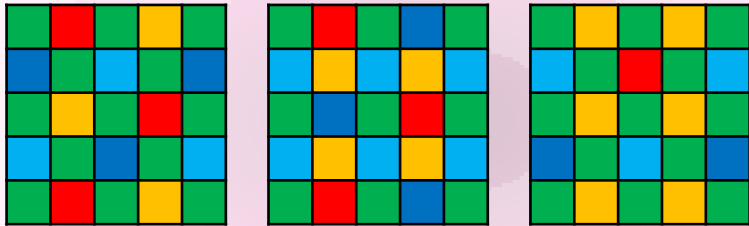
Finding: Jointly designing the SFA pattern and algorithm can provide superior performance.

Other demosaicing algorithms

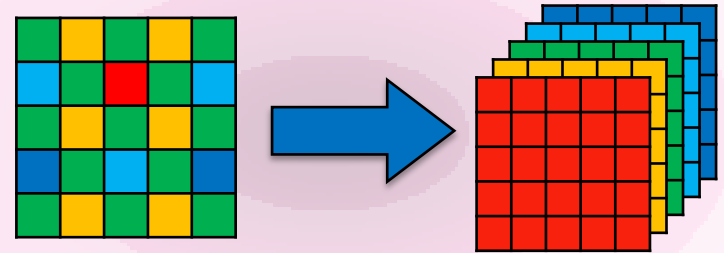
- Iterative spectral difference interpolation
 - Mizutani et al., “Multispectral demosaicking algorithm based on inter-channel correlation,” IEEE VCIP, 2014.
- Multispectral local directional interpolation
 - Shinoda et al., “Multispectral filter array and demosaicking for pathological images,” APSIPA Annual Summit and Conference, 2015.
- Interpolation with learned weights
 - Aggarwal and Majumdar, “Single-sensor multi-spectral image demosaicing algorithm using learned interpolation weight,” IEEE IGARSS, 2014.
- Multispectral residual interpolation
 - Monno et al., “Multispectral demosaicking with novel guide image generation and residual interpolation,” IEEE ICIP, 2014.
- Adaptive multispectral demosaicing
 - Jaiswal et al., “Adaptive multispectral demosaicking based on frequency-domain analysis of spectral correlation,” IEEE TIP, 2017.
- Demosaicing for Fourier spectral filter array
 - Jia et al., “Guided filter demosaicking for Fourier spectral filter array,” IS&T EI, 2016.
- N-LMMSE demosaicing
 - P. Amba, J-B. Thomas, and D. Alleysson, “N-LMMSE demosaicing for spectral filter arrays”, to appear in JIST and CIC, 2017.

Main components of SFA camera

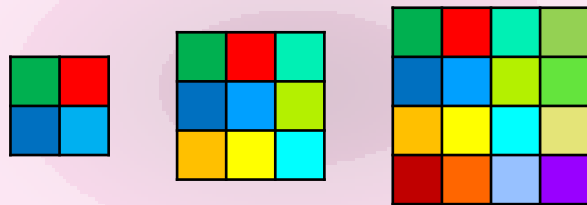
SFA pattern



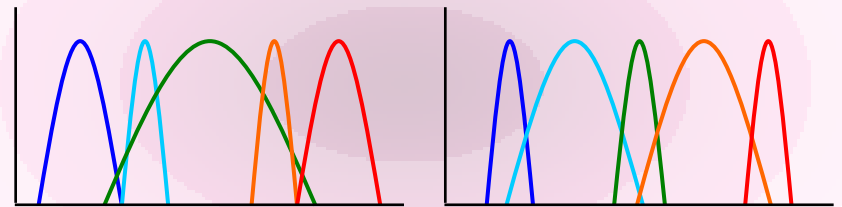
Demosaicing algorithm



Number of spectral bands



Spectral sensitivity

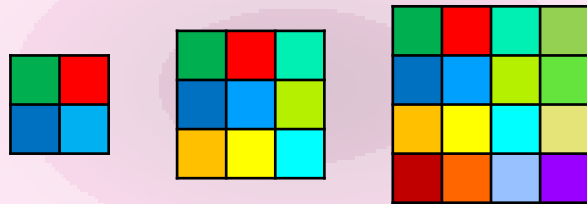


Spectral sensitivity design and number of spectral bands

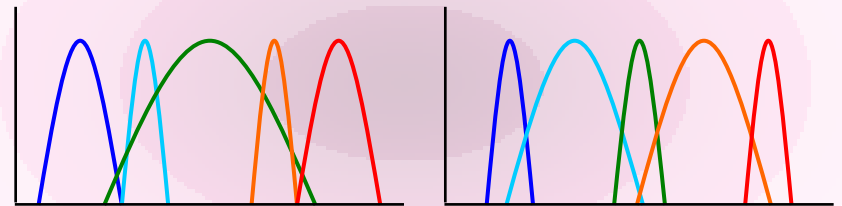
- They heavily depend on applications.
- Evaluation can be performed using hyperspectral image dataset.



Number of spectral bands



Spectral sensitivity



Public hyperspectral datasets

- TokyoTech dataset

- <http://www.ok.sc.e.titech.ac.jp/res/MSI/MSIdata31.html>
- Colorful objects with rich textures 30 scenes from 420nm to 720nm at 10nm intervals



Other hyperspectral datasets in visible domain

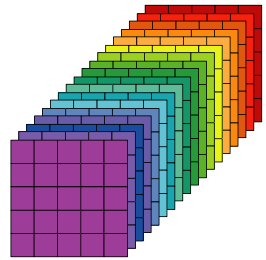
- Bristol hyperspectral images dataset
 - http://www.cvc.uab.es/color_calibration/Bristol_Hyper/
- Harvard real-world hyperspectral images
 - <http://vision.seas.harvard.edu/hyperspec/>
- UAE multispectral image database
 - <http://colour.cmp.uea.ac.uk/datasets/multispectral.html>
- NUS hyperspectral images database
 - http://www.comp.nus.edu.sg/~whitebal/spectral_reconstruction/
 - <https://sites.google.com/site/hyperspectralcolorimaging/dataset>
- Manchester hyperspectral images
 - <http://personalpages.manchester.ac.uk/staff/david.foster/default.html>

Other hyperspectral datasets in visible – NIR domain

- ICVL hyperspectral database
 - <http://icvl.cs.bgu.ac.il/hyperspectral/>
- University of Granada hyperspectral image database
 - <http://colorimaginglab.ugr.es/pages/Data>
- Stanford SCIEN hyperspectral image data
 - <https://scien.stanford.edu/index.php/hyperspectral-image-data/>

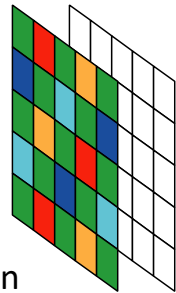
Spectral sensitivity design

Scene reflectance
(dataset)



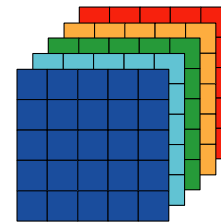
Simulation

SFA pattern



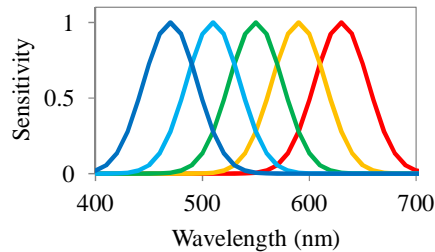
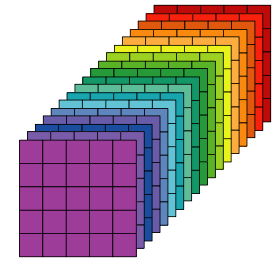
Demosaicking

Multispectral
image



Reflectance
estimation

Estimated scene
reflectance

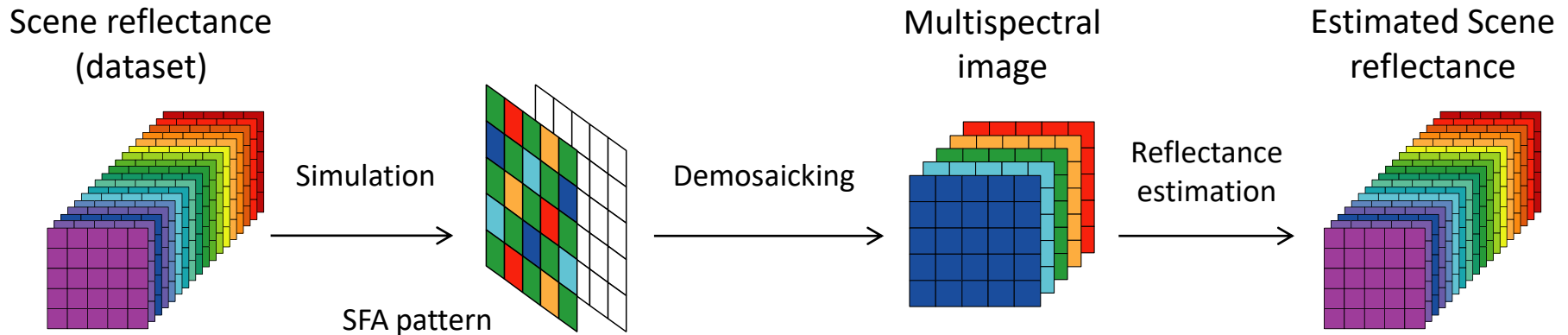


Spectral sensitivity functions
(SSFs)

Find optimal SSFs

Minimize some cost function
(sRGB or spectral)

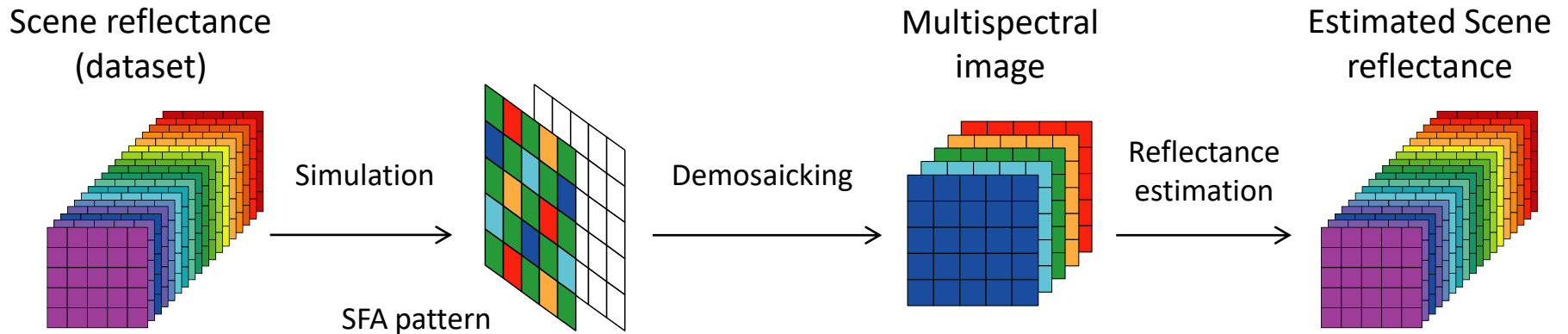
Spectral sensitivity design



Find optimal SSFs

- Analytically solve the problem by assuming linear CFA demosaicing
 - Parmar and Reeves, “Selection of optimal spectral sensitivity functions for color filter array,” IEEE TIP, 2010.
 - Sadeghipoor et al., “Optimum spectral sensitivity functions for single sensor color imaging,” SPIE/IS&T EI, 2012.

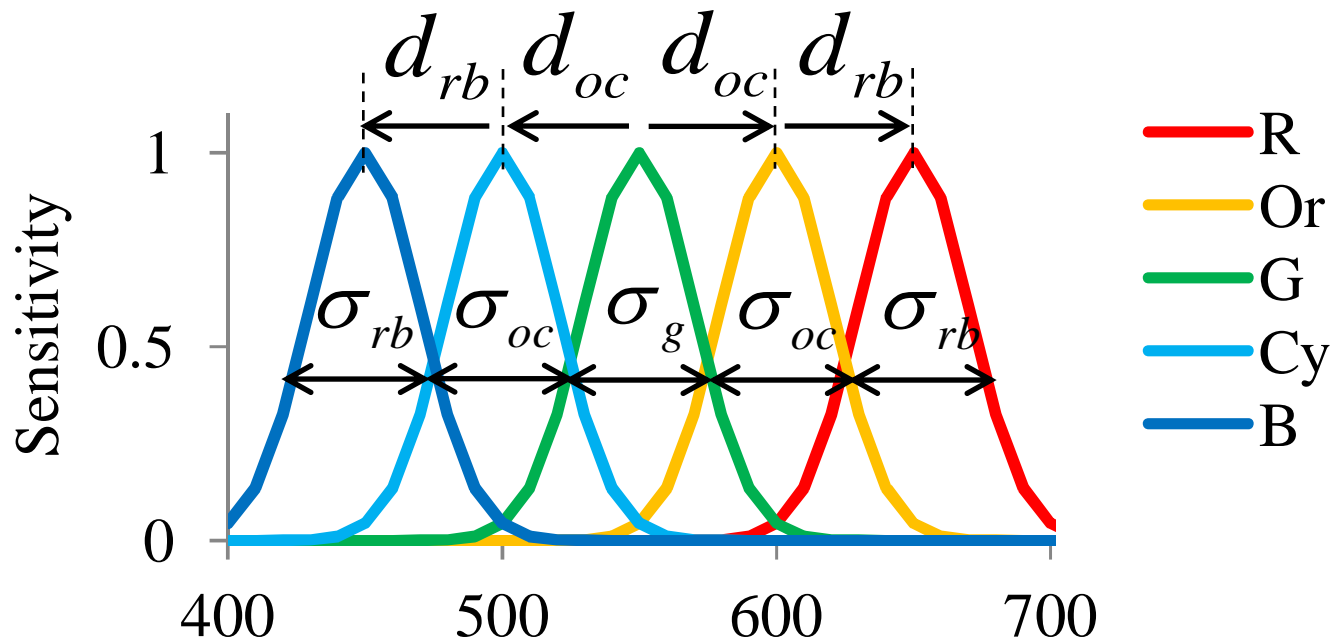
Spectral sensitivity design



Find optimal SSFs

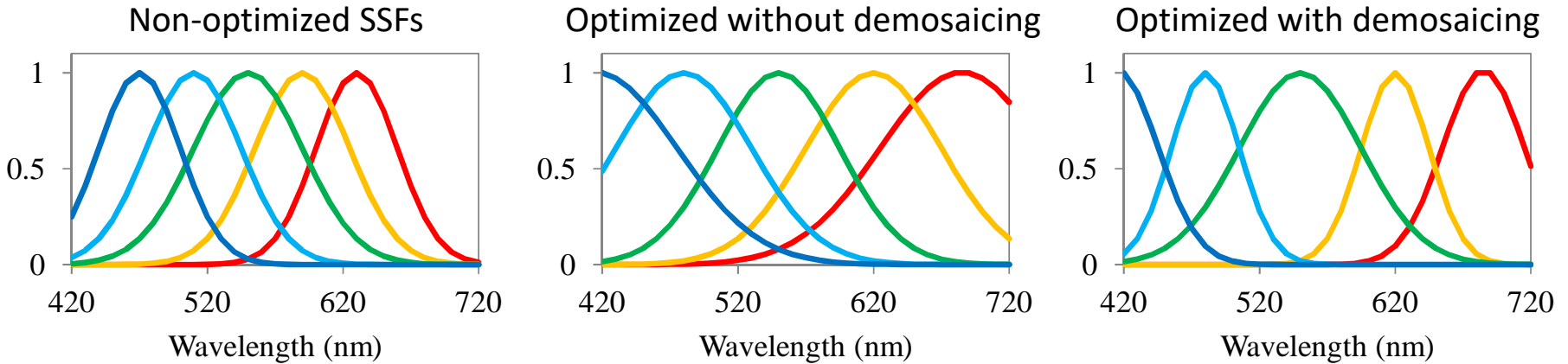
- Parameterize SSFs and find optimal parameters
- Include high-performance non-linear demosaicking algorithm
 - Monno et al., “Optimal spectral sensitivity functions for a single-camera one-shot multispectral imaging system,” IEEE ICIP, 2012.

- Often performed by Gaussian functions (but may not be perfect).

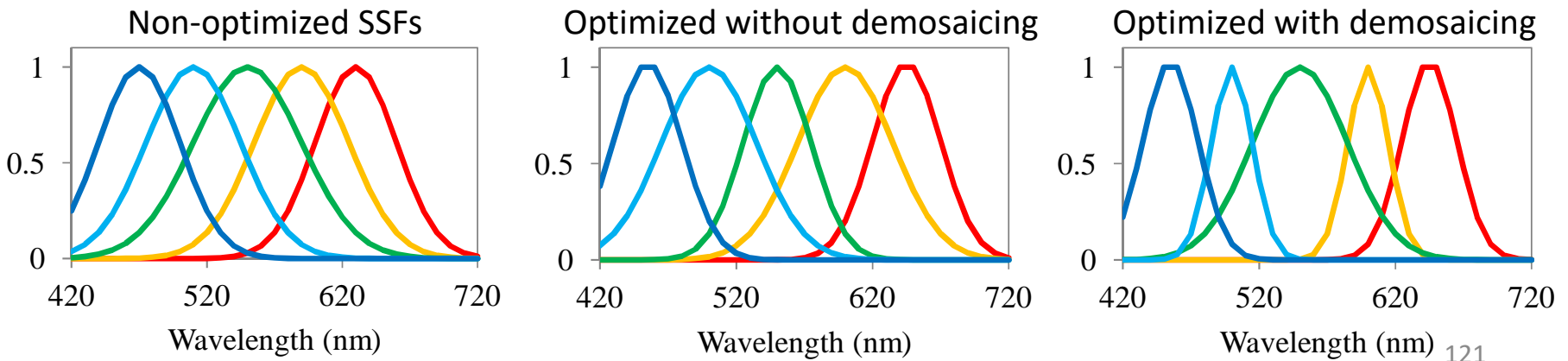


Some results for the 5-band case

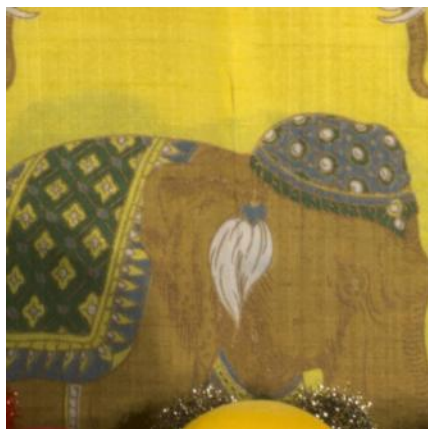
- Optimized for spectral reflectance recovery



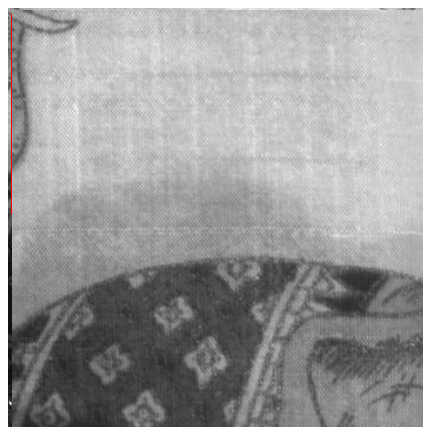
- Optimized for sRGB image acquisition



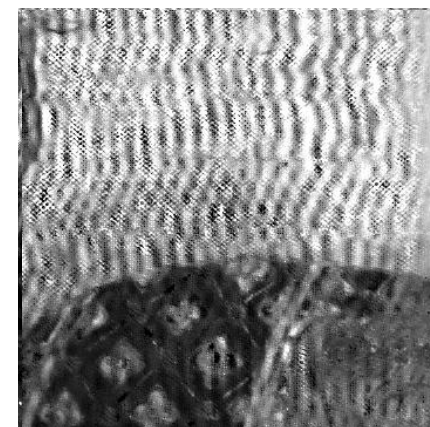
- Reflectance images (700nm)



Ground truth (sRGB)



Ground-truth



Non-optimized



Optimized without
demosaicing



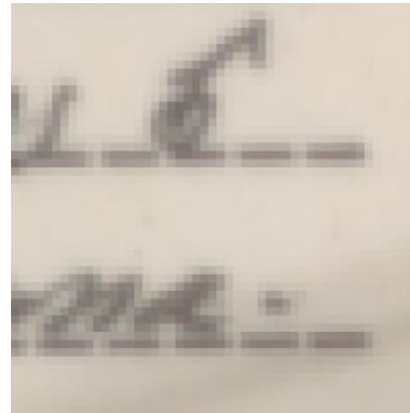
Optimized with
demosaicing

Results

- sRGB image



Ground truth (sRGB)



Ground-truth



Non-optimized



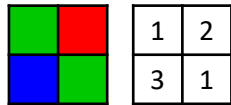
Optimized without demosaicing



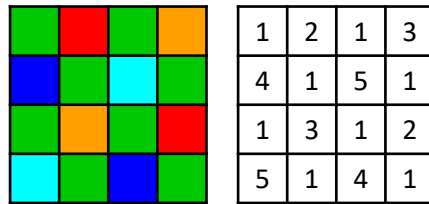
Optimized with demosaicing

Optimal number of spectral bands

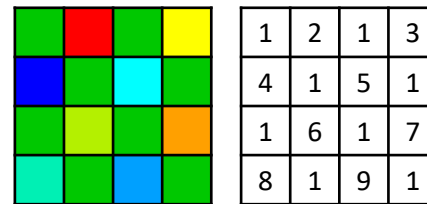
- Analysis for the Monno SFA case.



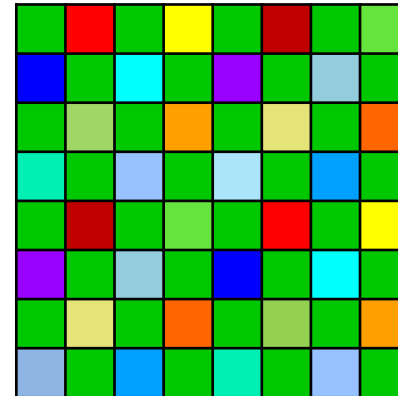
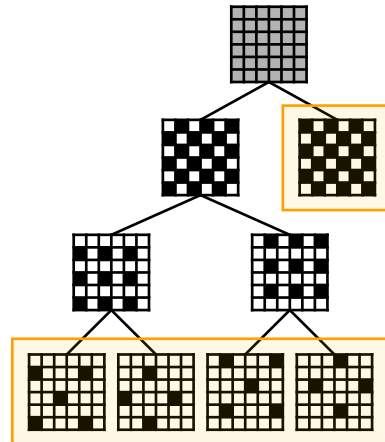
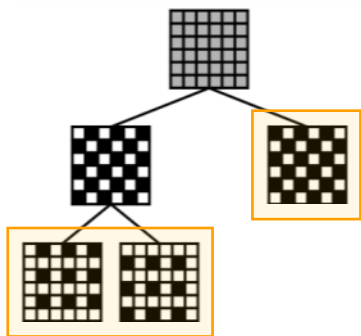
3 bands
(Bayer)



5 bands



9 bands



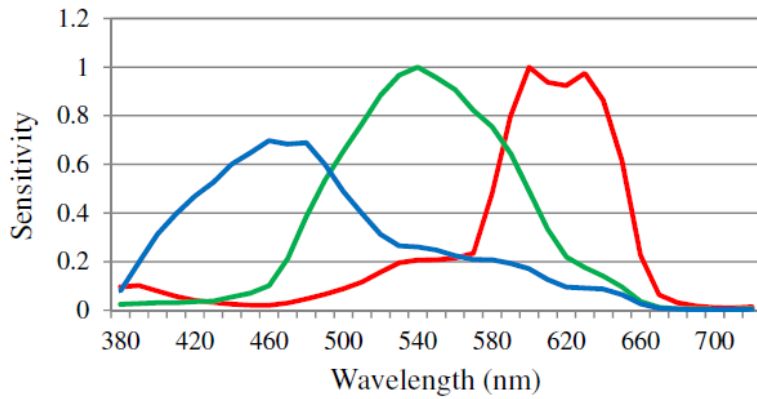
17 bands

1	2	1	3	1	4	1	5
6	1	7	1	8	1	9	1
1	10	1	11	1	12	1	13
14	1	15	1	16	1	17	1
1	4	1	5	1	2	1	3
8	1	9	1	6	1	7	1
1	12	1	13	1	10	1	11
16	1	17	1	14	1	15	1

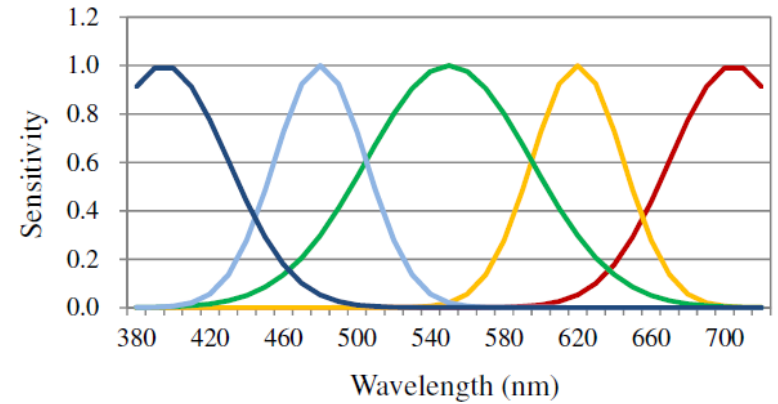
...



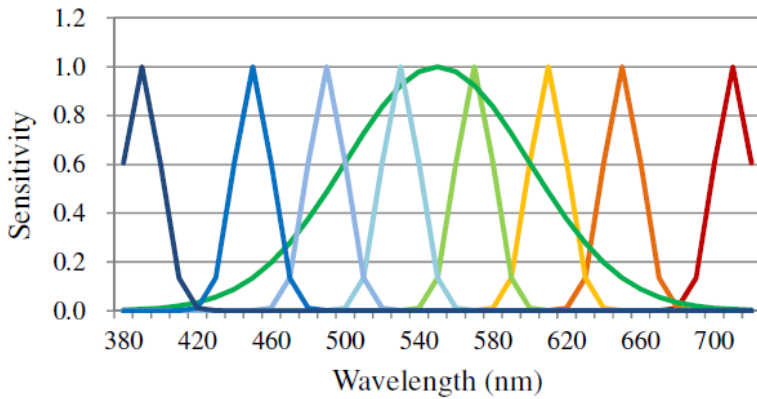
Optimized SSFs



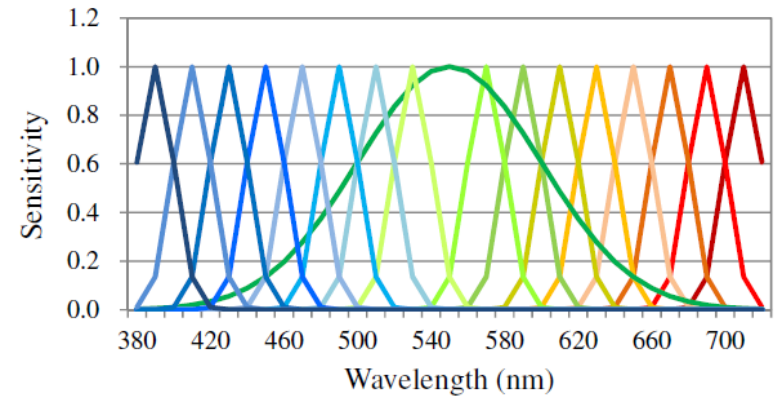
3 band (Standard SSFs)



Optimized 5 band



Optimized 9 band



Optimized 17 band

- Average PSNR comparison (31 band)



Doll

Image with rich textures

Scene	Bayer	5-band	9-band	17-band
Butterfly	27.88	33.75	35.29	32.88
Can	26.53	30.37	32.69	30.27
Doll	28.81	34.23	35.14	30.27
Origami	35.71	38.13	39.69	35.54
Color	31.17	35.45	42.80	42.93
SGchart	32.16	40.46	48.39	49.24
Tabasco	29.07	33.33	34.03	32.78
Flower	32.44	36.58	44.12	41.66
Wool	32.50	38.19	39.28	38.61
Average	30.70	35.61	39.05	37.55



Color



Flat images

SGchart

- Performance for relighting



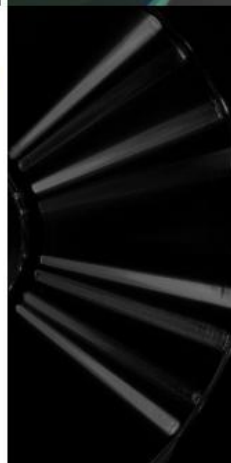
(a) Image under incandescent



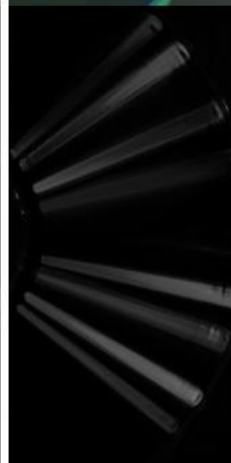
(b) Image under D65



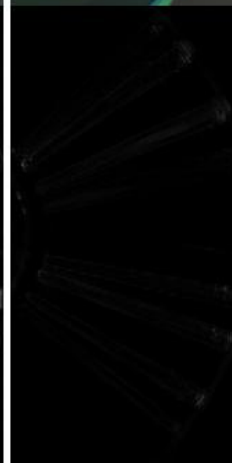
(g) 31-band
(Ground truth)



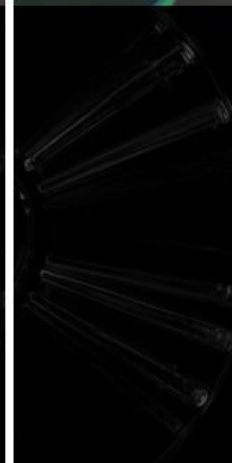
(h) 3-band



(i) 5-band



(j) 9-band



(k) 17-band₁₂₇

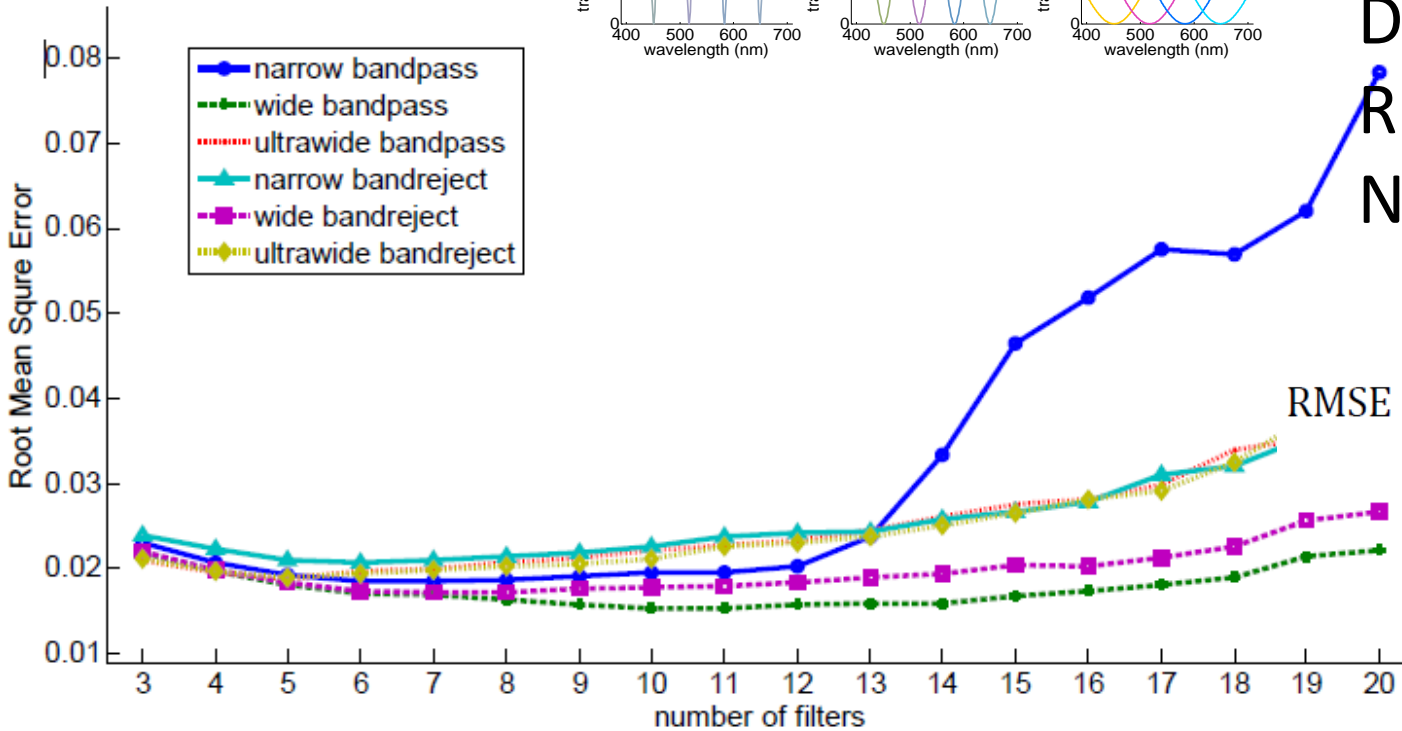
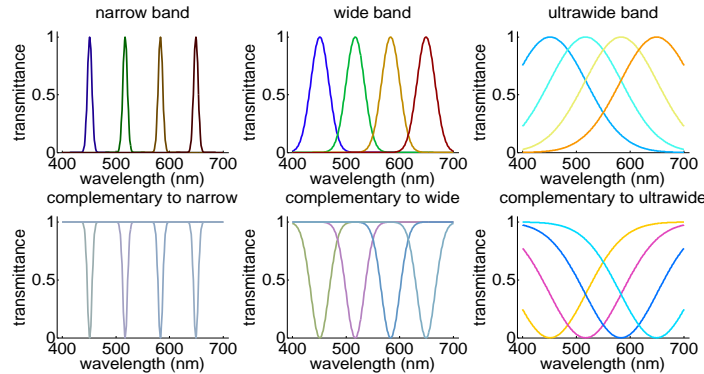
Sensitivities

Foster+CAVE

D65

RMSE VS

Number fo filters



$$RMSE = \sqrt{\frac{\sum_{j=1}^{301} |R(\lambda_j) - R'(\lambda_j)|^2}{301}}$$

"Multispectral imaging: narrow or wide band filters?", Xingbo Wang, Jean-Baptiste Thomas, Jon Yngve Hardeberg, Pierre Gouton. *Journal of the international colour association*, 2014, 12, pp.44-51

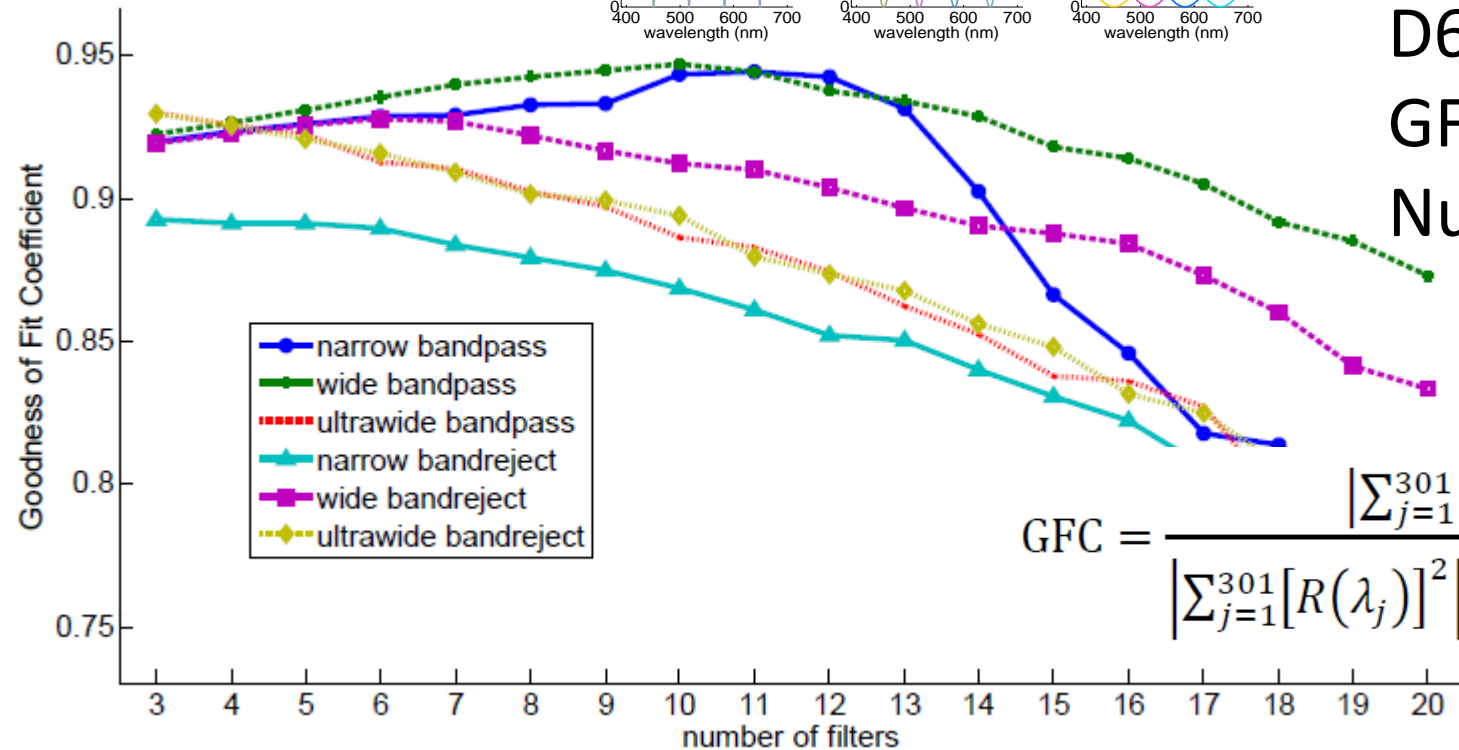
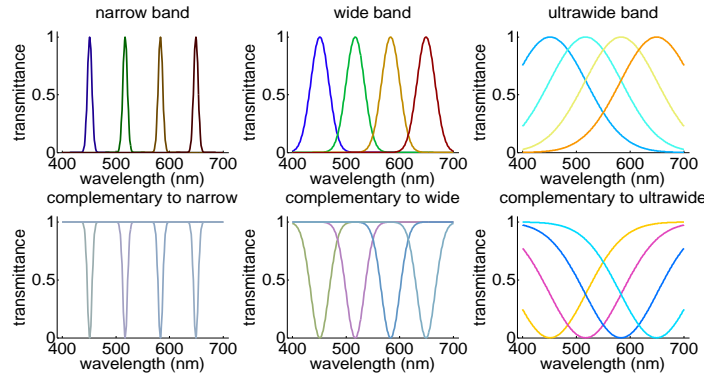
Sensitivities

Foster+CAVE

D65

GFC VS

Number of filters

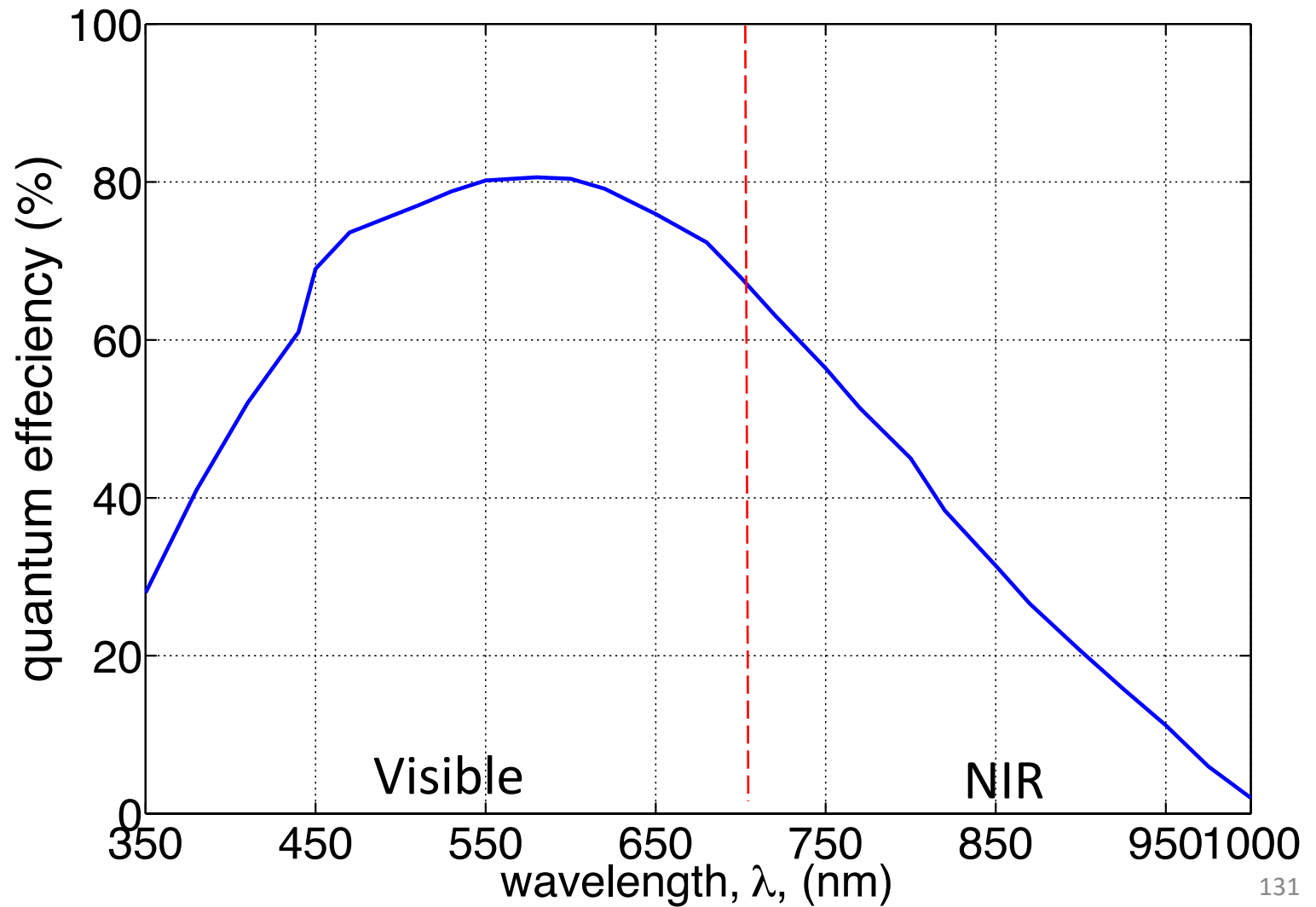


$$GFC = \frac{|\sum_{j=1}^{301} R(\lambda_j)R'(\lambda_j)|}{|\sum_{j=1}^{301}[R(\lambda_j)]^2|^{1/2} |\sum_{j=1}^{301}[R'(\lambda_j)]^2|^{1/2}}$$

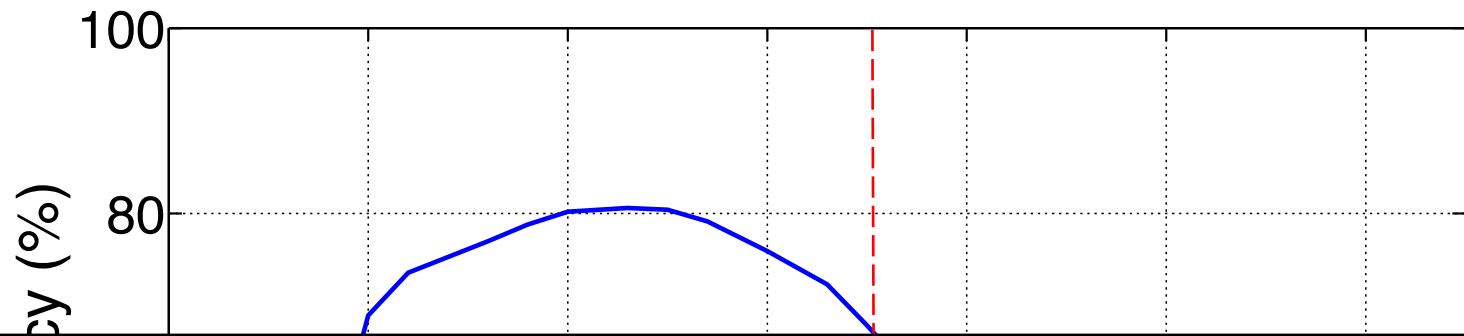
"Multispectral imaging: narrow or wide band filters?", Xingbo Wang, Jean-Baptiste Thomas, Jon Yngve Hardeberg, Pierre Gouton. *Journal of the international colour association*, 2014, 12, pp.44-51

RGB-NIR Image Processing

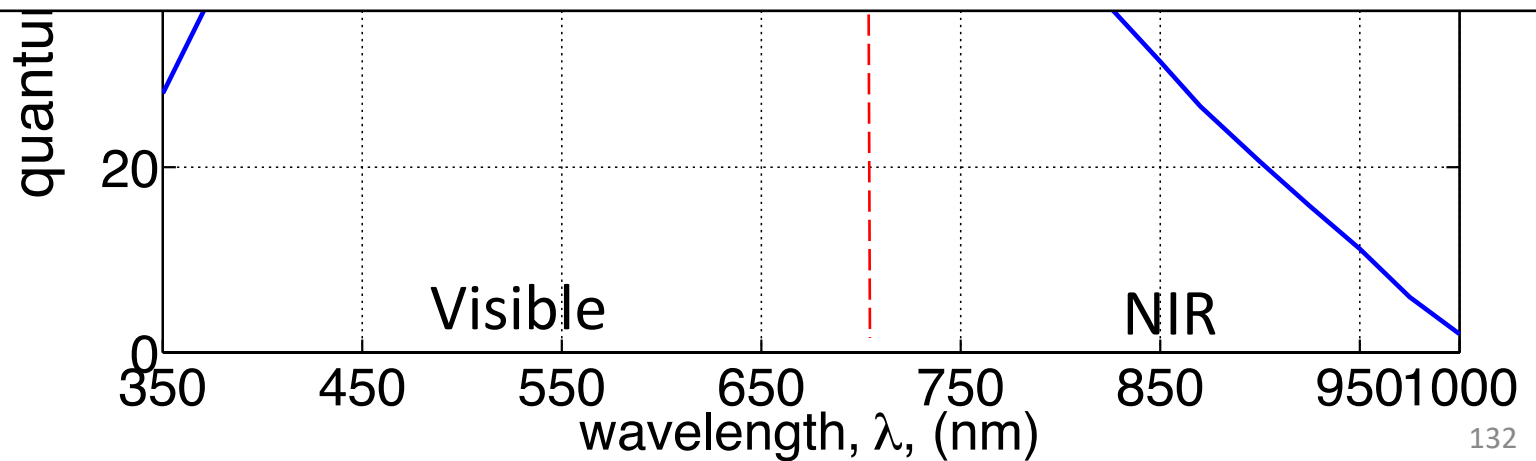
Silicon sensor



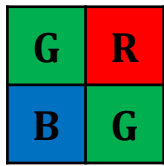
Silicon sensor



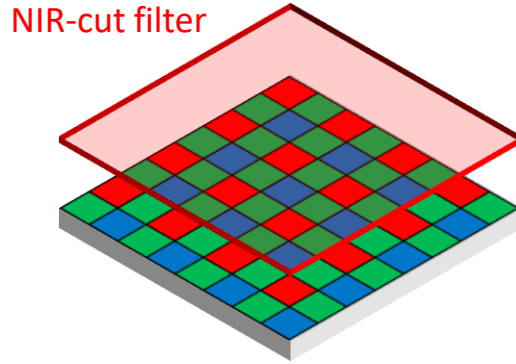
Joint acquisition of visible and NIR on a *single* sensor



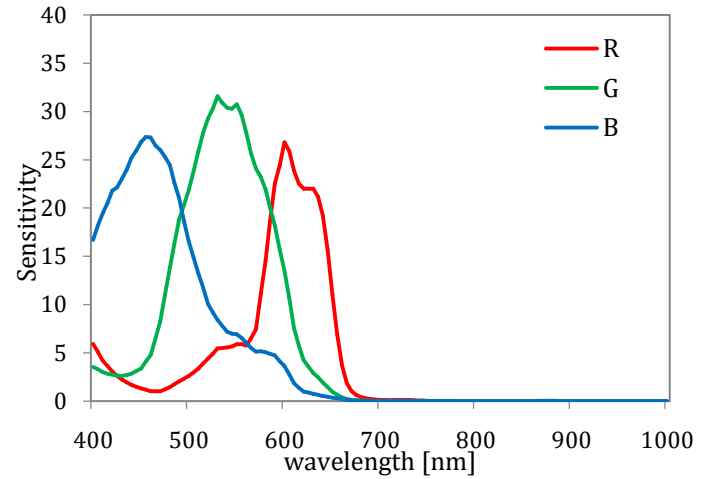
Removal of IR-cut filter



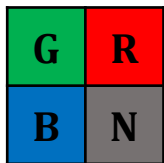
Bayer pattern



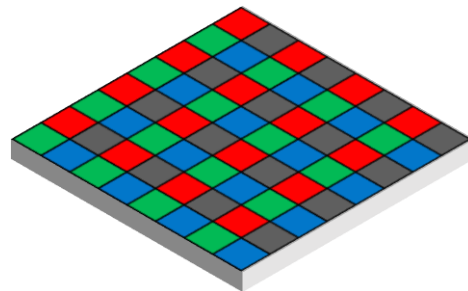
RGB sensor



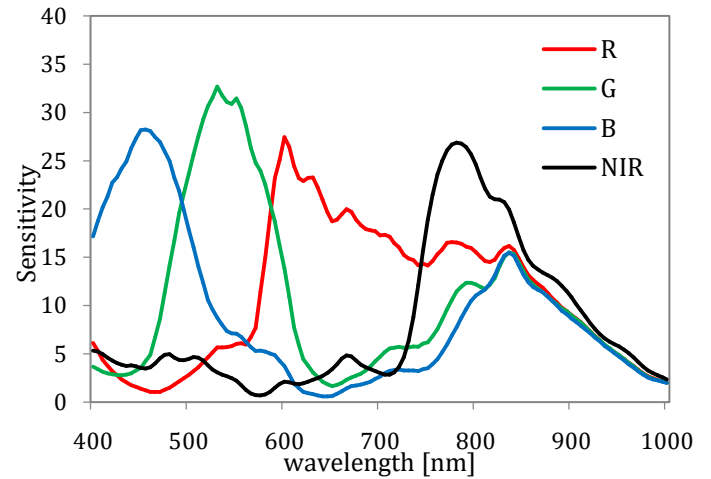
RGB sensor sensitivity



Uniform RGB-NIR pattern



RGB-NIR sensor

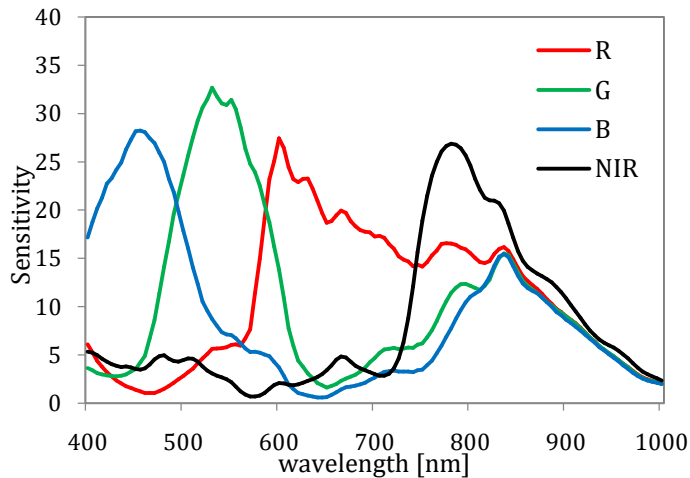


RGB-NIR sensor sensitivity

Realization of RGB-NIR sensor

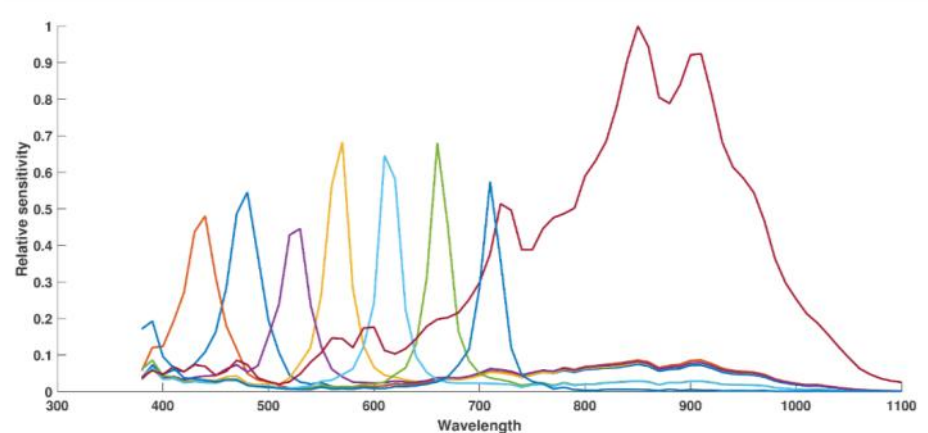
- Realizable sensor sensitivity is not ideal.
- Spectral contaminations or overlaps often exist and need to be corrected.

Monno RGB-NIR camera



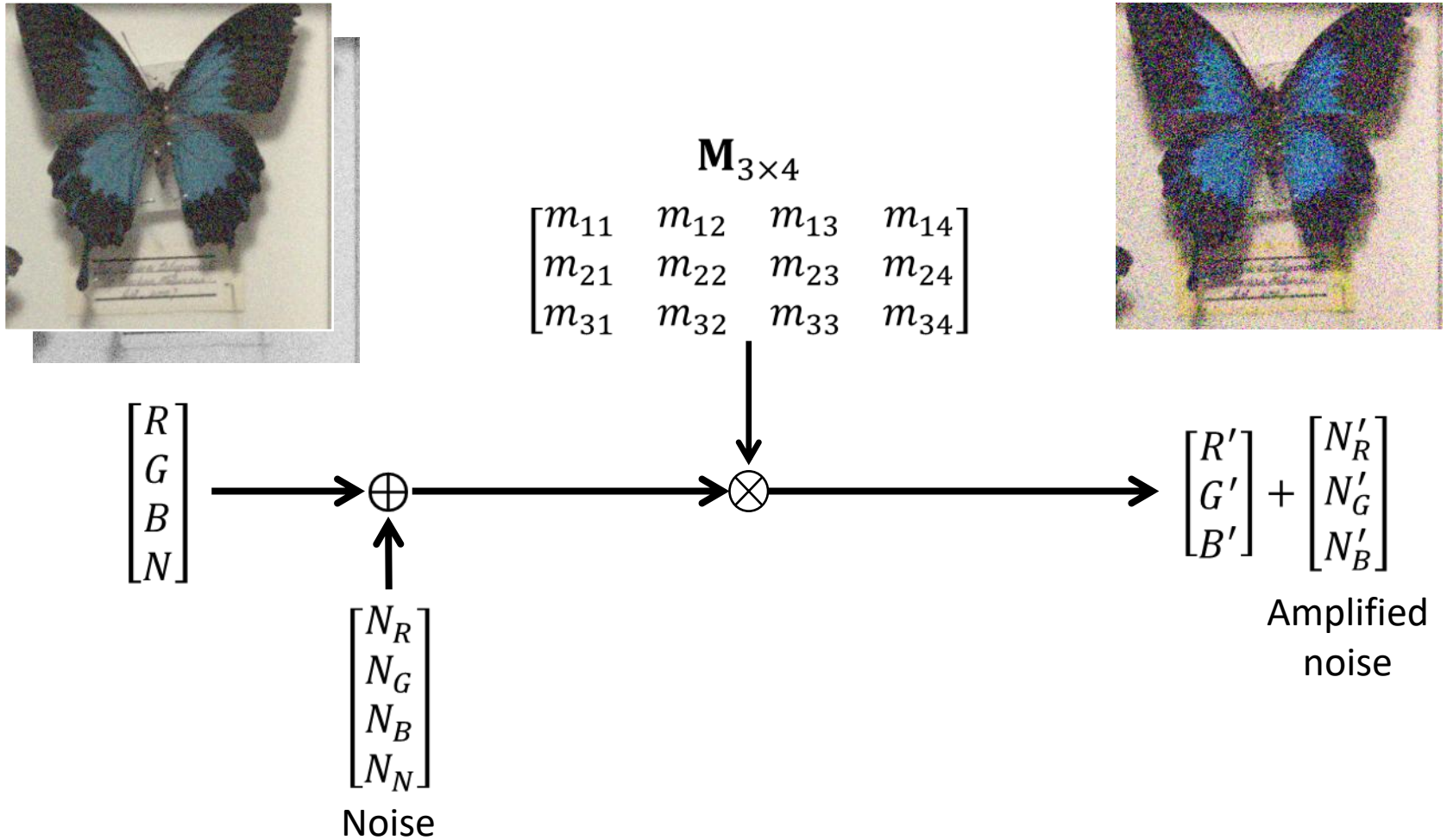
RGB-NIR sensor sensitivity

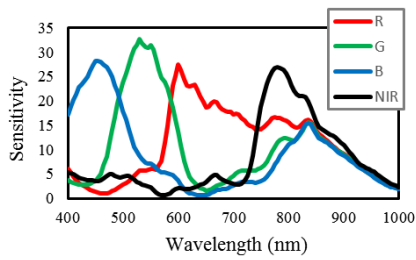
Thomas 8 band camera



8 band sensor sensitivity

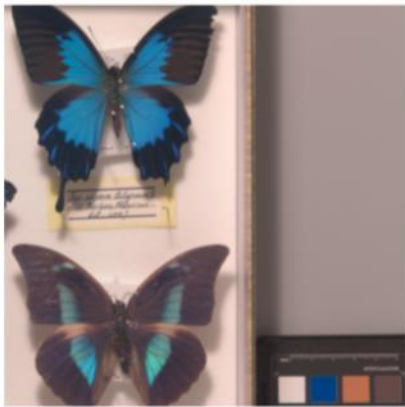
Problem of noise amplification





Simulation Results for the RGB-NIR sensor

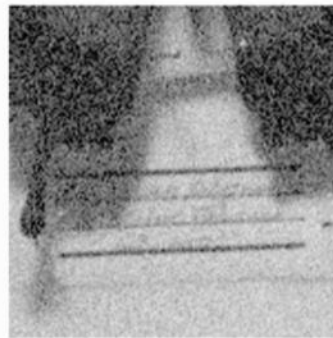
- Light: white light, Noise level: 20



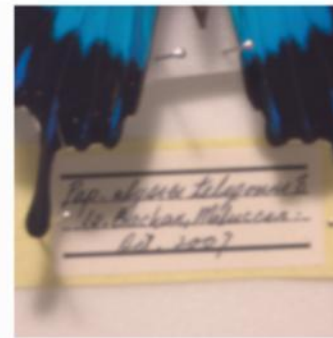
Ground truth



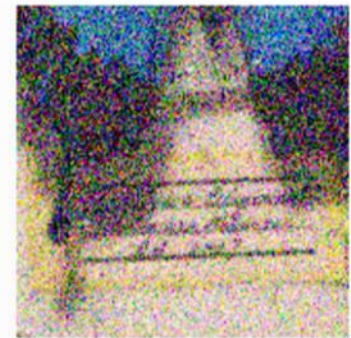
Input RGB



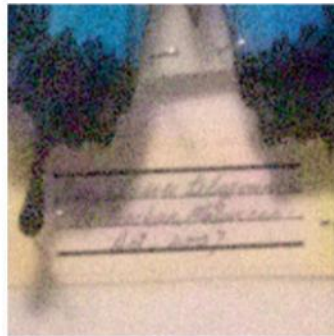
Input NIR



Ground truth



LCC



SVCC [1]



Denoising → LCC

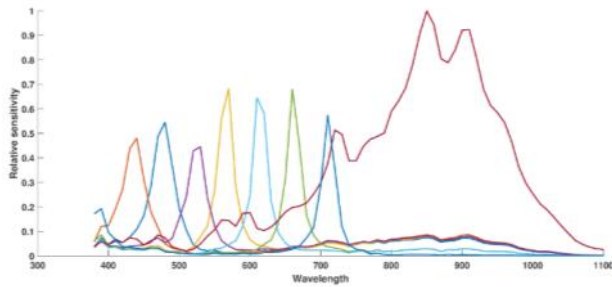


LCC → Denoising



Proposed

Example of correction for the 8-bands sensor



COLOR CAMERA



SFA CAMERA



SFA CORR.

Sadeghipoor Z, Thomas J-B and Susstrunk S (2016-11-03T00:00:00), "Demultiplexing visible and Near-Infrared Information in single-sensor multispectral imaging", Color and Imaging Conference. Vol. 2016(2016)

This presentation is intended for pedagogical purpose.
If you see borrowed material that is not properly acknowledged,
please inform us, we will give credits or modify the content!

Outlines

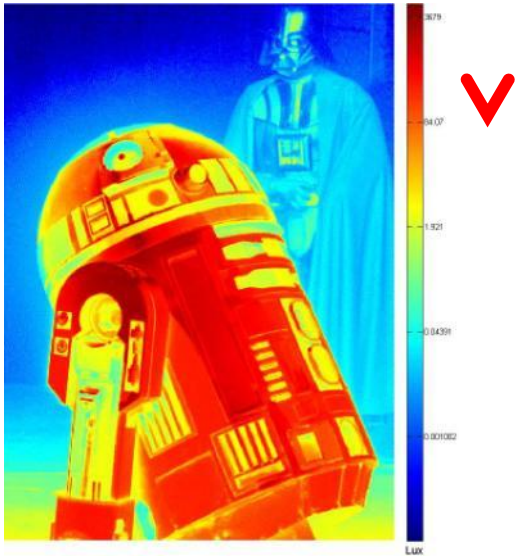
- 1-Generalities (20 min) (JB)
 - Intro on multispectral imaging
 - SFA definition and components
 - Imaging pipeline definition
- 2-Practical instantiations, databases and applications (40 min) (all of us)
 - Incl. a topo on architecture (PJ)
 - Five-bands camera in the visible domain (Y)
 - RGB-NIR camera (Y)
 - Eight-bands camera visible-NIR (JB/PJ)
 - Other state-of-the art
- 3-Demosaicing, pattern and data processing (30 min) (Yusuke)
 - Incl. color or spectral correction when NIR/visible overlap.
- 4-Insight on image quality (20 min)(PJ)
 - Incl. HDR
 - Incl. no-reference metrics tentative
- 5-Wrap up, future directions and questions (20 min) (all of us)

HDR imaging meets SFA imaging

HDR: What is it ?



Multiple exposures



HDR radiance map result



HDR tone mapped result

HDR: What is it ?

- Principle

- It is a combination of low dynamic range images (typically 8 bits) taken at different exposure times,
- Into an HDR radiance map image (32 bits)
- Optionnally visualize using tone mapping (32->8bits)



Low exposure



Middle exposure

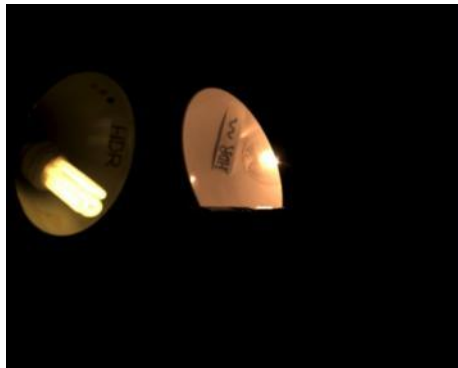


High exposure



HDR Tone mapped result

HDR: What is it ?



Low



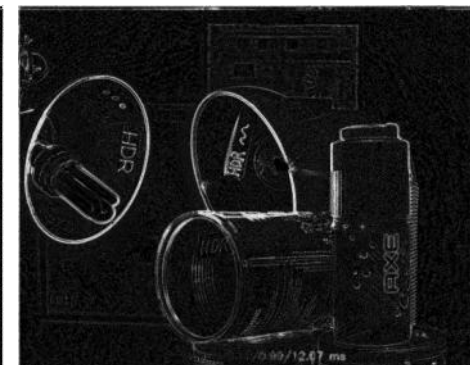
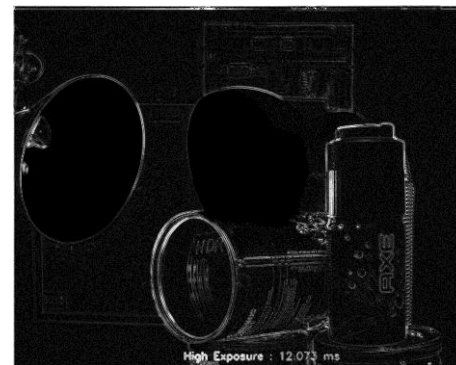
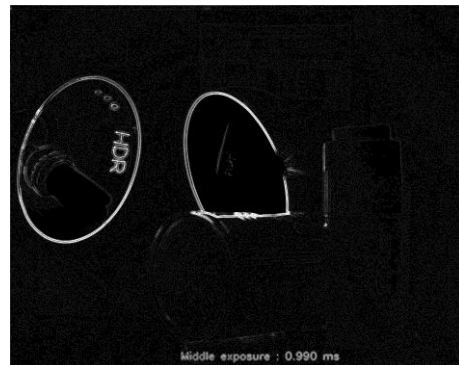
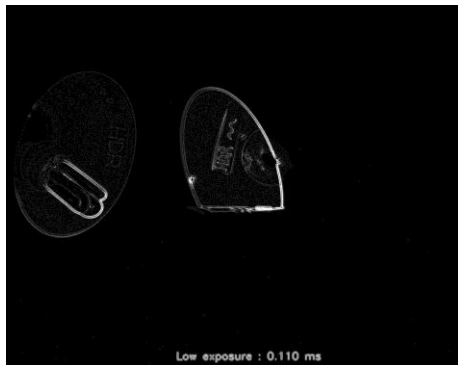
Mid



High



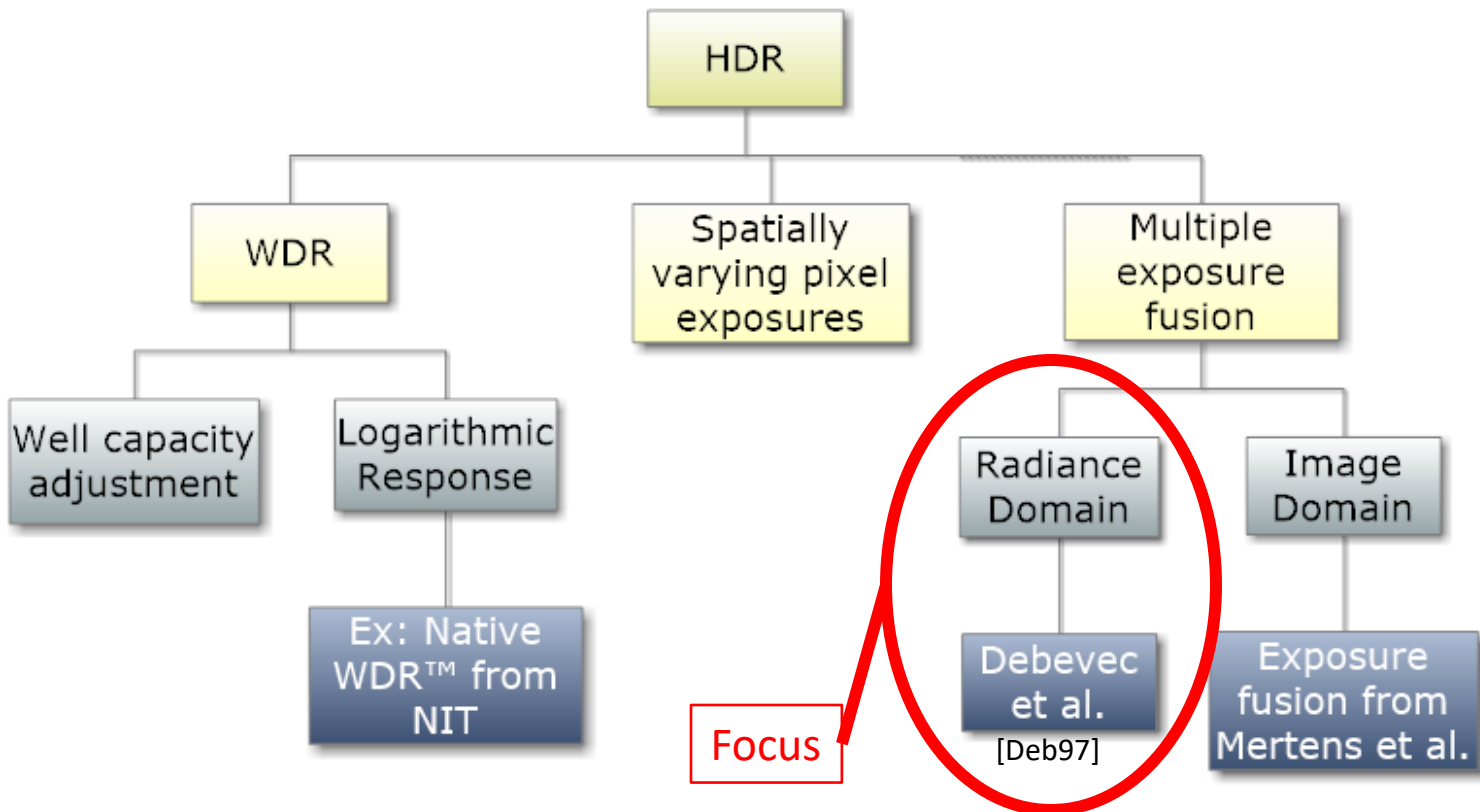
HDR



Simple edge detection on both low dynamic range images and HDR images

HDR: What is it ?

- What are the existing HDR methods ?
 - We will focus mostly on a multiple exposure method

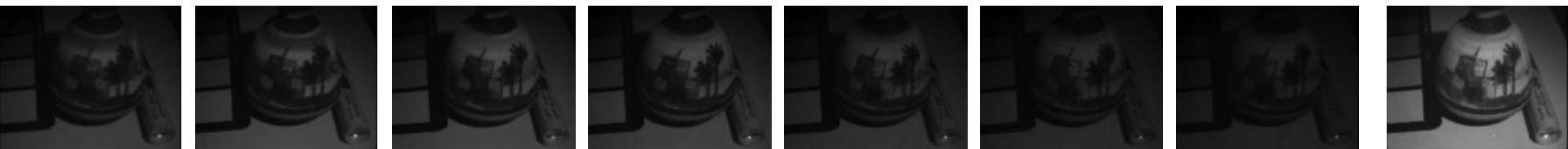
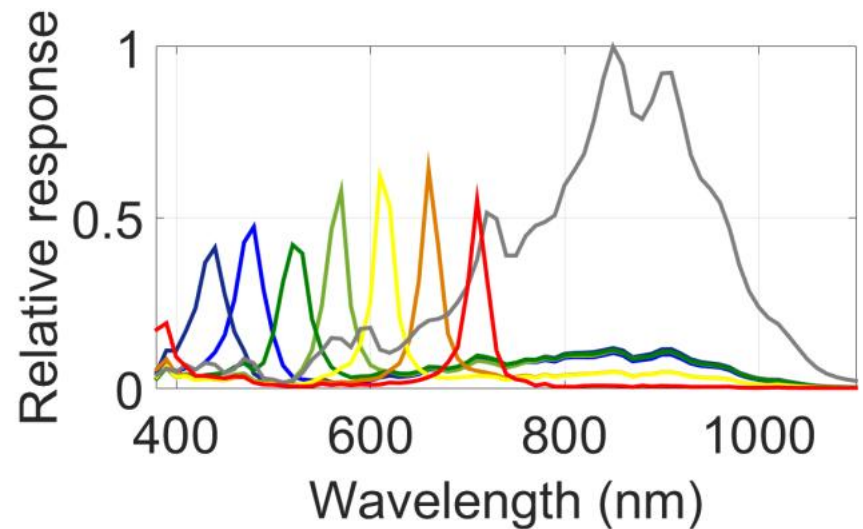


Why using HDR for SFA ?

- Example of demosaiced set from a real SFA sensor



Raw images



P1

P2

P3

P4

P5

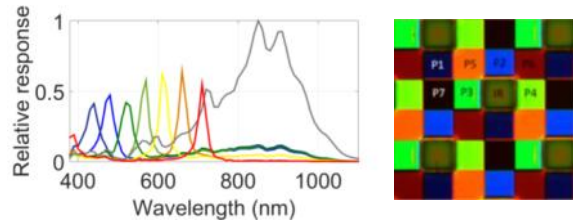
P6

P7

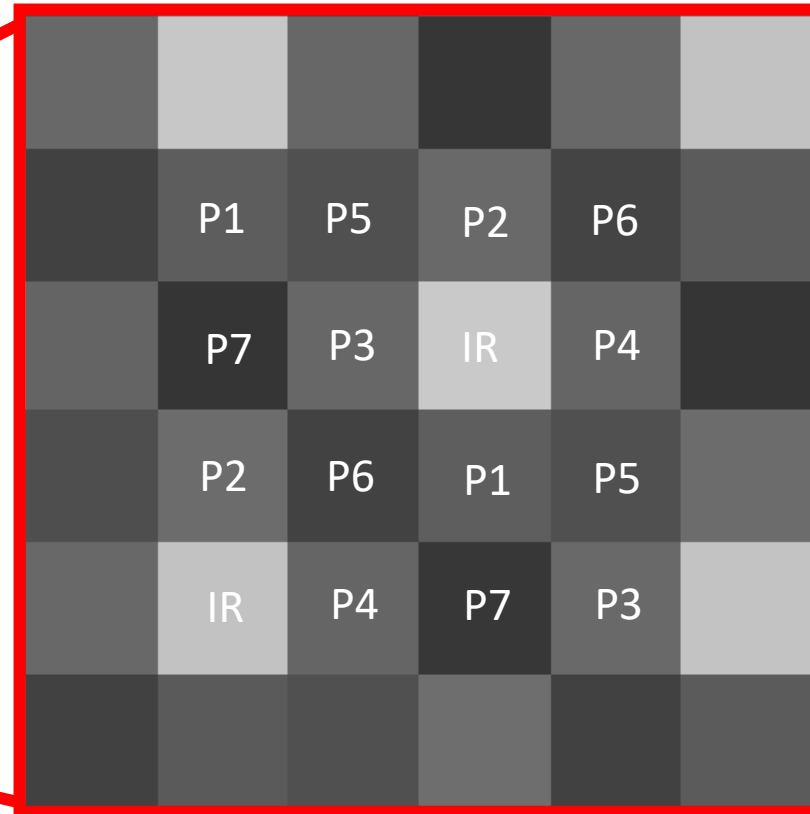
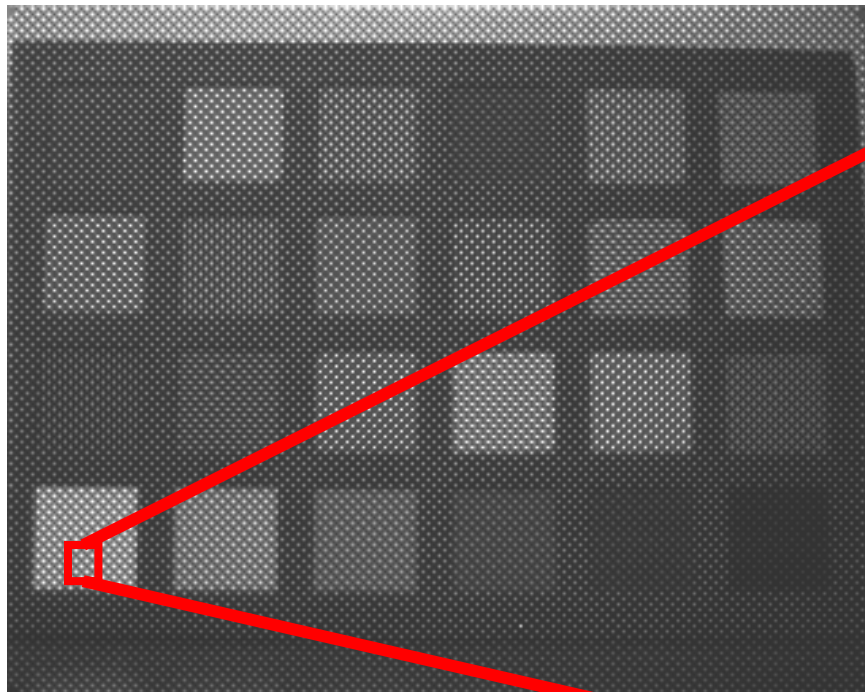
IR

Multispectral demosaiced images (8 channels)

Why using HDR for SFA ?



- Balance among channels & sensitivity problem



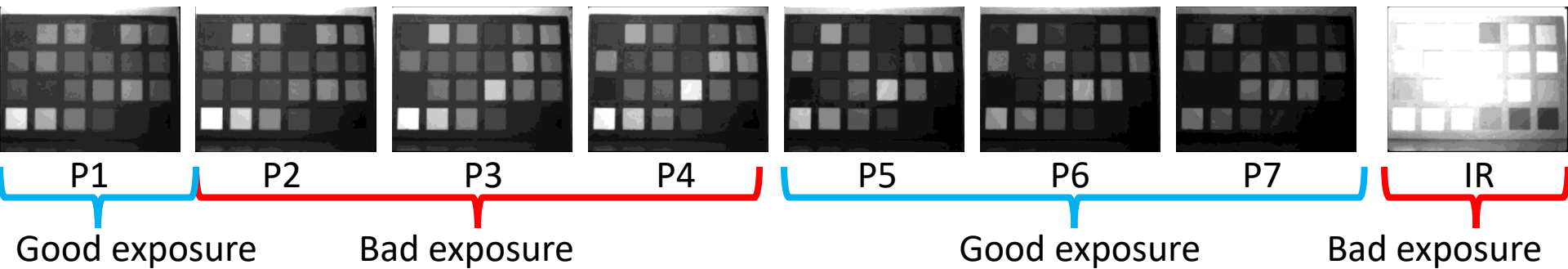
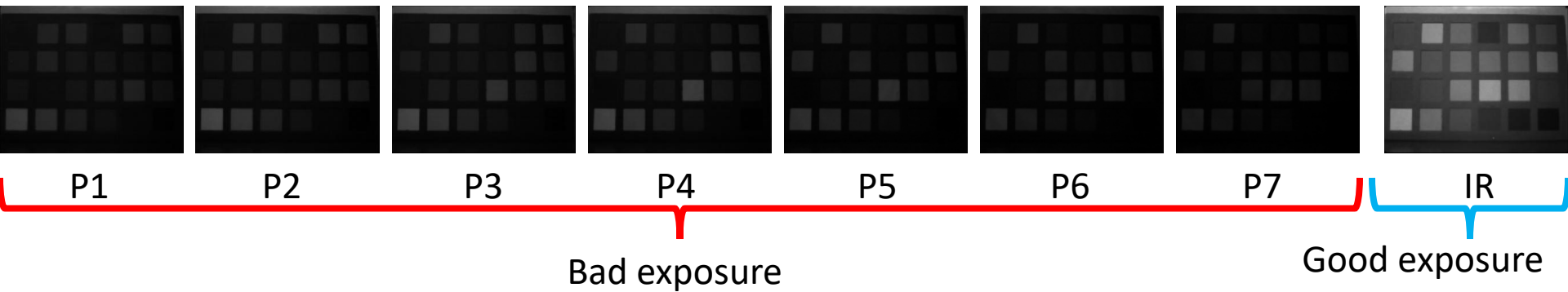
EXEMPLE: IMAGE OF COLOR CHART



ZOOMED REGION

Why using HDR for SFA ?

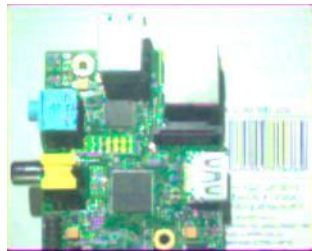
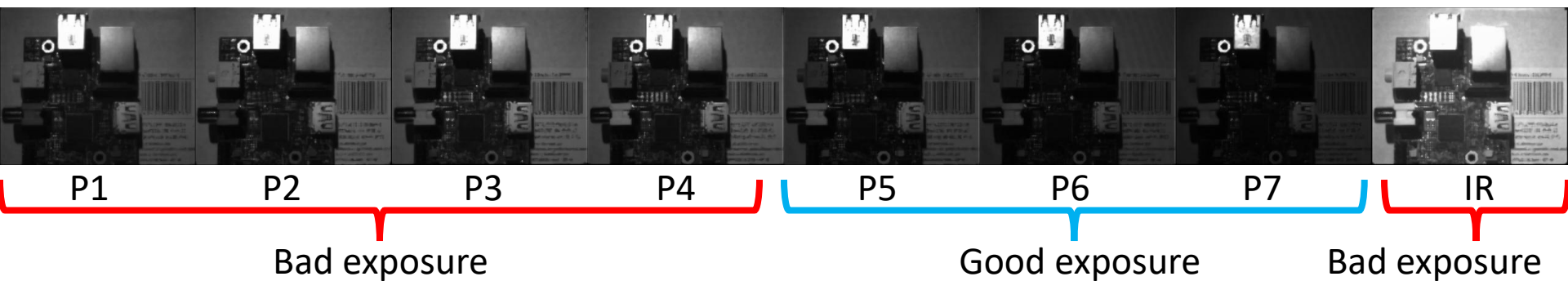
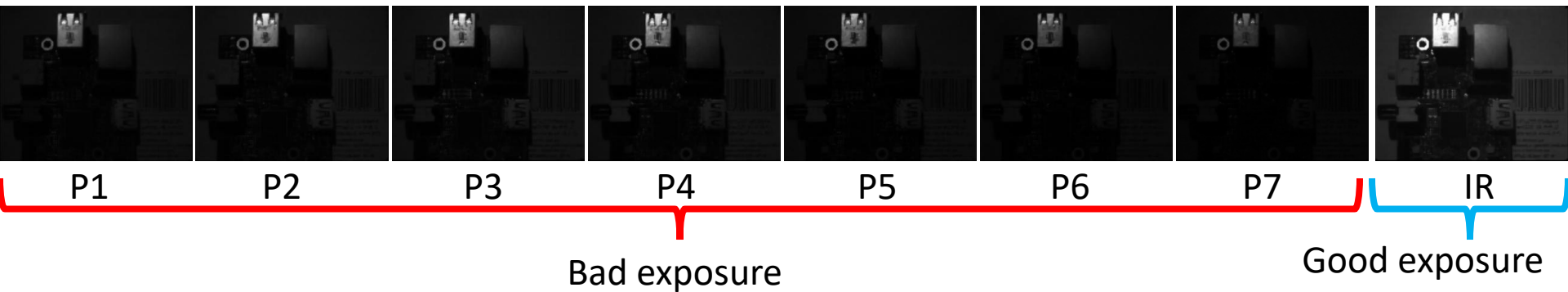
- 4ms and 16ms exposures



When computing sRGB visualization:
images are noisy

Why using HDR for SFA ?

- Other examples: 4ms and 16ms exposures

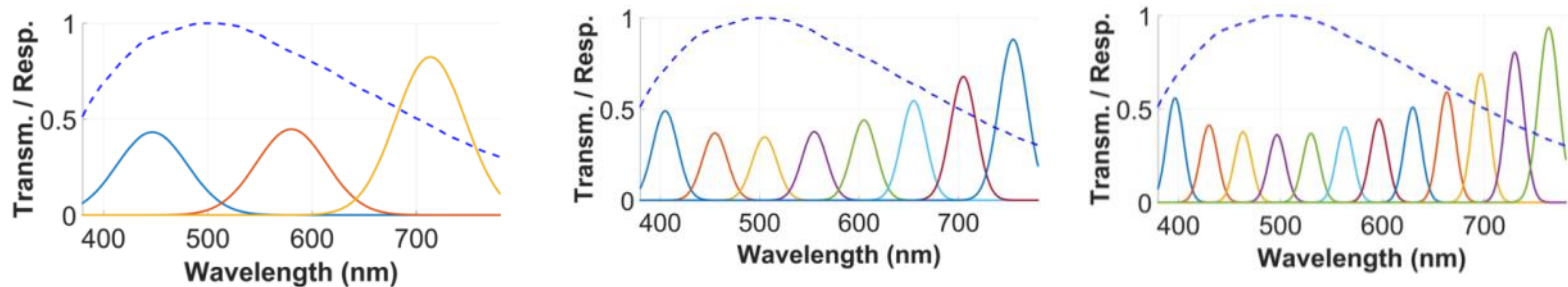


When computing sRGB visualization:
images are noisy

HDR imaging meets SFA imaging

- How to correct for **energy balance** among channels ?

1. Optimize the design: optimize the filter set -> Manufacturing [Lapray2017_1] ([code available here](#))



2. Optimize illumination: control the environment -> machine vision

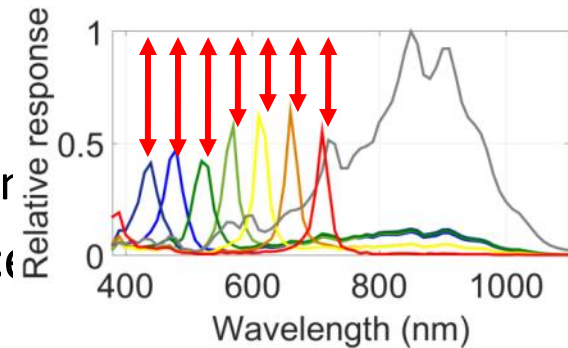
3. Optimize the capture: control the exposure and fuse -> **High Dynamic Range** [Lapray2017_2]

[Lapray2017_1] Pierre-Jean Lapray, Jean-Baptiste Thomas, Pierre Gouton, Yassine Ruichek. [Energy balance in Spectral Filter Array camera design](#). In Journal of the European Optical Society-Rapid Publications, January 1997.

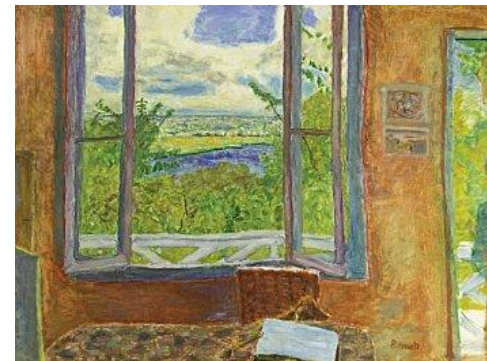
[Lapray2017_2] Pierre-Jean Lapray, Jean-Baptiste Thomas, Pierre Gouton. [High Dynamic Range Spectral Imaging Pipeline For Multispectral Filter Array Cameras](#). In Sensors, June 2017.

HDR imaging meets SFA imaging

- Benefits from extending the HDR methods to SFA ?
 - Can correct for energy balance
 - Correct for sensitivities, reduce noise
 - An homogeneous distribution of noise by char
 - Can extend the dynamic recovered of a scene
 - Domain of application extended



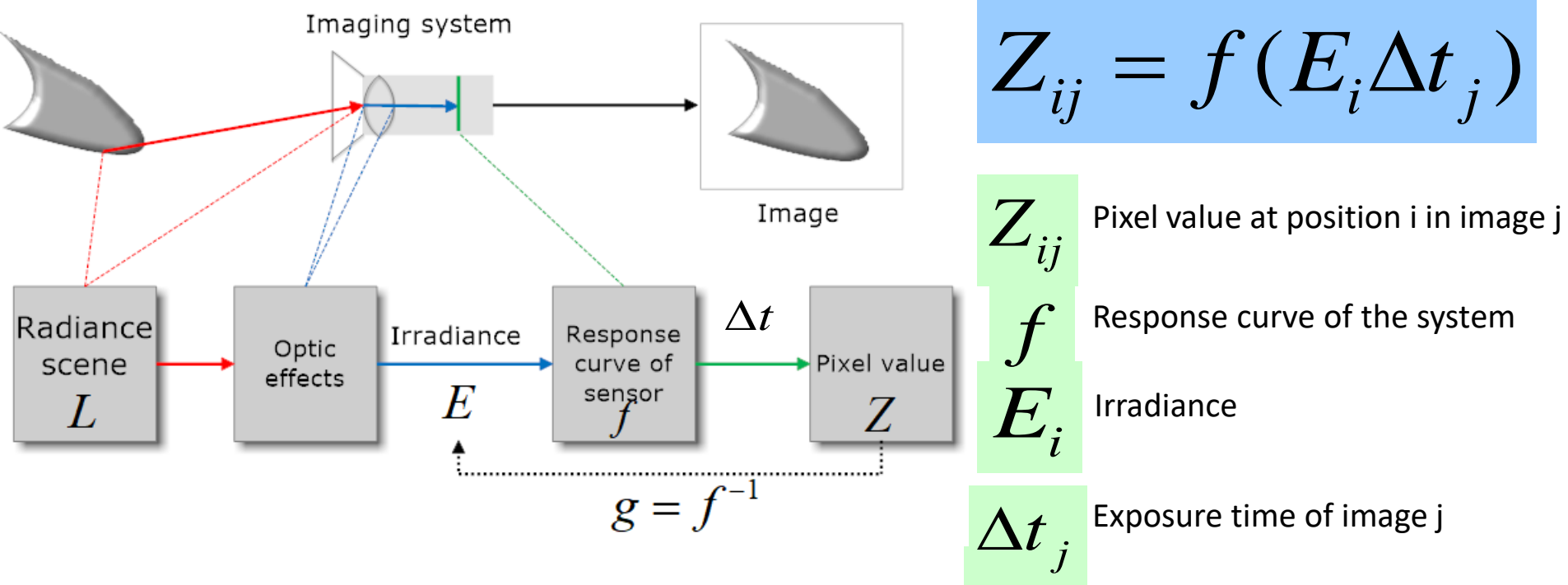
How standard cameras « see » it



How people « see » it

HDR: How to ?

- Debevec et al. [Deb97] HDR base theory



HDR: How to ?

- **Step 1:** Recover the response curve of the system
 - A camera sensor has a near-linear response to light

$$Z_{ij} = f(E_i \Delta t_j)$$

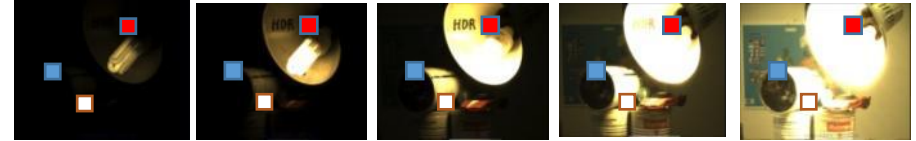
$$g = \ln f^{-1}$$

$$g(Z_{ij}) = \ln E_i + \ln \Delta t_j$$

N: Pixel number in image
P: Total image number

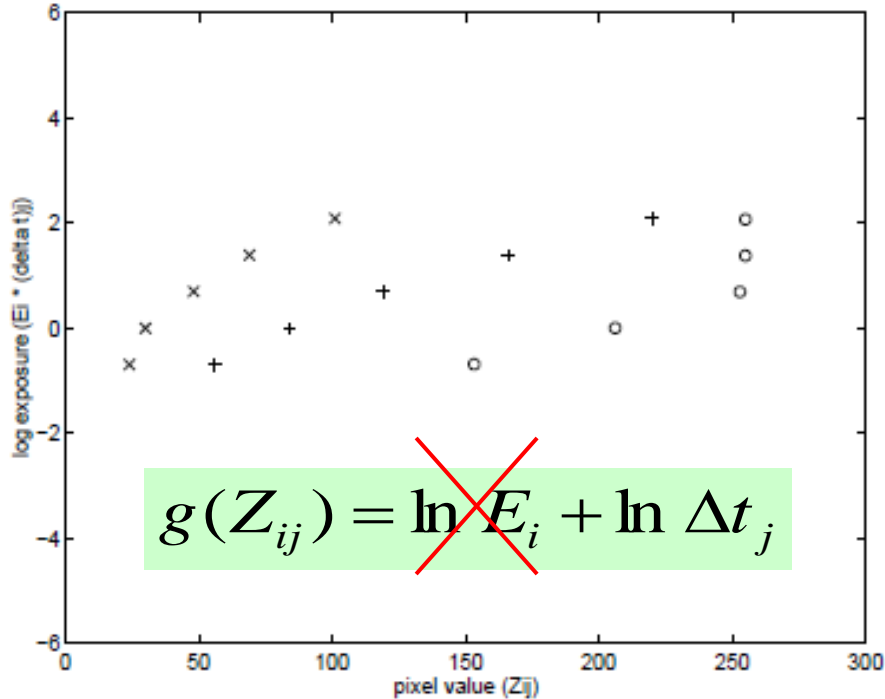
$$B = \sum_{i=1}^N \sum_{j=1}^P \left[g(Z_{ij}) - \ln E_i - \ln \Delta t_j \right]^2 + \lambda \sum_{z=Z_{\min}+1}^{Z_{\max}-1} g''(z)^2$$

HDR: How to ?

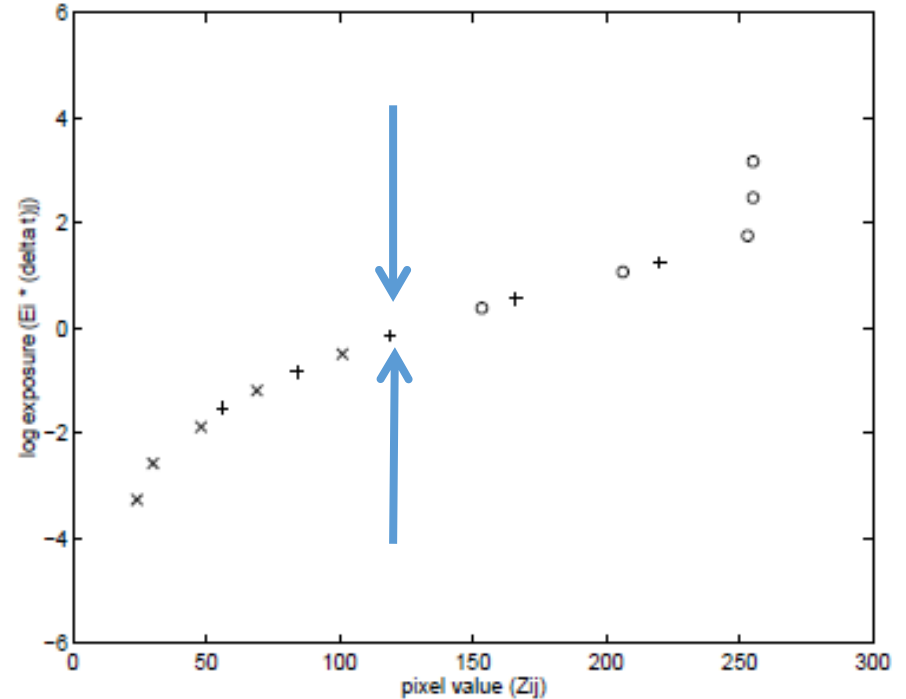


- **Step 1:** Recover the response curve of the system

plot of $g(Z_{ij})$ from three pixels observed in five images, assuming unit radiance at each pixel



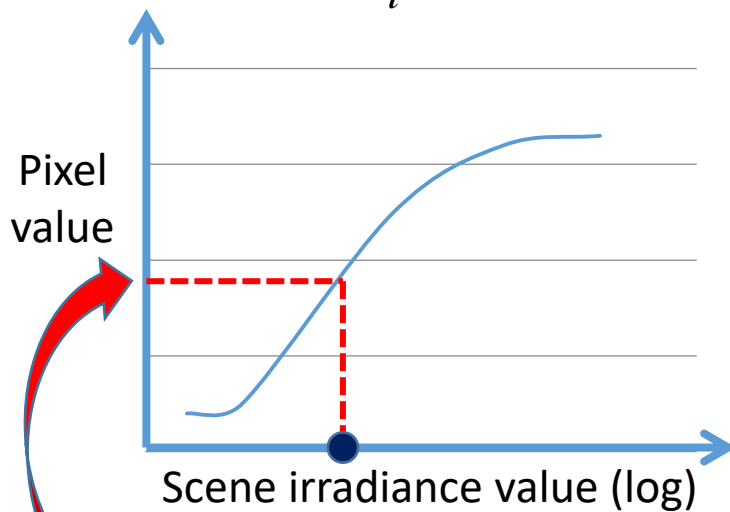
normalized plot of $g(Z_{ij})$ after determining pixel exposures



Response curve reconstruction $g(z)$ from a set of exposures

- **Step 2:** Create the SFA HDR image

$$\ln E_i = \frac{\sum_{j=1}^P \omega(Z_{ij})(g(Z_{ij}) - \ln \Delta t_j)}{\sum_{j=1}^P \omega(Z_{ij})}$$



E: Irradiance
g: Response curve of the system
N: Total pixel number
P: Image number
 ω : weighting function



The weighting function permits to ignore saturated pixels (near to extrem values 0/255)

HDR: How to ?

- **Step 3: Apply a tone-mapping for visualization (optional)**
 - Global or local tone-mapping
 - Global operators apply one operation for all pixels in HDR image
 - Local operators applies specific operations according to neighborhood, illumination conditions, etc.
 - Apply tone-mapping for specific display

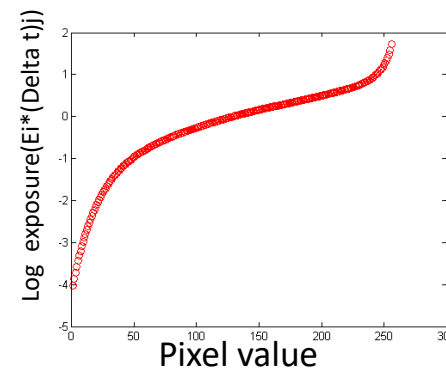
<i>Méthodes TMO</i>	<i>Année</i>	<i>Titre</i>	<i>Type</i>
Pattanaik et al.	2000	Time-Dependent Visual Adaptation for Realistic Image Display	Global
Reinhard et al.	2002	Photographic Tone Reproduction for Digital Images	Global & Local
Durand et al.	2002	Fast Bilateral Filtering for the Display of High-Dynamic-Range Images	Local
Ashikhmin et al.	2002	A Tone Mapping Algorithm for High Contrast Images	Local
Fattal et al.	2002	Gradient Domain High Dynamic Range Compression	Local
Drago et al.	2003	Adaptive Logarithmic Mapping for Displaying High Contrast Scenes	Global
Reinhard et al.	2003	Dynamic range reduction inspired by photoreceptor physiology	Global
Mantiuk et al.	2006	Perceptual Framework for Contrast Processing of High Dynamic Range Images	Local
Duan et al.	2010	Tone-mapping high dynamic range images by novel histogram adjustment	Global & Local

HDR: How to ?



- Summary

Multiple exposures



1. Response curve recovery

2. HDR creation
From multiple
Exposures (not
necessary the
same images
as 1.)

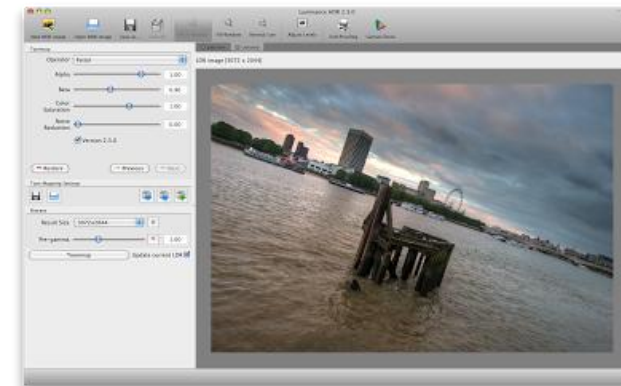


3. Tone mapping



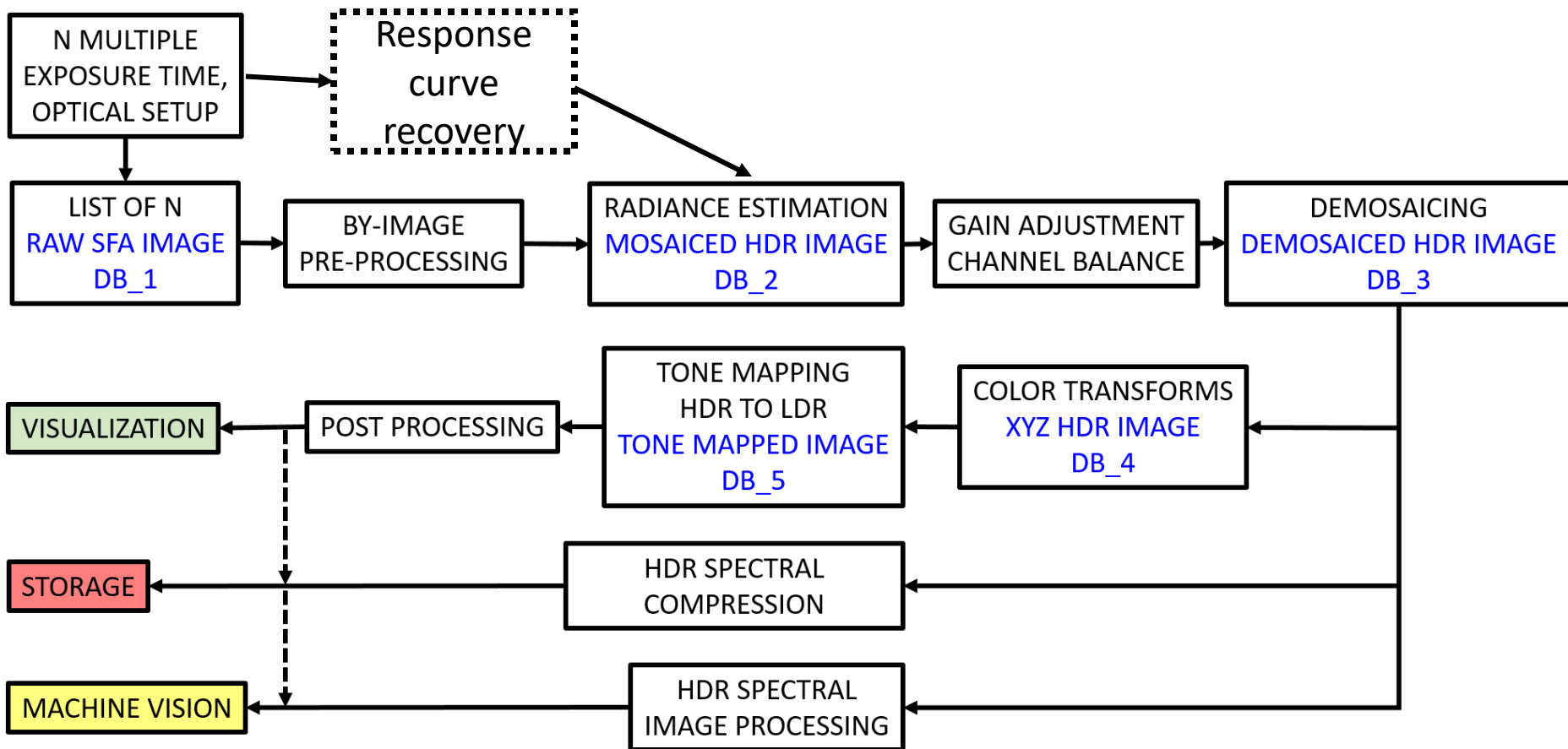
HDR: How to ?

- HDR: Test or retry it !
 - Using existing softwares
 - With GUI interface:
 - <http://qtpfsgui.sourceforge.net>
 - <http://software.bergmark.com/enfusegui/>
 - With Matlab Toolbox (ref)
 - https://github.com/banterle/HDR_Toolbox
 - Lot of fonctionnalities, tone mapping, image processing tools...
 - With Photoshop



SFA HDR: How to ?

SFA HDR: How to ?



Dedicated pipeline for SFA HDR imaging (ref)

- **Step 1:** Response curve recovery (by using Debevec algorithm)

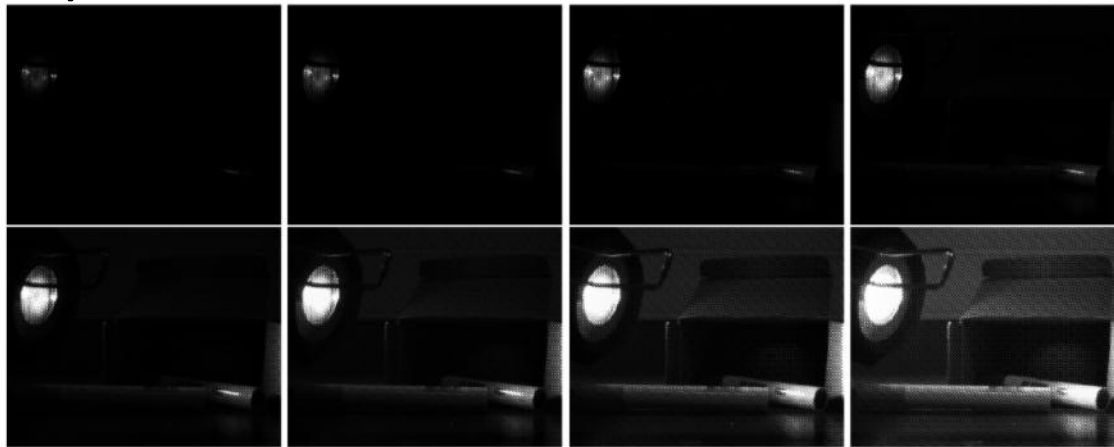
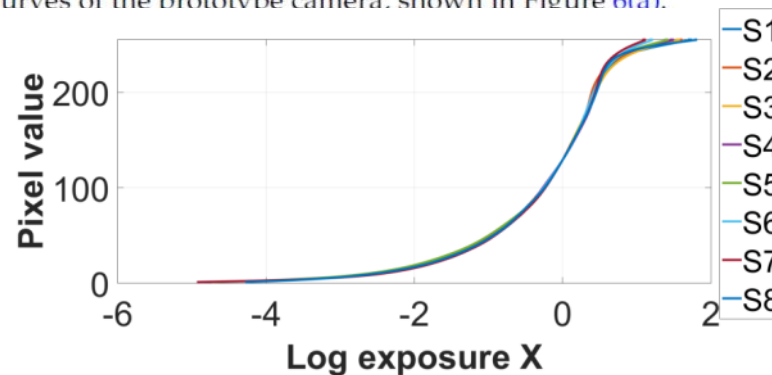


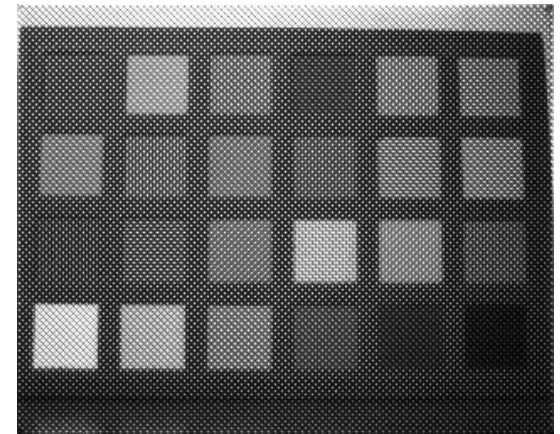
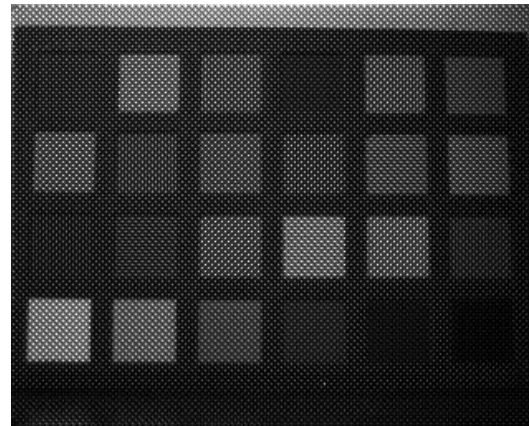
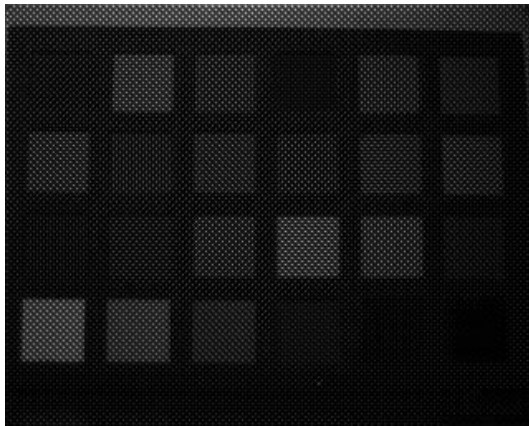
Figure 5. The set of SDR raw mosaiced images acquired with different exposure times: $\{0.125, 0.22, 0.5, 1, 2, 4, 8, 16\}ms$ (all spaced by one stop). These exposures are used to compute the global response curves of the prototype camera, shown in Figure 6(a).



8 response curves recovered:
we can use the median of
these curves for a good
approximation

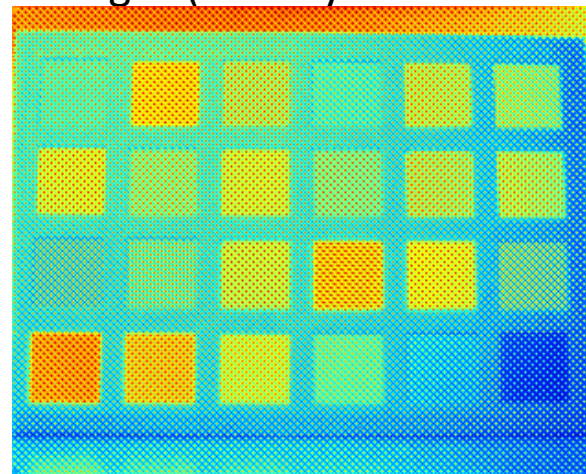
SFA HDR: How to ?

- **Step 2:** By-image pre-processing and radiance estimation



Using pre-processed raw images (already corrected for dark current noise)

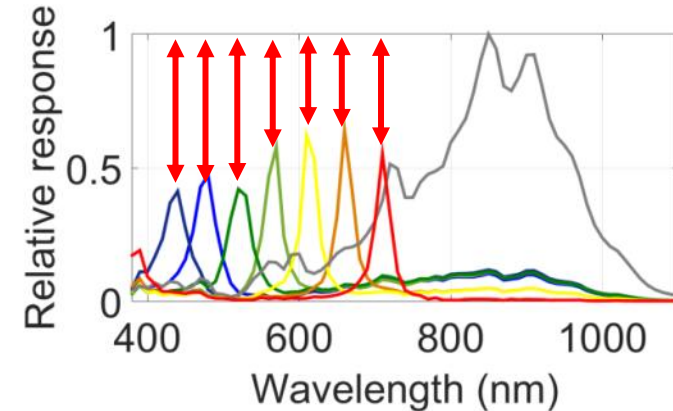
It is a per pixel operation



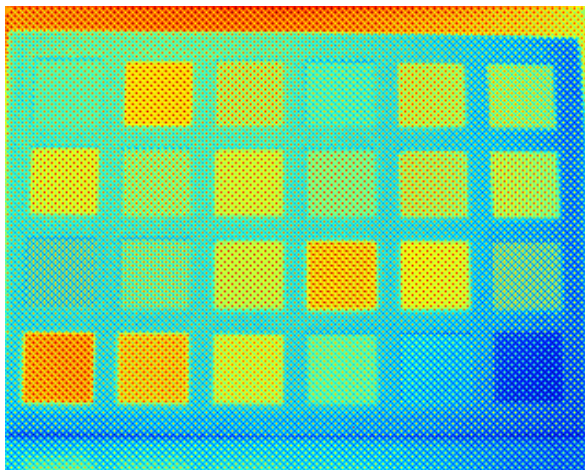
HDR mosaiced radiance
HDR image

SFA HDR: How to ?

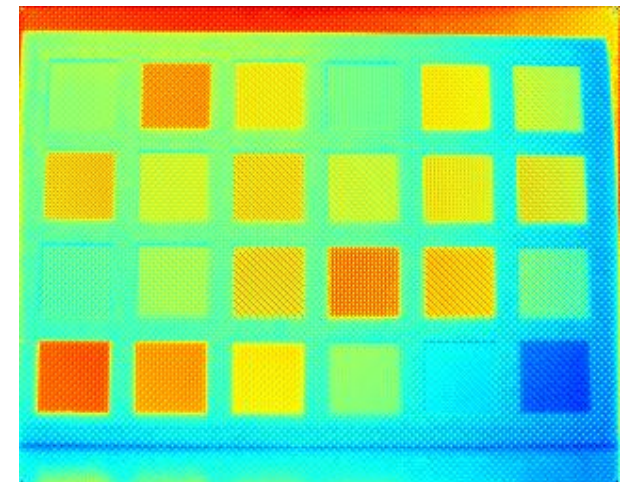
- **Step 3: Gain adjustment**
 - 8 multiplication factors are obtained from the study of the different spectral sensitivities



$$8 \text{ factors } F_{S_1-S_8} = \{3.15, 2.86, 3.29, 2.90, 4.34, 5.39, 6.41, 1.00\}$$



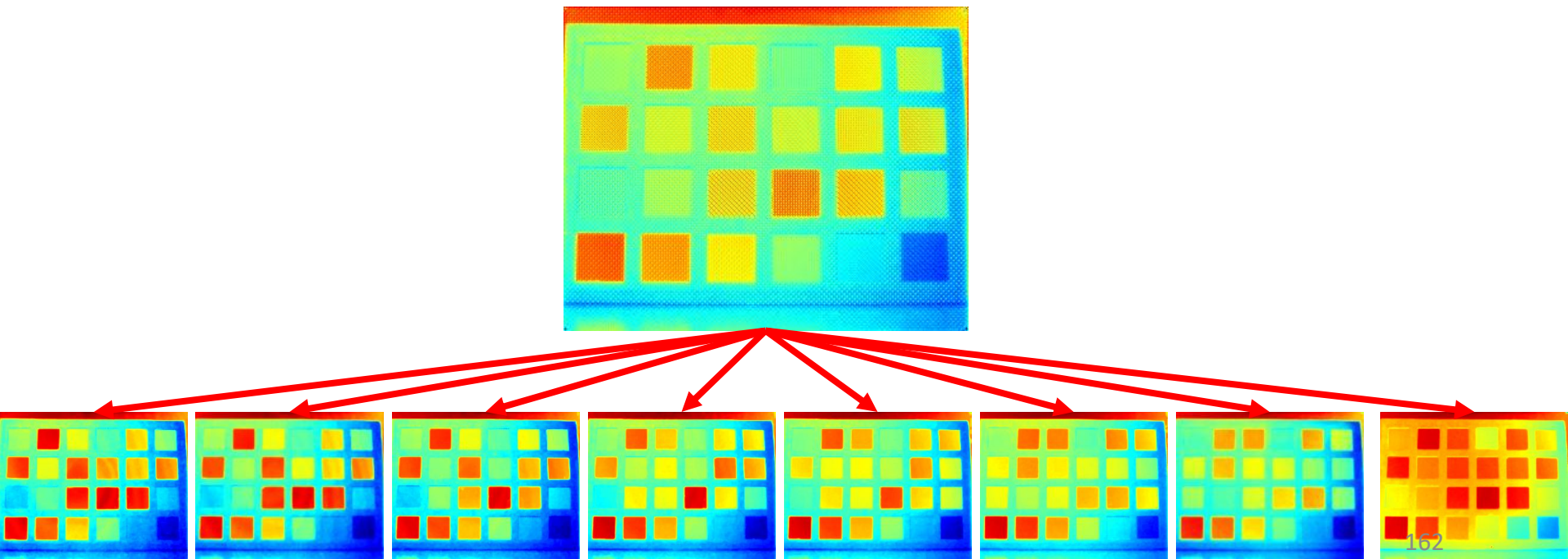
*HDR mosaiced radiance
HDR image*



*HDR mosaiced radiance
HDR image after channel balance*

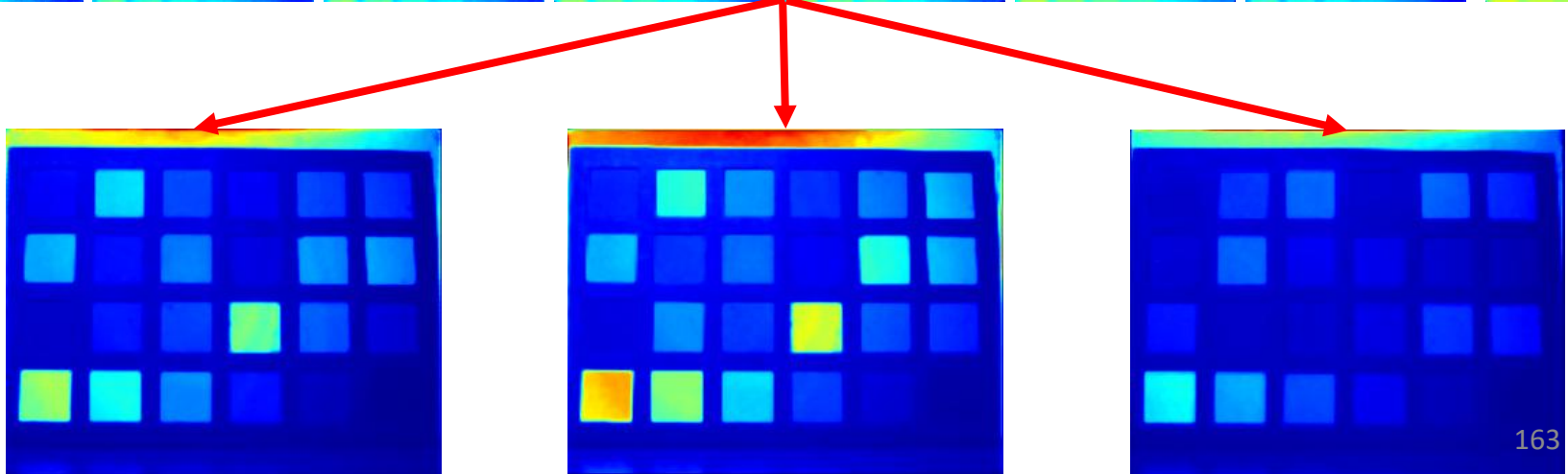
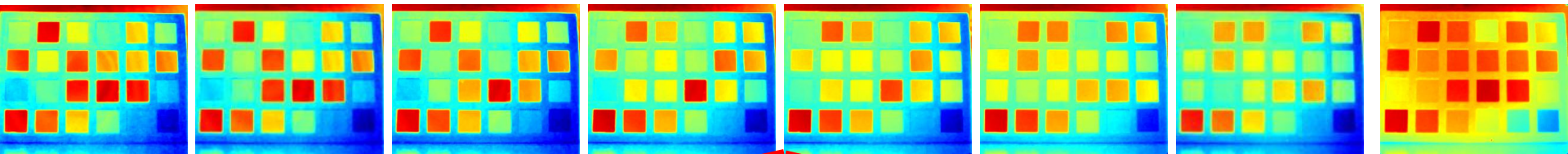
- **Step 4: Demosaicing**

- Do it after HDR generation !
- Can use the same methods as for SFA pipeline, but using 32 bits HDR data (Miao et al. method in our case)

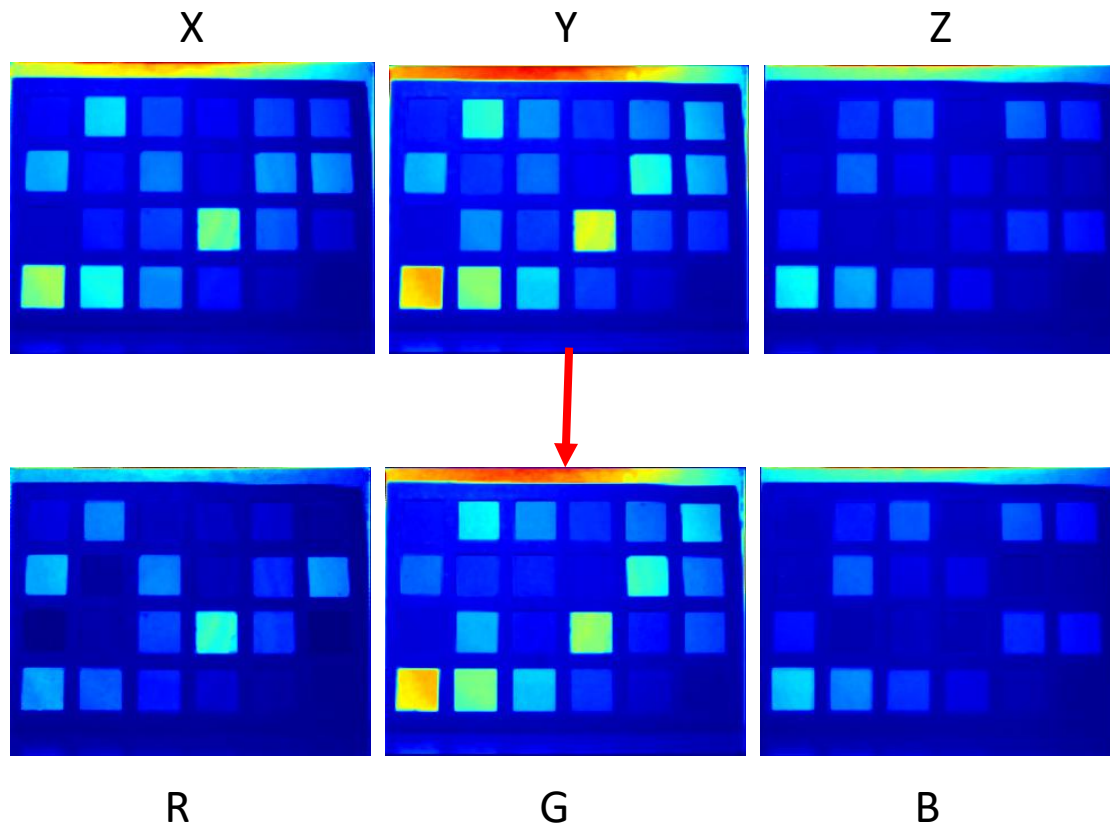


- **Step 5: Color transform**

- N bands to CIEXYZ HDR image
- Use a linear colorimetric calibration computed on the Macbeth ColorChecker

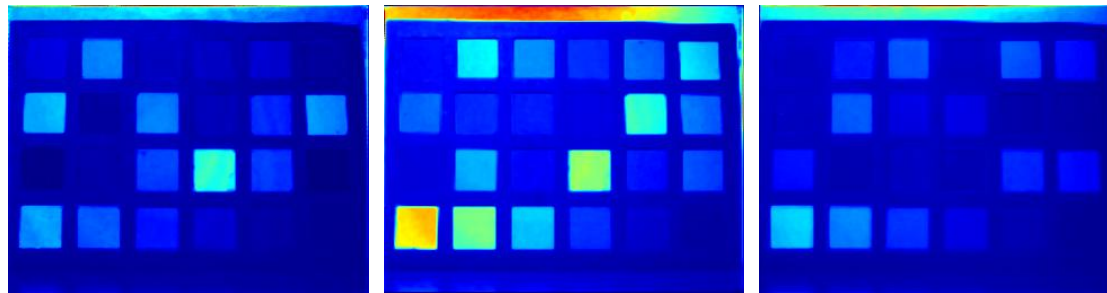


- **Step 6: RGB transform**
 - Transformation from CIEXYZ to linear RGB is applied



- **Step 7: Tone-Mapping**

- Apply a tone-mapping method for visualization



32 bits data
domain

NB: you could use Luminance HDR software to test different tone-mapping on HDR images (<http://qtpfsgui.sourceforge.net/>)



8 bits data
domain

- **Step 7: Tone-Mapping**

- Different Tone-Mapping Operators (TMO) exist (a lot !)
- Local VS Global Tone-mapping



Global TMO:

- Same global operation for all pixels
- Scene with high local contrasts look gray...
- Easy to implement (soft or hard)



Local TMO:

- Can have better local contrast
- But is hard to implement in real-time !
- Be careful, can generate edge artifacts in case of highlights (due to local behaviour)



(a)CD (4ms)



(b)Knife (4ms)



(c)Water (4ms)



(d)Train front (16ms)



(e)Pens (4ms)



(f)Kerchief (8ms)



(g)Kiwi (4ms)



(h)Macbeth CC (4ms)



(i)Black swimsuit (16ms)



(j)Orange object (4ms)



(k)Origan (4ms)



(l)Pastel (4ms)



(m)Battery (4ms)



(n)Train side (16ms)



(o)Raspberry (8ms)



(p)Ruler (4ms)



(q)SD card (4ms)



(r)Painting (16ms)



(a)CD



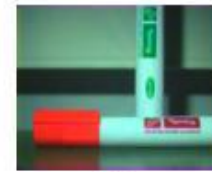
(b)Knife



(c)Water



(d)Train front



(e)Pens



(f)Kerchief



(g)Kiwi



(h)Macbeth ColorChecker



(i)Black swimsuit



(j)Orange object



(k)Origan



(l)Pastel



(m)Battery



(n)Train side



(o)Raspberry



(p)Ruler



(q)SD card



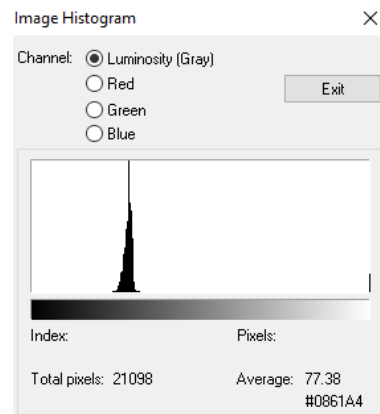
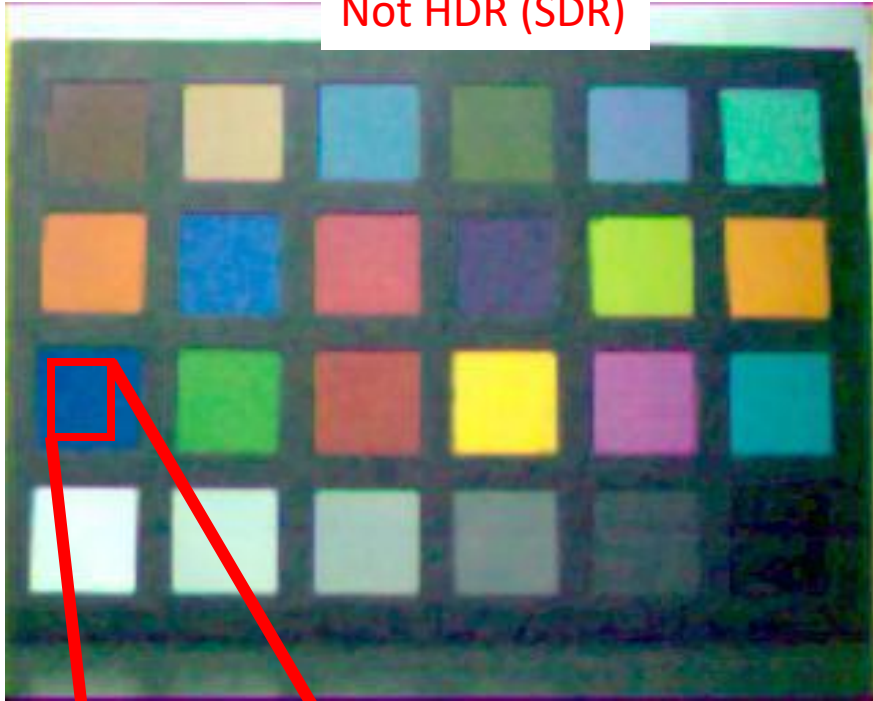
(r)Painting

Single Dynamic Range (SDR) VS High Dynamic Range (HDR)

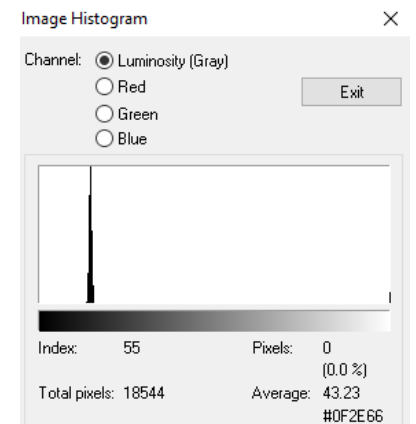
You could see other tone-mapped results (right) at <http://chic.u-bourgogne.fr/> (select HDR_SFA-Sensors2017)

Results

Not HDR (SDR)



HDR Tone Mapped



How to evaluate quality of SFA HDR images ?

- Non reference quality metrics
 - Use HIGRADE if measuring quality of color tone-mapped HDR image
 - Need to train a dedicated-SDR no-reference quality metrics if measuring multi/hyper spectral HDR images per band
 - Results show that it is difficult to evaluate quality of HDR SFA data without a good reference.

How to evaluate quality of SFA HDR images ?

- Using HIGRADE for tone-mapped images
- SDR is the worst
- Global+Local TMO is the best

	SDR	TM Banterle	TM Fattal	TM Log	TM Krawczyk
black_swimsuit	-1.33	-0.84	-0.92	-0.91	-0.57
train_side	-0.79	-0.94	-0.96	-1.19	-0.71
cd	-0.72	-0.12	-0.09	-0.93	-0.08
kiwi	-1.07	-0.86	-1.02	-0.62	-0.45
sd	-1.31	-0.39	-0.13	-0.45	-0.47
pens	-1.23	-0.54	-0.70	-0.56	-0.46
origan	-0.90	-0.41	-0.44	-0.13	-0.14
painting	-0.60	-0.64	-0.84	-0.47	-0.43
macbeth	-0.90	-0.50	-0.42	-0.45	0.02
knife	-0.79	-0.39	-0.49	-0.87	-0.07
water	-1.01	-0.92	-0.80	-0.86	-0.70
train_front	-0.95	-0.64	-0.66	-1.18	-0.72
kerchief	-2.02	-2.05	-1.53	-1.77	-1.46
pastel	-1.13	-0.59	-0.55	-0.73	-0.32
orange_object	-0.99	-0.96	-0.42	-0.61	-0.73
battery	-0.92	-0.34	-0.38	-0.79	-0.14
raspberry	-0.95	-0.81	-0.89	-0.93	-0.24
ruler	-0.40	-0.74	-0.77	-1.21	0.02
Mean	-1.00	-0.70	-0.67	-0.81	-0.42
STD	0.34	0.40	0.34	0.36	0.36

How to evaluate quality of SFA HDR images ?

- Using BRISQUE for tone-mapped/HDR images...

	SDR	TM Banterle	TM Fattal	TM Log	TM Krawczyk	S1	S2	S3	S4	S5	S6	S7	S8
black_swimsuit	50.2	63.5	72.1	77.5	54.6	88.4	90.4	88.3	92.6	90.2	88.8	78.7	87.5
train_side	29.4	56.8	53.8	65.8	50.7	84.9	85.2	78.8	81.8	87.8	83.4	66.4	89.5
cd	34.0	53.5	53.9	59.7	46.2	54.0	52.5	48.9	47.7	53.5	50.1	44.4	44.2
kiwi	28.4	45.7	39.9	47.0	44.3	46.9	49.3	42.0	42.1	36.5	41.4	32.1	37.3
sd	36.4	50.8	52.0	51.6	47.6	51.7	51.4	49.1	50.8	53.1	56.9	49.5	45.3
pens	18.4	58.1	60.0	63.1	59.3	74.7	76.2	69.0	70.7	73.9	76.0	64.2	75.8
origan	26.9	52.0	50.2	53.1	50.4	55.3	60.7	49.4	57.3	53.1	52.8	49.3	50.3
painting	42.4	45.9	41.2	46.4	39.5	58.6	54.9	52.5	54.2	42.7	51.2	47.7	49.6
macbeth	29.6	61.2	46.1	69.1	66.2	62.0	67.1	63.8	67.5	69.9	69.9	54.4	65.1
knife	32.0	53.3	62.0	58.9	47.9	51.0	49.0	46.4	50.9	54.8	43.4	33.3	44.7
water	24.4	52.4	49.2	53.3	51.9	59.3	56.4	54.3	54.9	52.2	53.8	47.2	53.8
train_front	34.9	60.5	58.4	77.5	51.4	84.1	85.0	77.1	81.6	82.6	79.9	64.2	85.8
kerchief	87.4	102.6	97.5	105.0	105.1	93.6	96.5	98.8	99.0	102.3	99.4	52.9	45.9
pastel	52.1	71.9	59.6	69.7	67.8	70.4	73.5	71.3	69.9	73.9	73.8	68.0	68.3
orange_object	31.5	59.2	49.8	67.5	54.9	60.7	69.9	55.5	59.7	65.8	68.8	56.0	46.5
battery	42.7	56.7	48.4	60.3	49.8	55.0	57.4	55.8	51.3	52.6	49.8	48.7	50.5
raspberry	45.7	59.7	50.7	60.5	56.1	71.0	71.0	63.6	65.1	65.1	66.6	61.8	63.8
ruler	34.5	53.8	49.2	68.3	39.5	44.8	45.6	48.7	47.7	53.1	52.3	46.3	39.3
Mean	37.8	58.8	55.2	64.1	54.6	64.8	66.2	61.8	63.6	64.6	64.3	53.6	58.0
STD	15.2	12.6	13.0	13.7	14.7	15.0	15.6	15.8	16.3	17.7	16.6	12.0	17.0

Digression: HDR in real-time

- Hardware considerations to meet real-time HDR imaging
 - Need appropriate processing architecture to perform HDR
 - Some real-time implementations exist or could be purchased
 - Research: [Lapray_2014]
 - Industry: <https://www.xilinx.com/products/intellectual-property/1-h8x9c8.html>
- Video drawback
 - HDR reconstruction of dynamic scenes needs careful handling of dynamic objects to prevent ghosting.
 - Some real-time ghost removing exist
 - Research: [Bouderbanne_2016]
 - See example next slide...



[Lapray_2014] PJ Lapray, B Heyrman, D Ginjac. [HDR-ARTiSt: an adaptive real-time smart camera for high dynamic range](#) imaging. In Journal of Real-Time Image Processing, 2014.

[Bouderbanne_2016] Mustapha Bouderbane, Pierre-Jean Lapray, Julien Dubois, Barthélémy Heyrman, Dominique Ginjac. [Real-time ghost free HDR video stream generation using weight adaptation based method](#). In ICDSC, 2016.

Digression: HDR drawback

- Ghost artefacts may appear after HDR reconstruction [Granados_2013]



HDR tone mapped image
With ghost artefact



Ghost removed

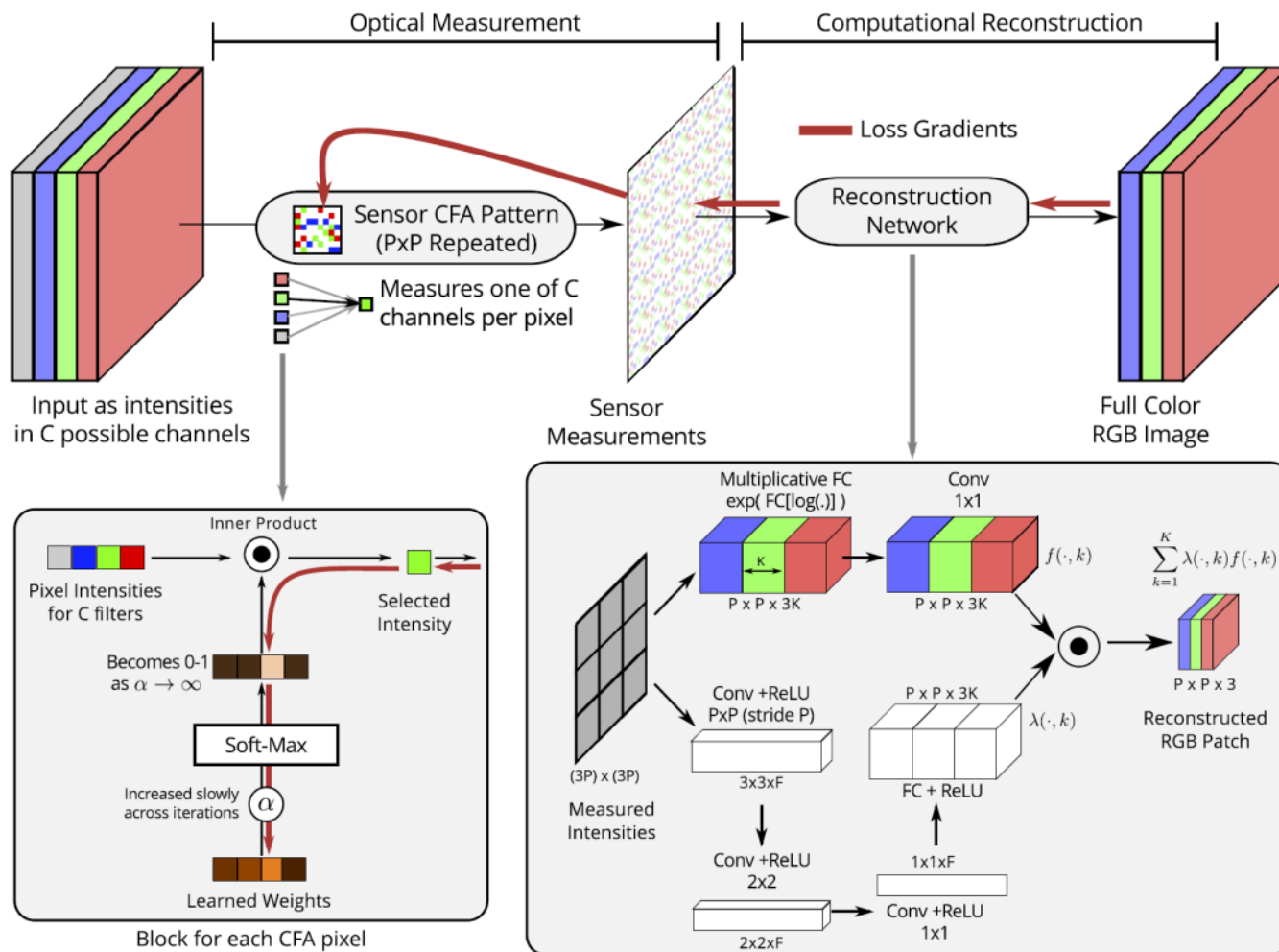
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Outlines

- 1-Generalities (20 min) (JB)
 - Intro on multispectral imaging
 - SFA definition and components
 - Imaging pipeline definition
- 2-Practical instantiations, databases and applications (40 min) (all of us)
 - Incl. a topo on architecture (PJ)
 - Five-bands camera in the visible domain (Y)
 - RGB-NIR camera (Y)
 - Eight-bands camera visible-NIR (JB/PJ)
 - Other state-of-the art
- 3-Demosaicing, pattern and data processing (30 min) (Yusuke)
 - Incl. color or spectral correction when NIR/visible overlap.
- 4-Insight on image quality (20 min)(PJ)
 - Incl. HDR
 - Incl. no-reference metrics tentative
- 5-Wrap up, future directions and questions (20 min) (all of us)

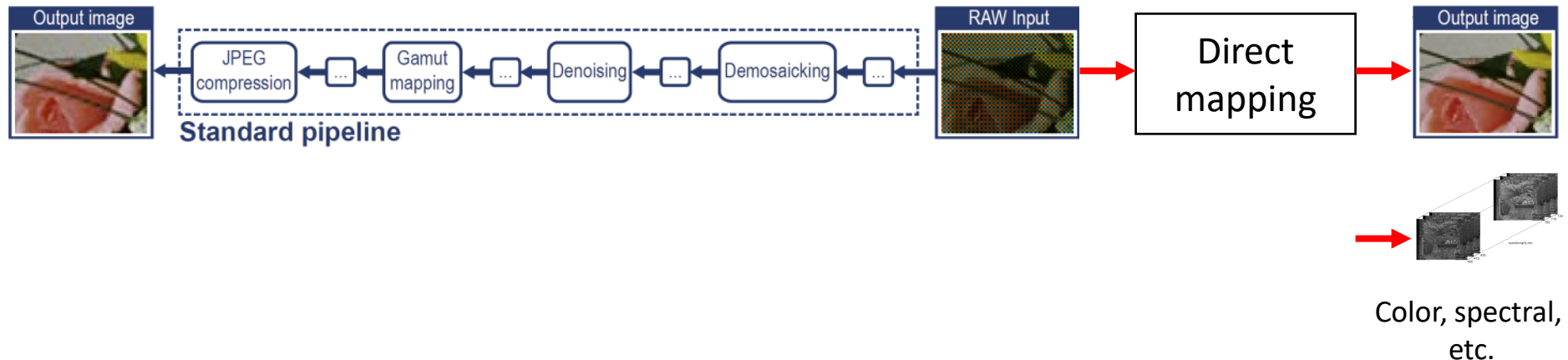
Learning-based sensor desing and processing

- CFA pattern design based on learning



Future directions: Direct RAW to target mapping/reconstruction

- Directly reconstruct target images/data from RAW spectral data
 - Deep learning
 - Optimization with natural image priors
 - etc.

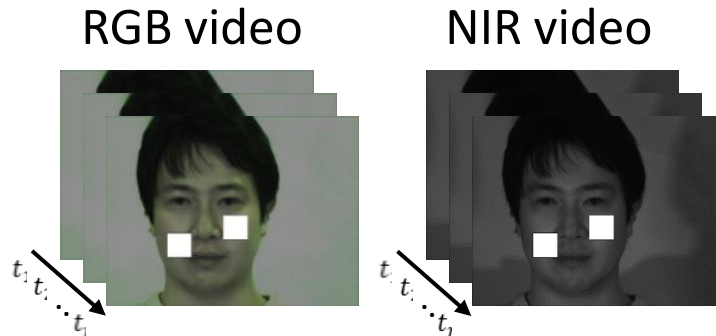


Heide et al., "FlexISP: A flexible camera image processing framework," Siggraph Asia, 2014.

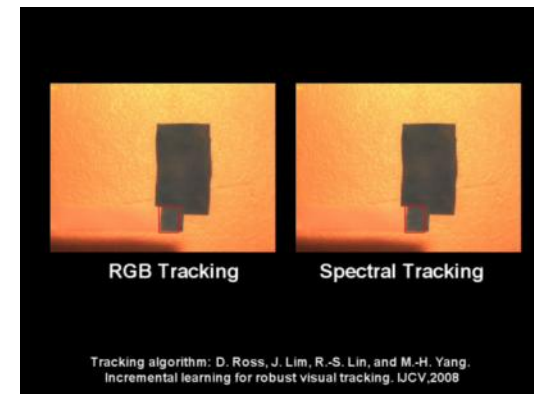
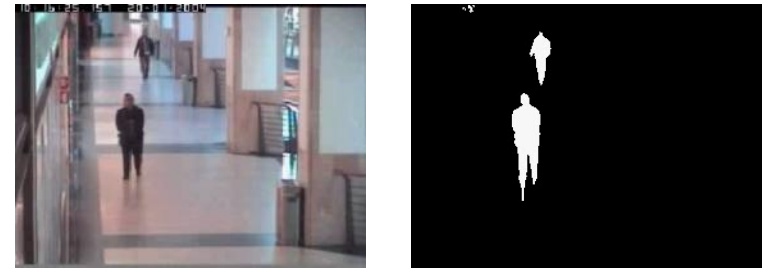
Future directions: Spectral video sensing

- SFA technology reduces the cost of video sensing
 - Applications with spectral video sensing

Spectral biomedical imaging



Spectral tracking



X. Cao et al., "High resolution multispectral video capture with a hybrid camera system", CVPR, 2011.

Open questions

- How to evaluate the image quality?
- Do we really need demosaicing?
- Can we provide a stable and normalized spectral representation across sensors, time, illuminant and materials?
- What really matters?
- **One** generic sensor or niche-market sensor**S**?
- We discussed spectral, but it could be polarization or integration time that varies