Computational Colour and Spectral Imaging

"Advanced Colour and Spectral Imaging"

Chapter 3: Spectral characterization of imaging devices

Javier Hernández-Andrés and Eva M. Valero
javierha@ugr.es valerob@ugr.es
Colour Imaging Lab (*colorimaginglab.ugr.es*)

COLOUR IMAGING LAB
University of Granada
SPAIN

UNIVERSIDAD DE GRANADA

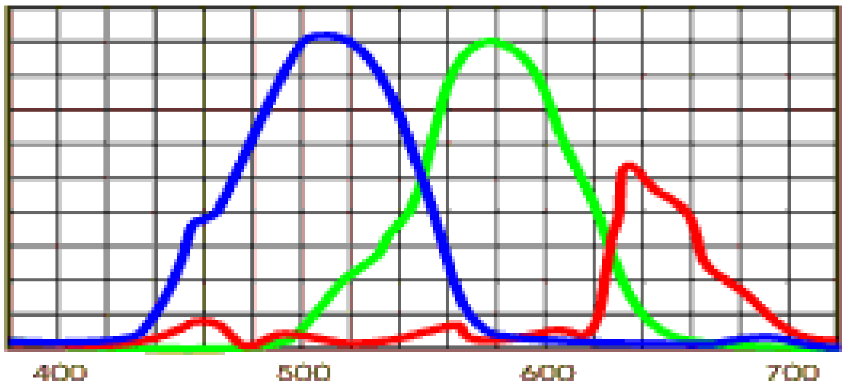
Departamento de Óptica, Facultad de Ciencias,
Universidad de Granada, 18071-Granada (SPAIN)

- Light $L(\lambda)$ Light Spectral Power Distribution
- Sample $R(\lambda)$ Sample Spectral Reflectance
- Optical path $O(\lambda)$ Optical path Spectral Transmittance
- Filter $T(\lambda)$ Filter Spectral Transmittance
- Sensor $S(\lambda)$ Sensor Spectral Responsivity
- Final response ρ Final response

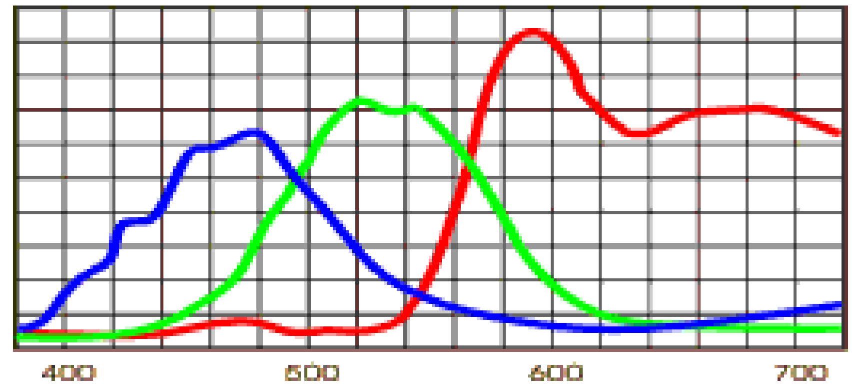
$$\rho = k \int_{\lambda_{\min}}^{\lambda_{\max}} L(\lambda)\, R(\lambda)\, O(\lambda)\, T(\lambda) \boxed{S(\lambda)} d\lambda + n$$

$$\rho = k \int_{\lambda_{\min}}^{\lambda_{\max}} L(\lambda)\, R(\lambda)\, O(\lambda)\, T(\lambda)\, \boxed{S(\lambda)}\, d\lambda + n$$

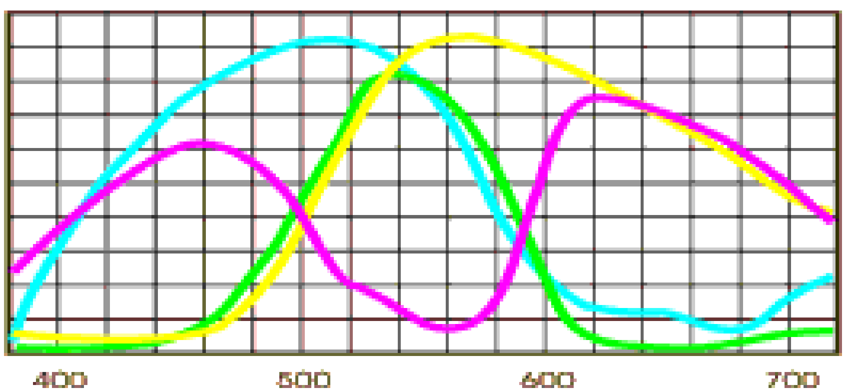
Nikon D1X



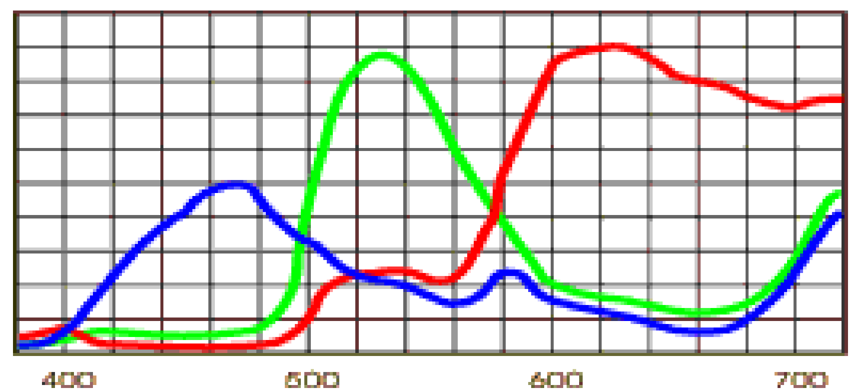
Leaf Aptus



Canon CGMY



Kodak



Some questions for this chapter

1. What a demosaicing algorithm is?
2. What are DAC values and ADC values?
3. If you need to use your camera for scientific purposes what will be the most convenient image format?
4. The quality of a image acquisition device depends on….
5. Why a Bayer sensor array has 2 G pixels, 1 R and 1 B?
6. What does SLR mean?
7. What does LCTF mean?
8. What is the “fill factor” of a pixel?
9. How could you know if your camera is sensitive to the near-IR?
10. What is a cut-off filter?
11. What is speckle? How we can reduce it?
12. What is a tunable laser?

Some questions for this chapter

13. Do we have to take care about polarization when using LCTFs?
14. How many types of errors do we have to consider?
15. How the responsivity of a sensor could be measured?
16. Others…

1. Some basics on image acquisition devices.

1.1. Color image capture devices

2. Experimental measurement of spectral response curves

3. Spectral characterization with color filters

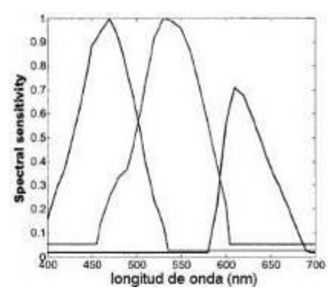
3.1. Direct procedure for a monochrome camera with a LCTF

3.2. Indirect procedure for an RGB digital camera

4. Sources of noise. How to minimize its influence on the image capture process.

4.1. Sources of noise in image acquisition with a digital camera

4.2. Camera characterization and noise minimization procedures



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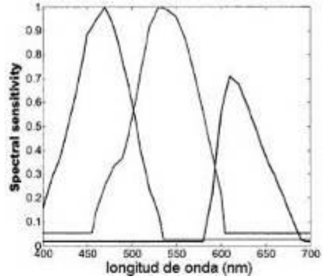
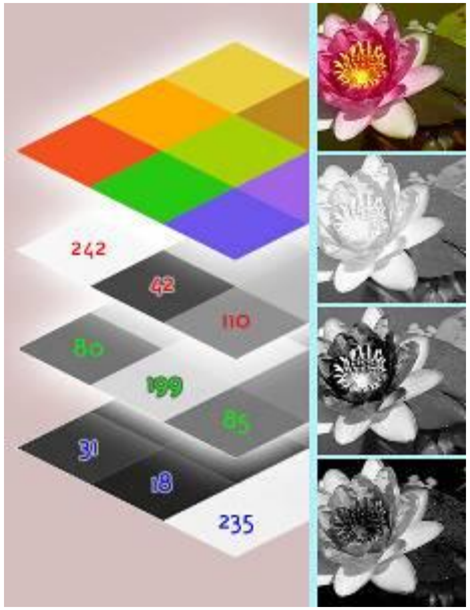


1.1. Color image capture devices

Image capture devices: used to "read" the real world by transforming the real images in RGB values (flat quantized values).

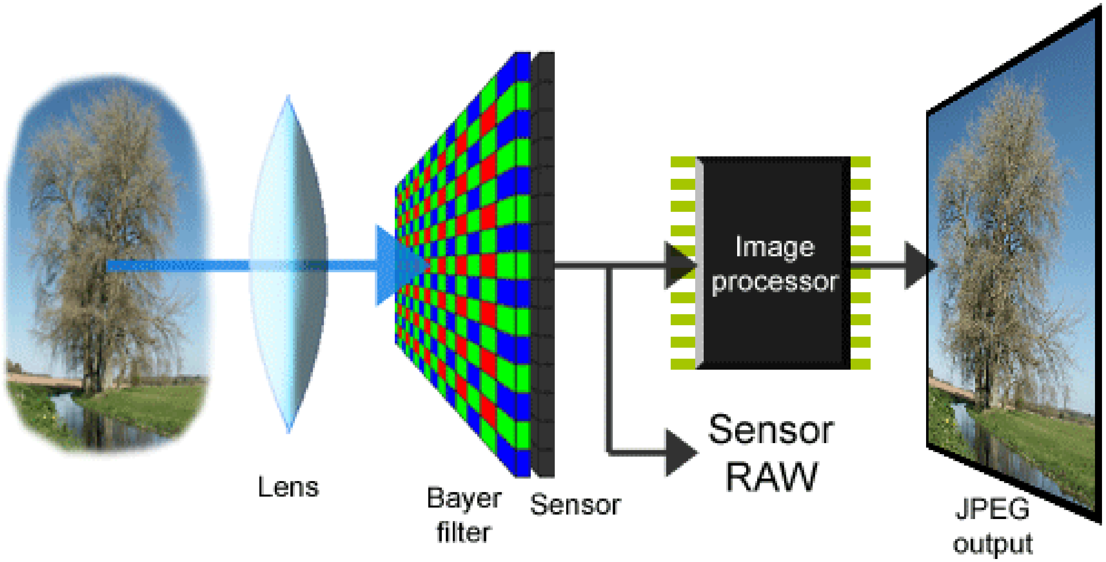
CCD color camera

Flatbed color scanner



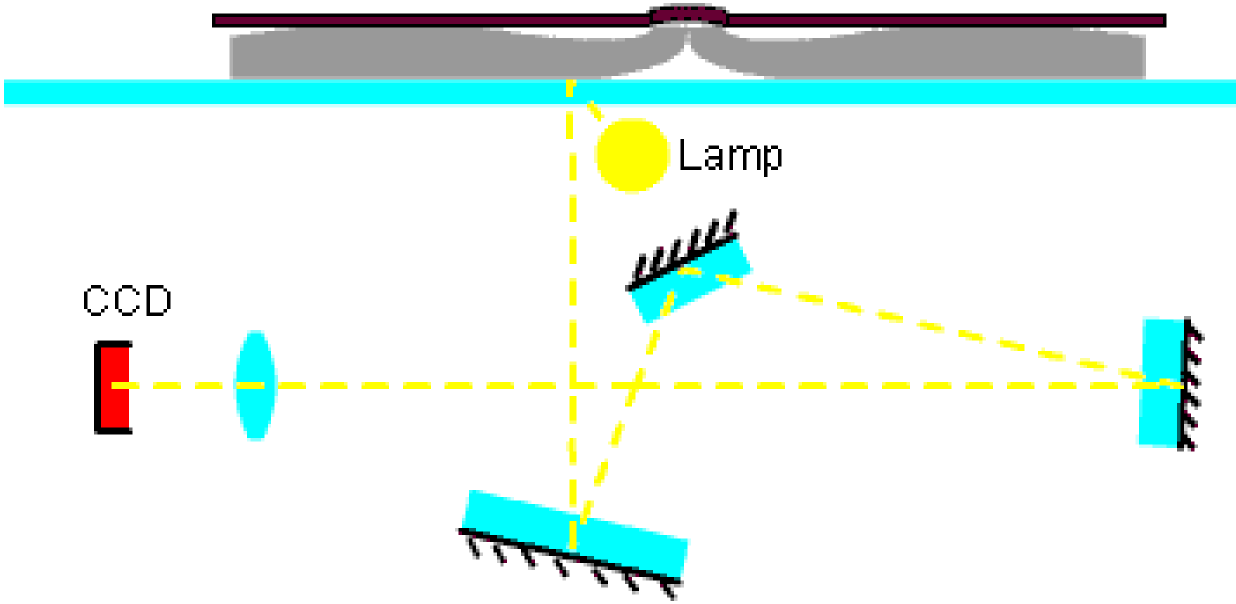
Images: organized sets of RGB pixels (three values).

A digital camera works by focusing the image in the sensor area (CCD or CMOS)…



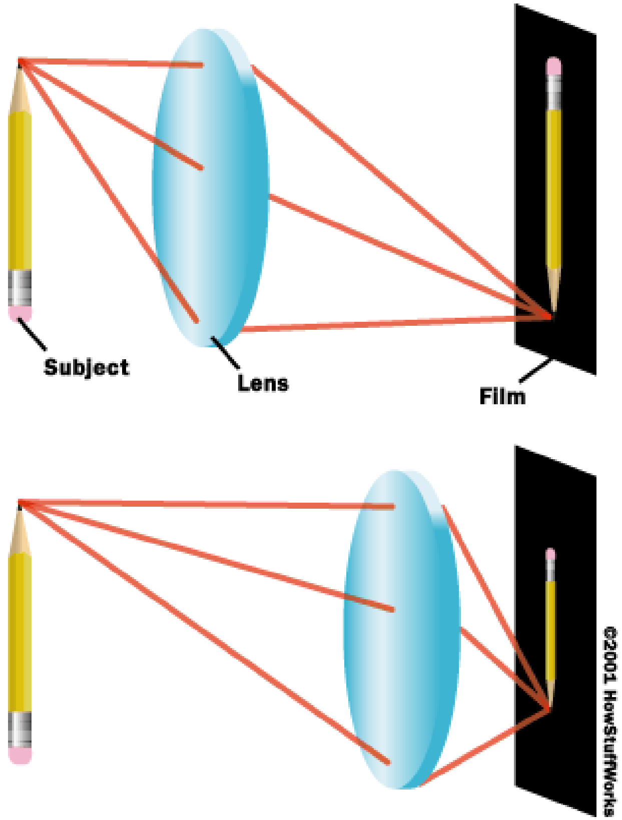
… and then, processing the image (digitalization, compression, etc).

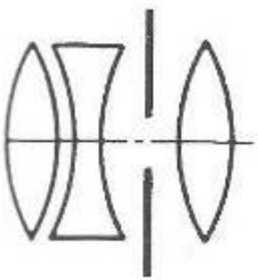
- A color scanner works by focusing lines of the sheet into the sensor (usually with the aid of mirrors)…

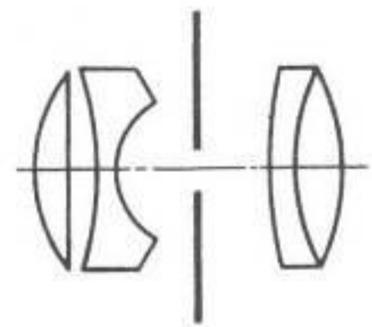


… and then, processing the image (digitalization, compression, etc).

The first acquisition element: the lens or optical system





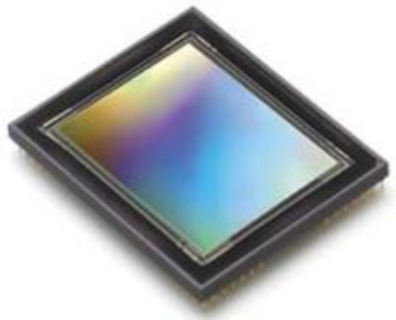


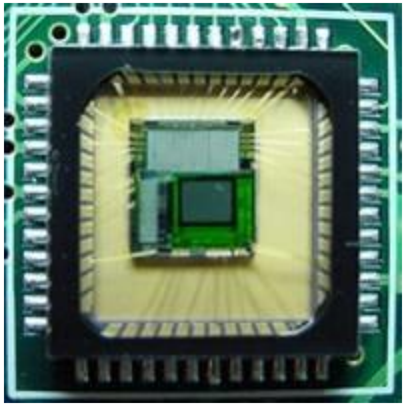
For digital cameras (conventional or reflex), optimized design according to focal length and aberration control

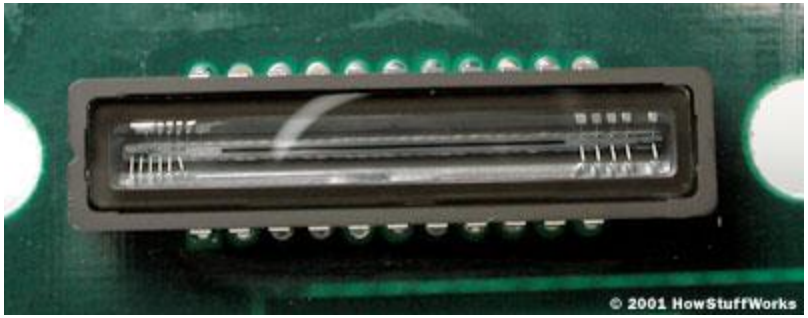
Focal length, SLR (single lens reflex), depth of focus, aberrations, field of view, lens aperture, F-number, optical quality, etc.

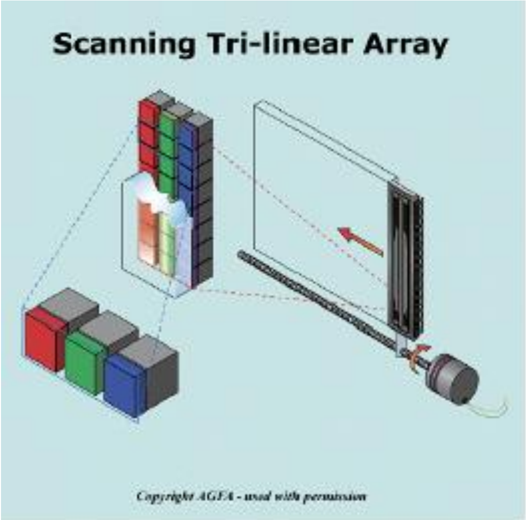
At the core of a color image capture device is placed the SENSOR.

Surface sensors for cameras (CCD or CMOS)





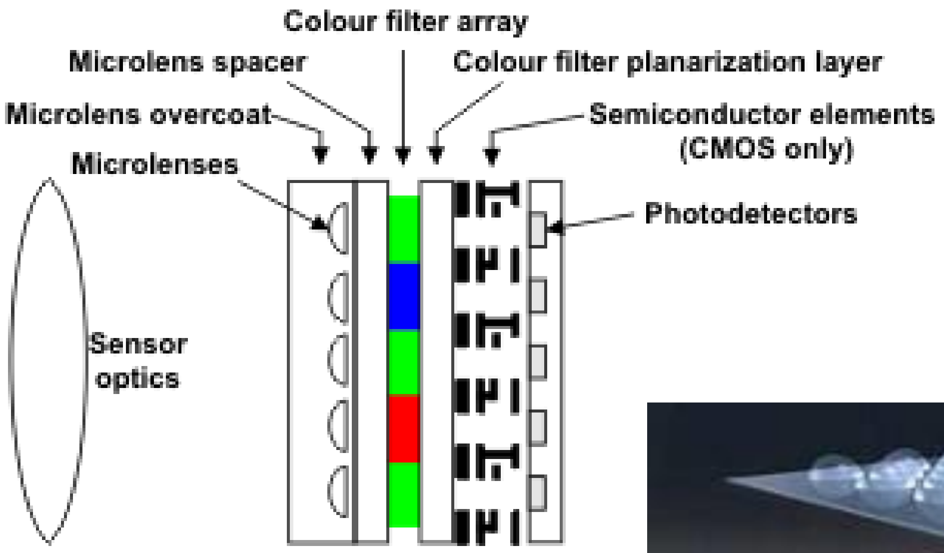


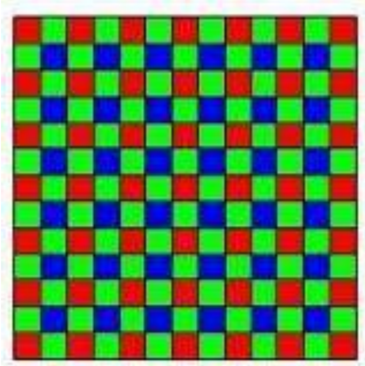


Line sensors for scanners (CCD or CIS)

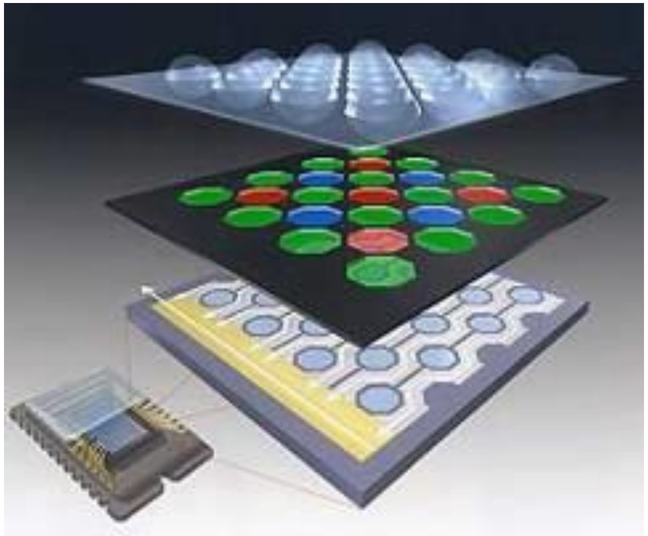
Spatial resolution: limited by number of pixels, pixel size, optics, motor movements

For conventional (non 3-CCD) cameras (one-shot capture technology), a color mask is placed in front of the sensor to capture a color image and interpolating...





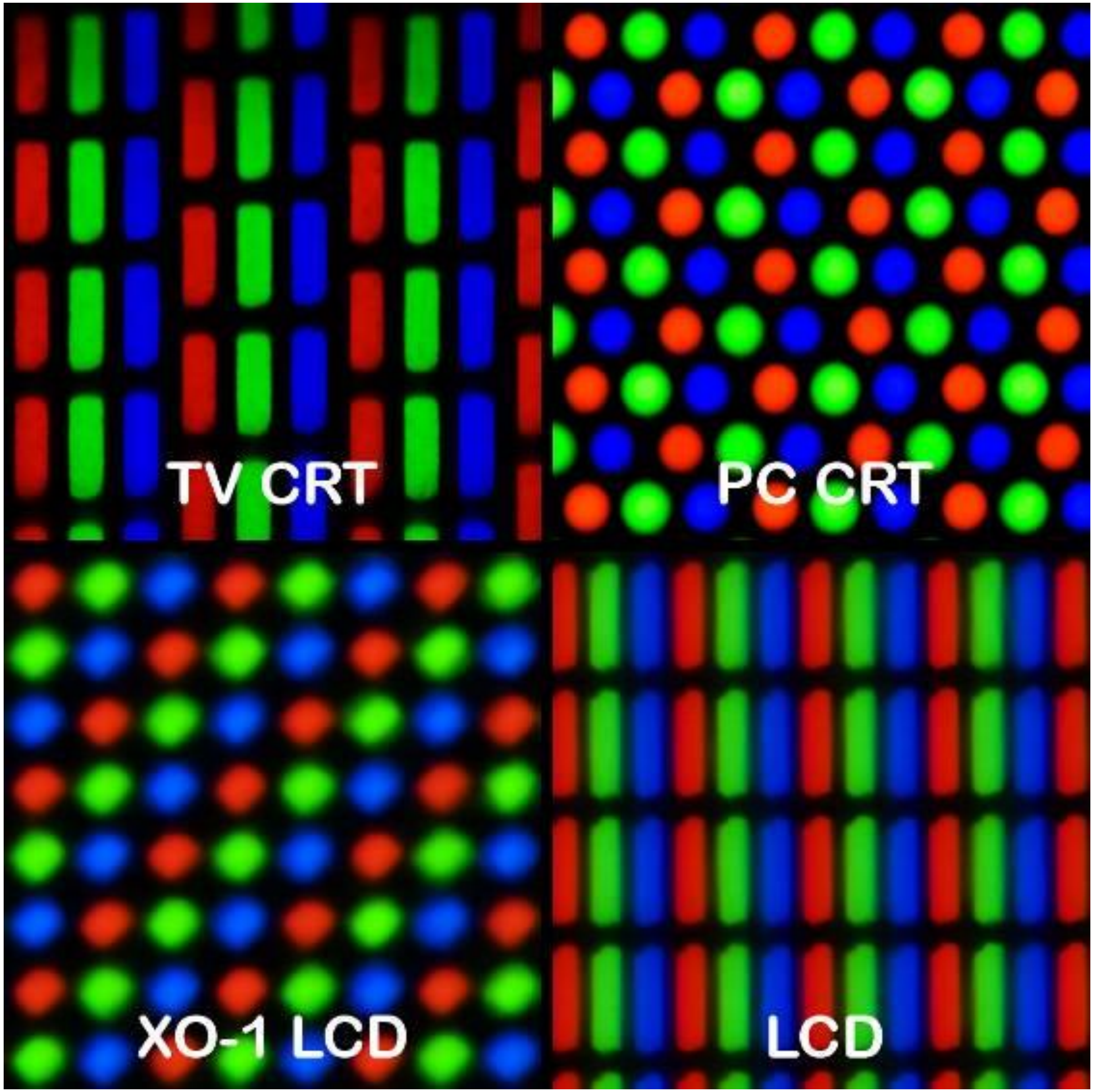
Bayer filter



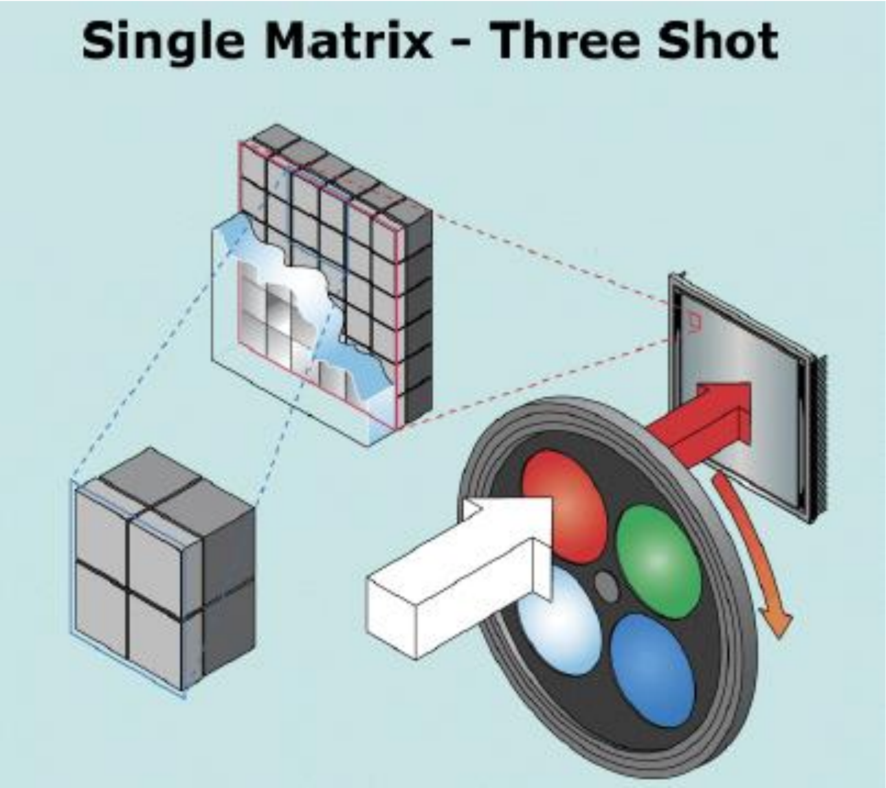
The RGB values correspond actually to adjacent pixels...

Interpolation: demosaicing

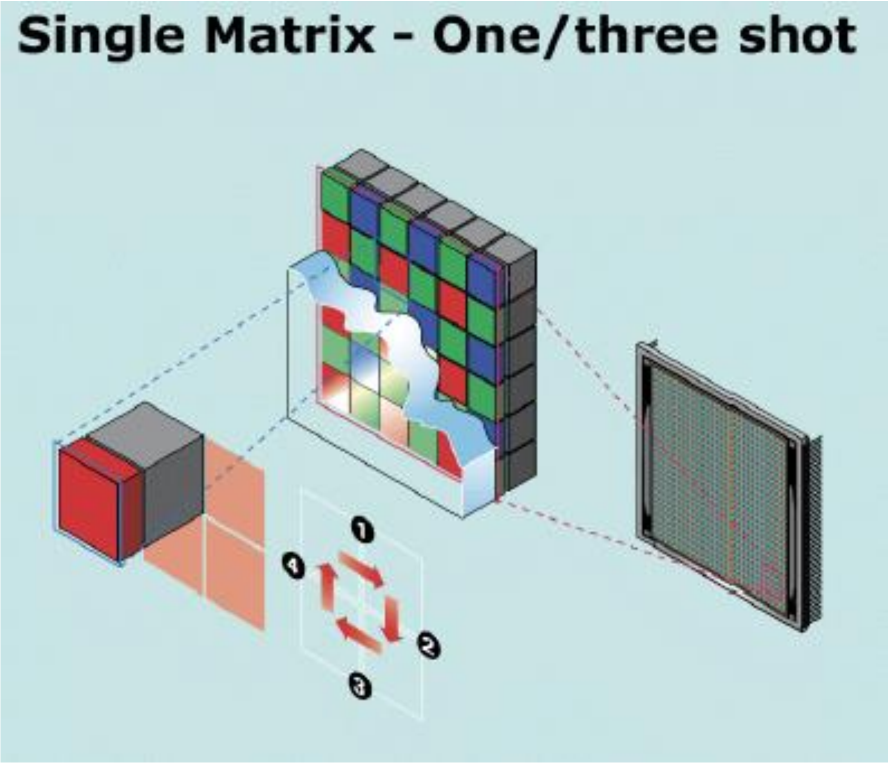
Bee-hive arranging


TV CRT
PC CRT
XO-1 LCD
LCD

Available technologies for attaining full-color resolution (I)



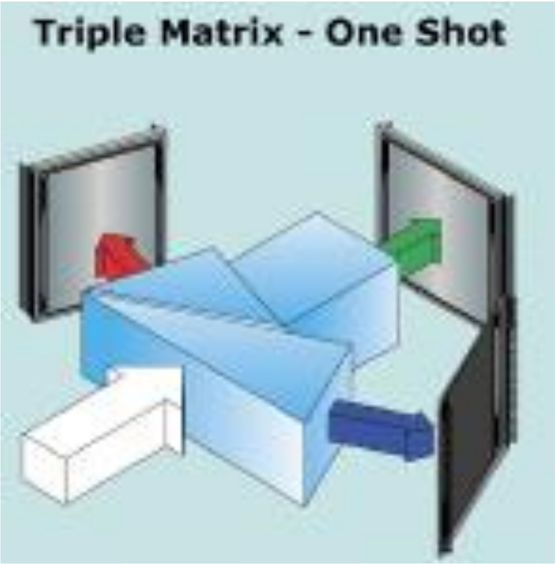
Filter wheel implemented into the camera body. Does not allow “real action” captures. No interpolation is needed.

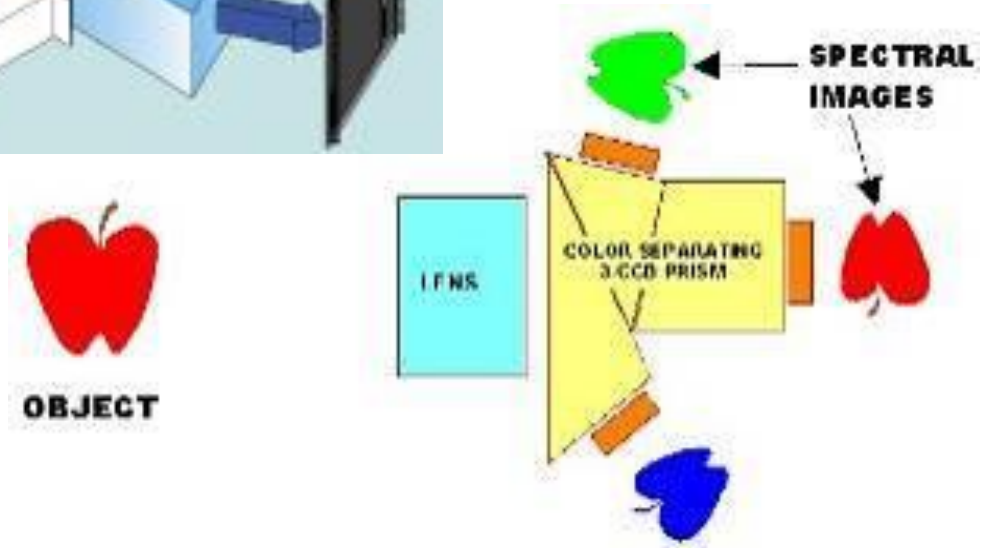


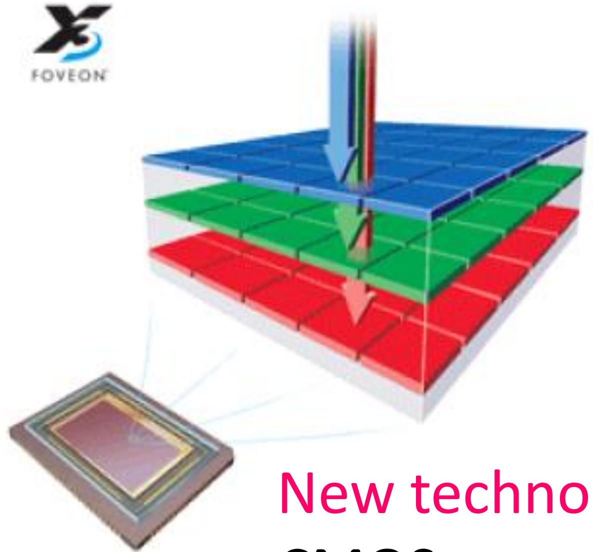
Displacing the sensor by one pixel in three different directions. Does not allow “real action” captures.

Available technologies for attaining full-color resolution (II)

For 3-CCD cameras, the light is filtered through three different huge color filters so that each RGB corresponds to 1 pixel



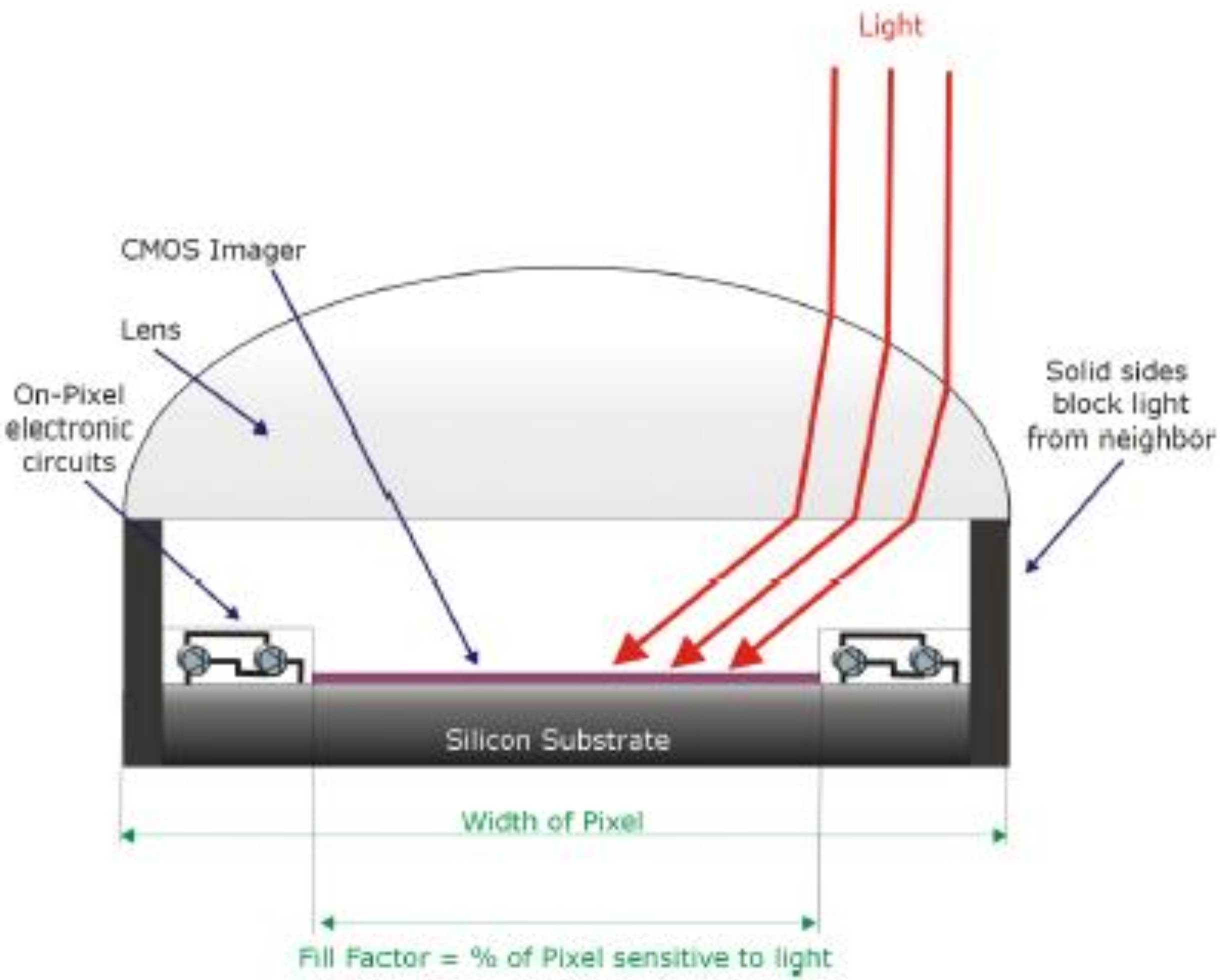




Copyright Foveon,

New technology by Foveon (X3). Three successive CMOS sensors with absorb selectively blue, green and red (based on sensor depths)

Micro-lenses are placed in front of the sensor to bend light towards the sensitive part of the pixel.



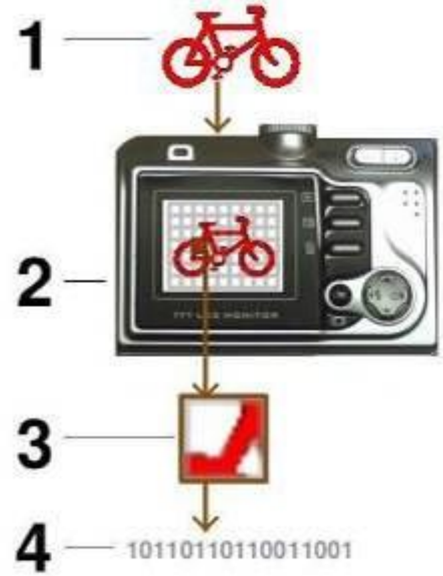
Fill factor: amount of the pixel surface which is sensitive to light.

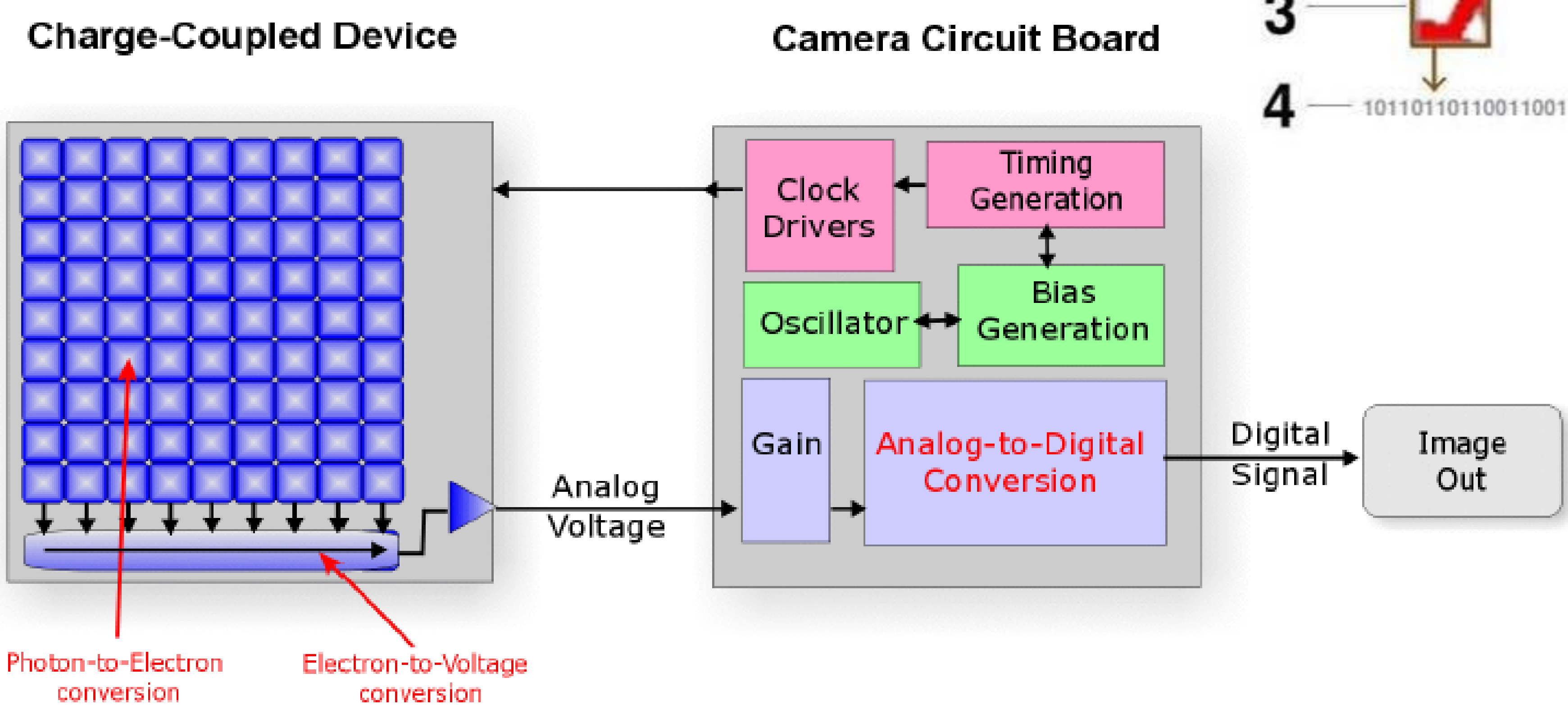
Typical values of fill factor:

CCD: 95 %

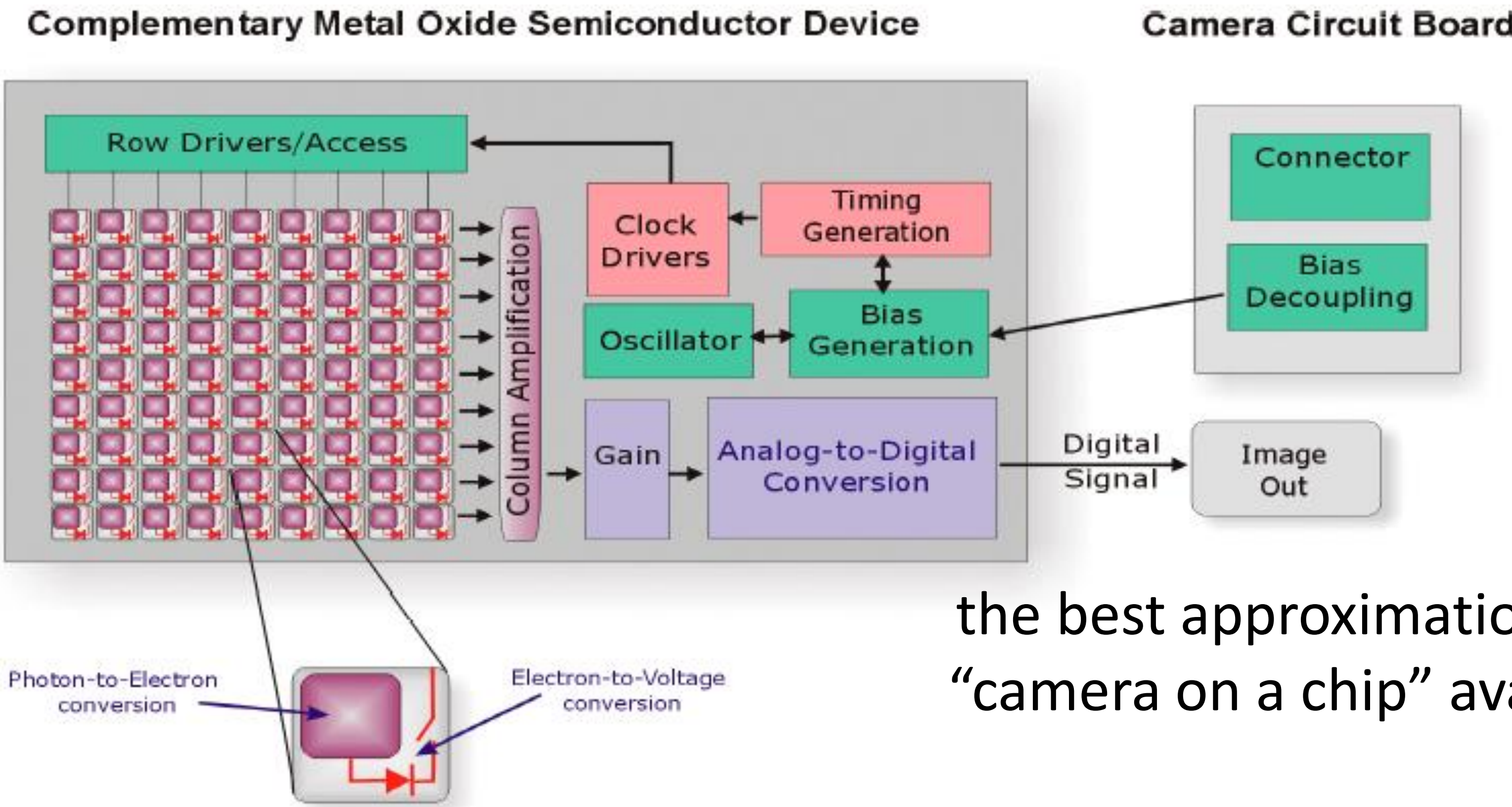
CMOS: 50-60%

CCD sensors: the charge is stored in each pixel and then read line-by-line and transferred in this way to the voltage conversion, which is placed below the sensor matrix and protected from stray light





CMOS sensors: charge storage and electro-to-voltage conversion pixel-wise. The rest of the circuitry for timing the readings and analog-to-digital conversion is implemented apart but in the same chip.



the best approximation to a "camera on a chip" available

- small transistor in each pixel
- it needs a lower number of chips to perform all the necessary operations of image capture than CCD cameras

Summary of differences between CCD and CMOS (probably old!)

CCD	CMOS
Long history of high quality performance	Lower performance in past, but now providing comparable quality
High Dynamic range	Moderate Dynamic range
Low noise and best dMax	Noisier, but getting better quickly
Well established technology	Newer technology
High power consumption	Relatively low power consumption
Moderately reliable	More reliable due to integration of chip
Small pixel size (small sensors – best to develop new cameras and lenses)	Larger pixel size (larger sensors – easier to use within current camera technology)
Needs lots of external circuitry	All circuitry on chip
High Fill Factor	Lower Fill Factor
CCD creates analogue signal that is digitised off the chip	CMOS creates a digital signal on chip

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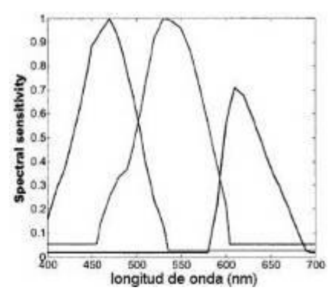


Spectral imaging acquisition process:

1. **Spectral characterization of the imaging system**
2. Image acquisition
3. **Correction of the camera responses for noise, non-linearity, and non-uniformity. Probably an image registration process!**
4. Obtaining spectral reflectances (or radiances or irradiances or transmitances) from the corrected camera responses

Spectral imaging acquisition process:

1. Spectral characterization of the imaging system

- All the settings of the device (lens aperture, integration time, etc.) are set to known values.
- Integration time:
  - Minimal
  - Image signal high
  - Avoid saturated pixels
- Camera spectral responsivities (sensitivities), non-linearities, non-uniformities, etc.

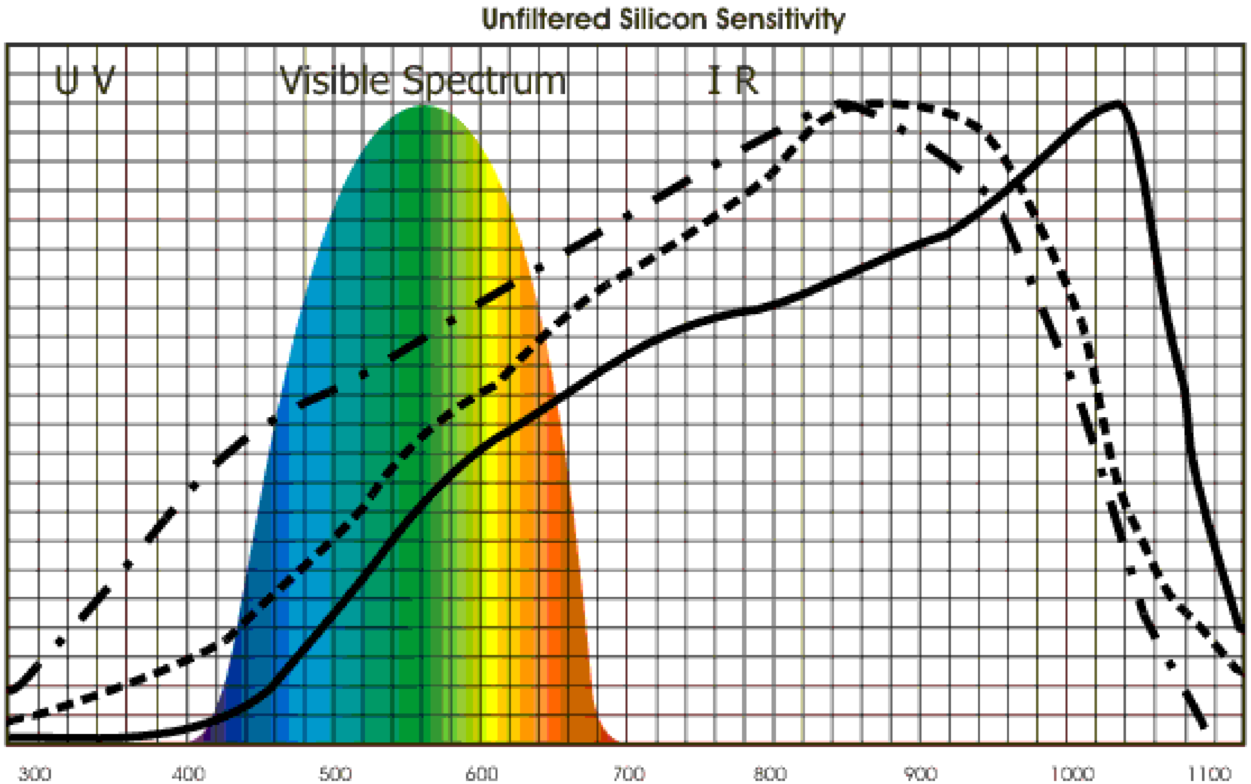
Spectral responsivity (sensitivity) of sensors:

$$\rho = k \int_{\lambda_{\min}}^{\lambda_{\max}} L(\lambda)\, R(\lambda)\, O(\lambda)\, T(\lambda)\, \boxed{S(\lambda)}\, d\lambda + n$$

Which $\lambda_{\max}$ $\lambda_{\min}$?

Spectral responsivity (sensitivity) of sensors:

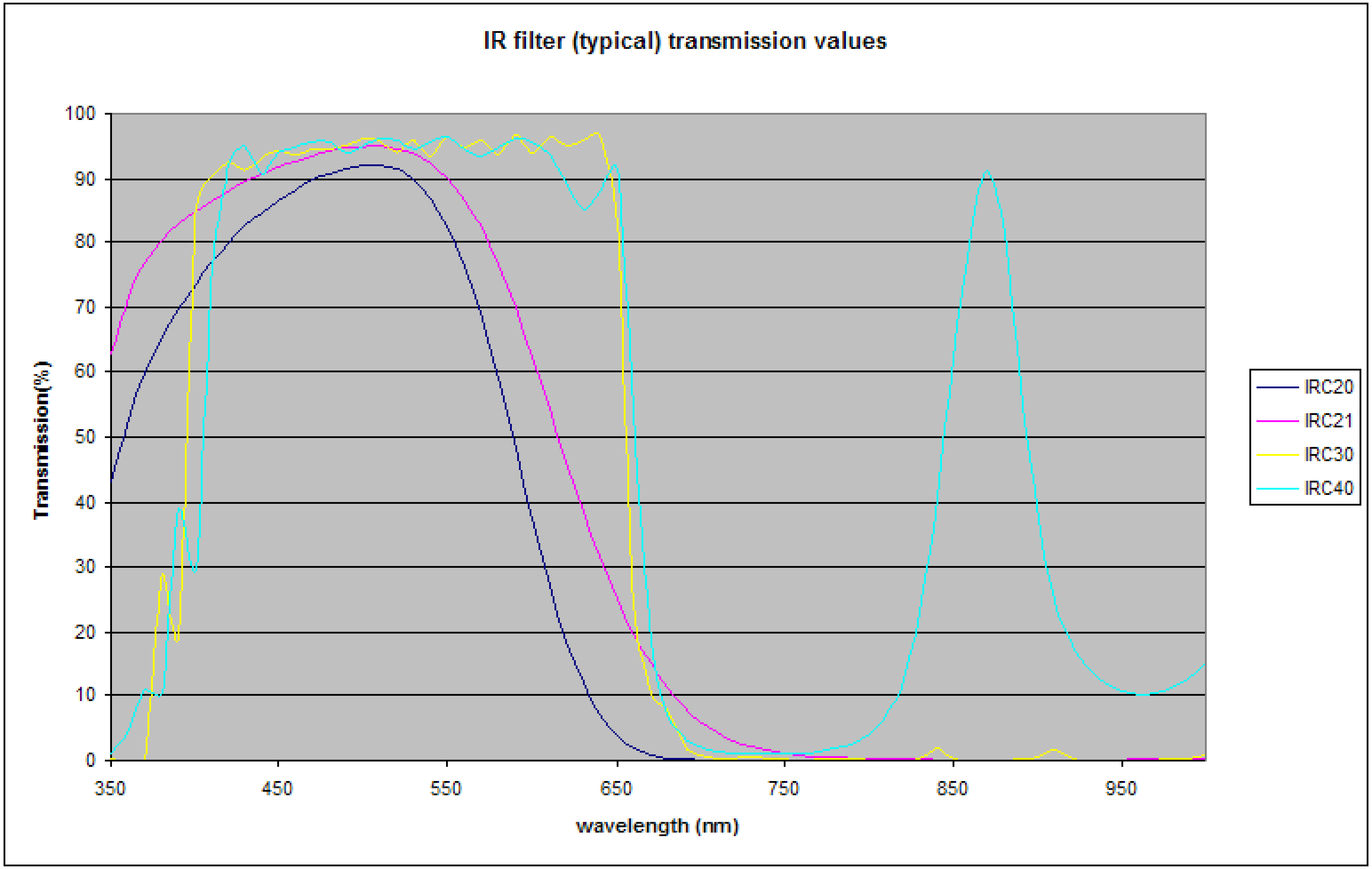
Units?



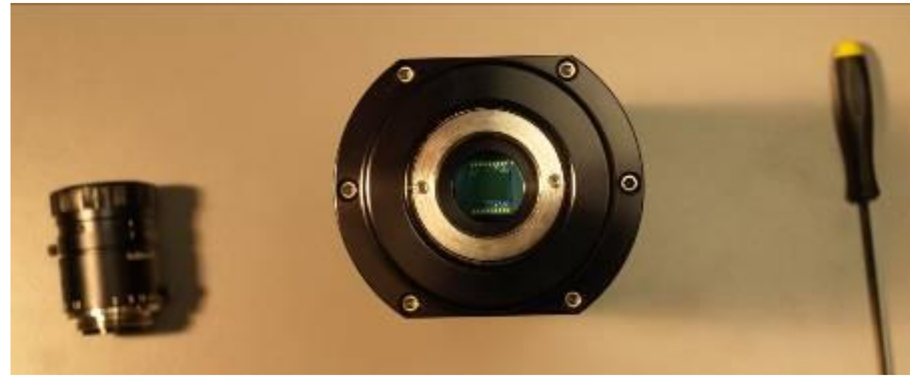
Sensor relative response to different wavelengths in or out the visible spectrum. Silicon sensors are usually more sensitive outside the visible spectrum. Can we take advantage of this?

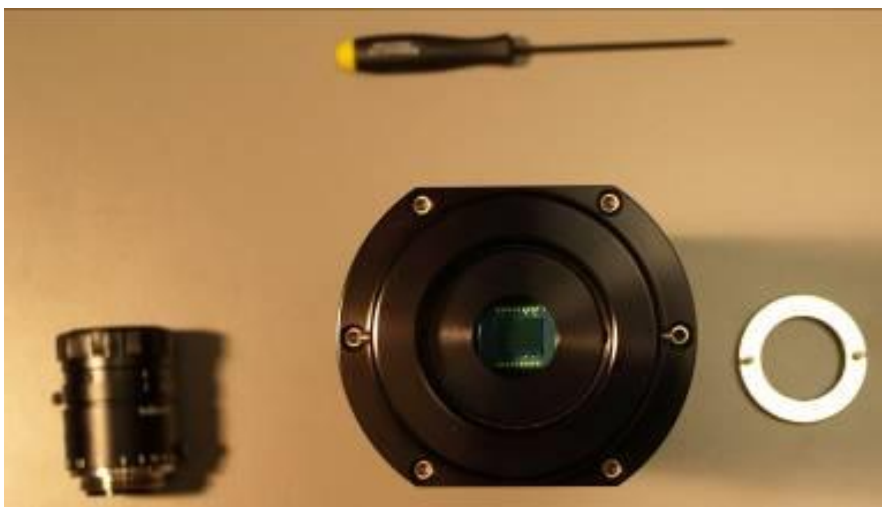
Curiosity: Fredembach & Süsstrunk, *"Colouring the near-infrared"* or L Schaul et al. *"Color image dehazing using the near infrared"*

Infrared (IR) cut-off filters are used with color CCD or CMOS imagers to produce accurate color images. An IR cut-off filter blocks the transmission of the infrared while passing the visible.

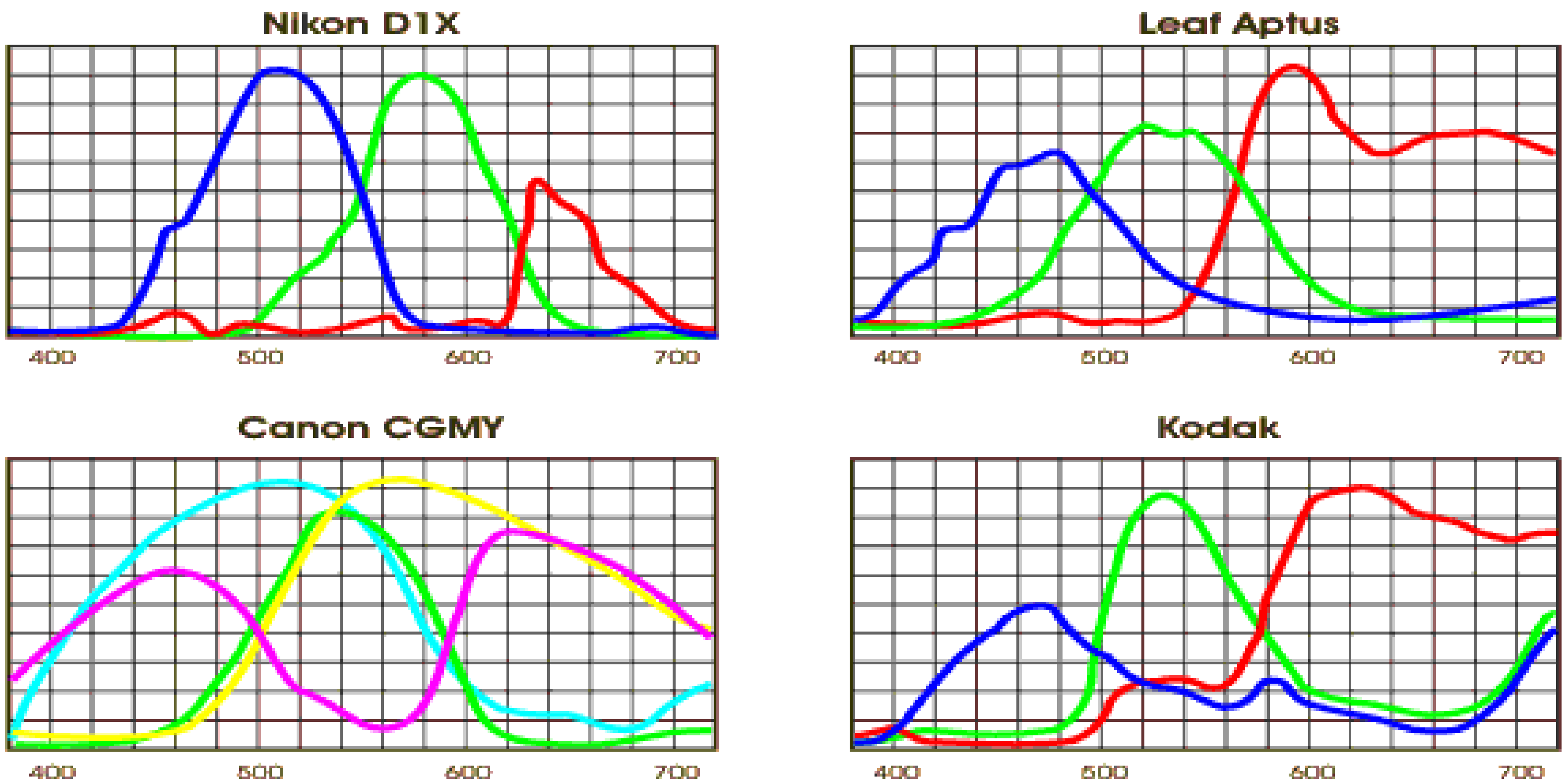


Removing the IR cut-off filter in the Retiga RGB camera





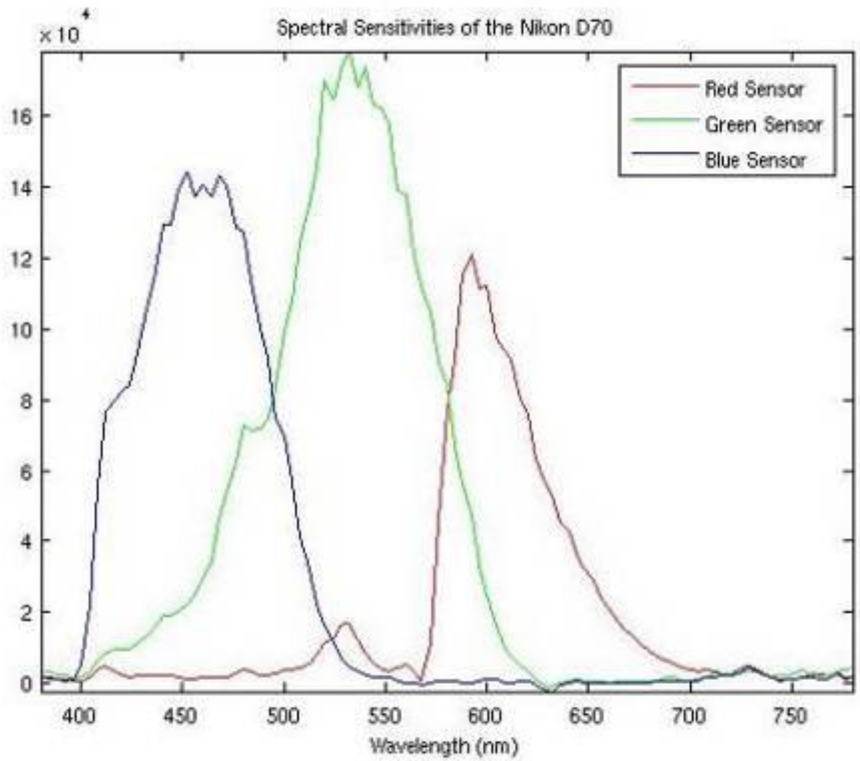
For RGB devices, we have usually a IR-blocking filter and the three color filters (either Bayer or whole-area).



So we say that these systems have three channels or sensors. **If we place additional color filters in front of the lens, we will have three additional "sensors" for each color filter. More about that in a next chapter…**

What do we want the spectral response curves for?

????



Nikon D70 digital camera (measured)

Useful for computing simulations or camera or system responses (noiseless case).

$$\rho_k = \sum_{n=1}^{N} L(\lambda_n)\, S_k(\lambda_n) \qquad (1)$$

Camera responses (RGB)

Sensor spectral responsivity

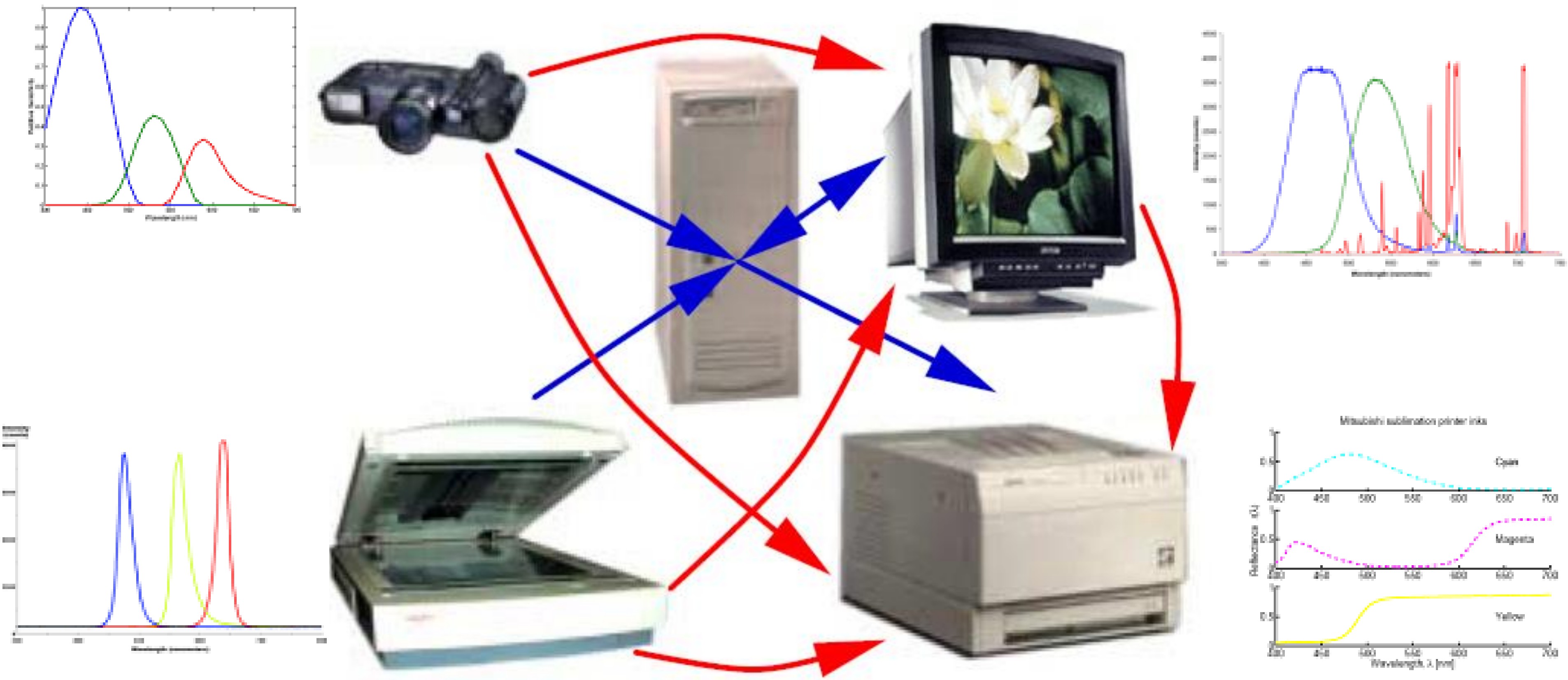
Any assumptions in the equation?

$$\rho = S^t L$$

kx1 kxN Nx1

Useful for implementing “translators” between different digital devices in a **color management system** (CMS).

Image from Hardeberg’s dissertation.



How can we measure them?

Which devices do we need to measure S(λ)?

How should we do the measurements?

Could we estimate S(λ) instead of measuring?

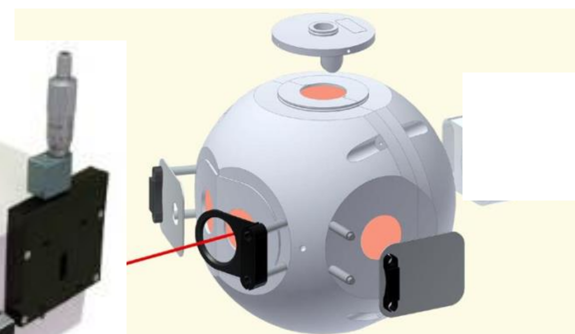
How can we measure them?

Direct method: determination of camera responses for stimuli of a given wavelength

Experimental arrangement (I)

1. Light source

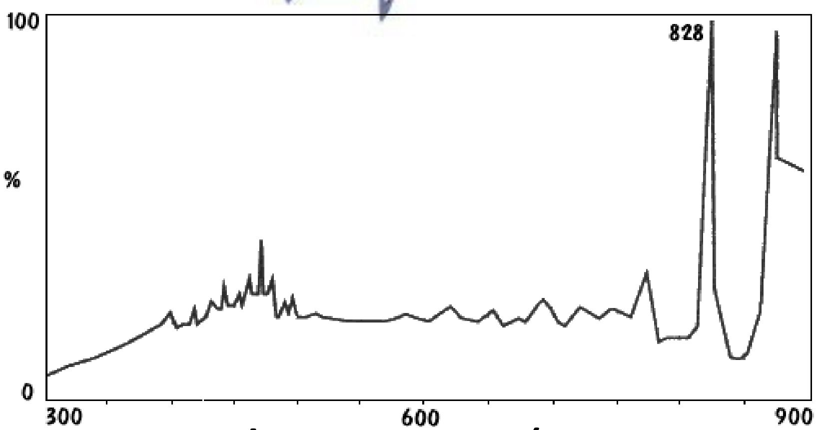
2. Monochromator



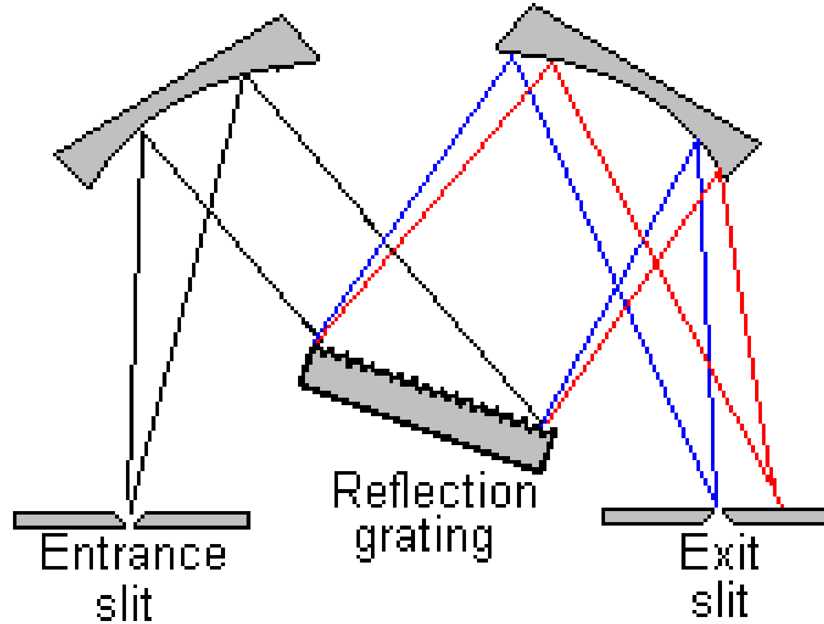
3. Integrating sphere

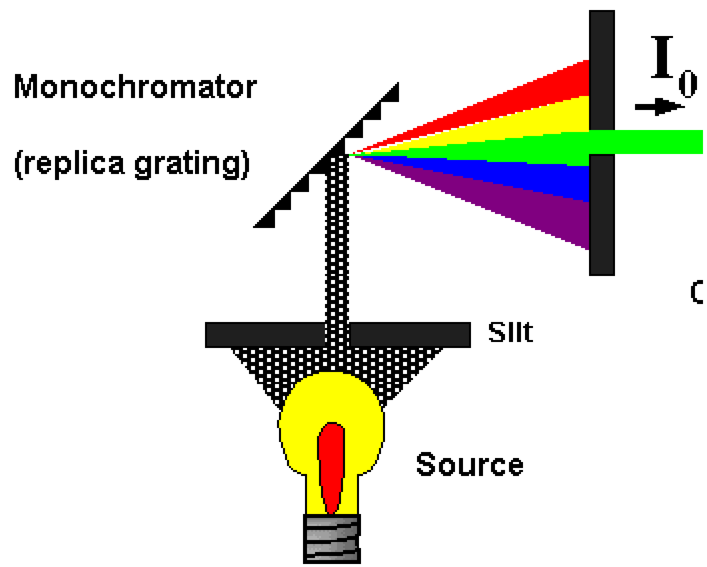
4. RGB camera

Experimental arrangement (I)



1. Light source (eqs. Xenon Lamp)

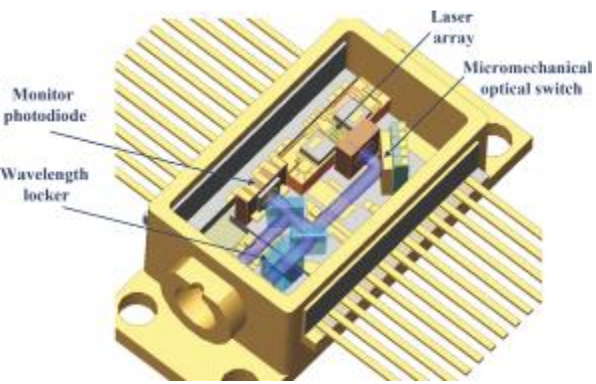




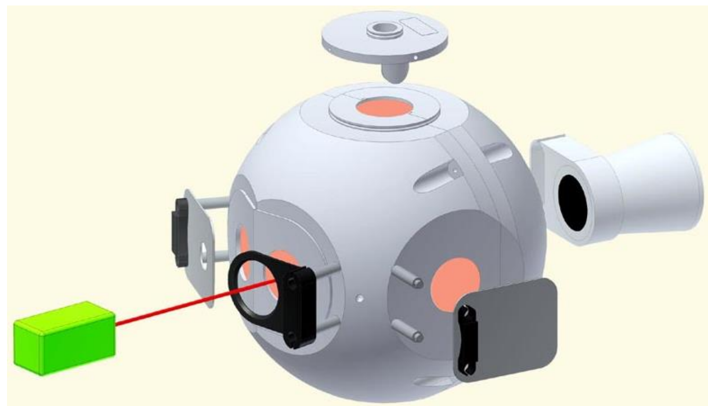
2. Monochromator

Direct method: determination of camera responses for stimuli of a given wavelength

Experimental arrangement II



1. Light source (tunable LASER)



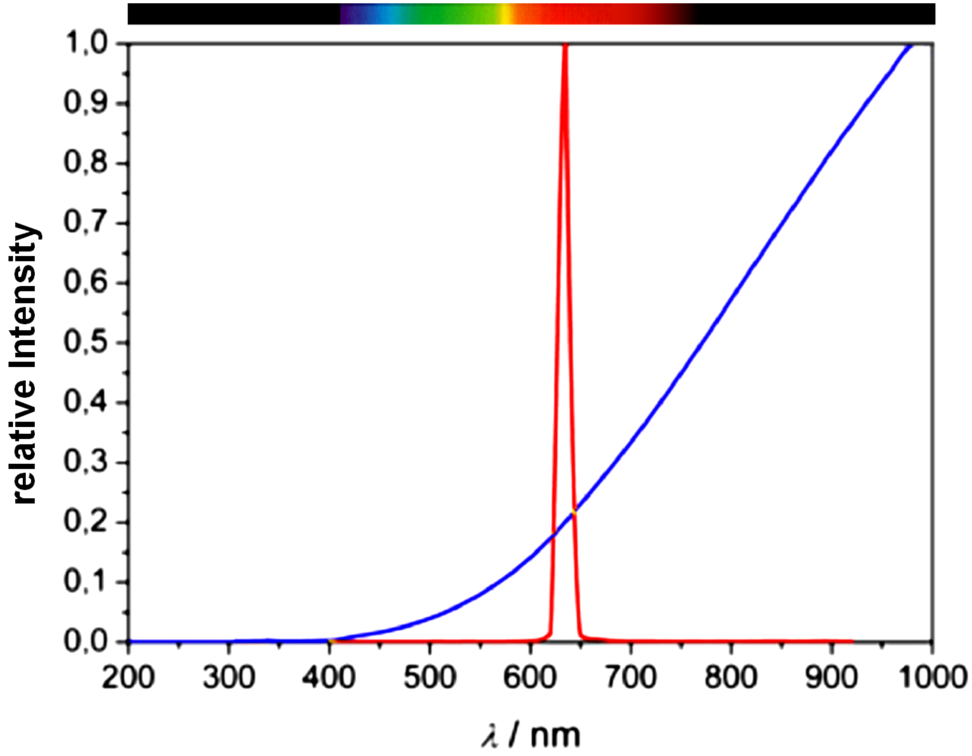
2. Integrating sphere

3. RGB camera

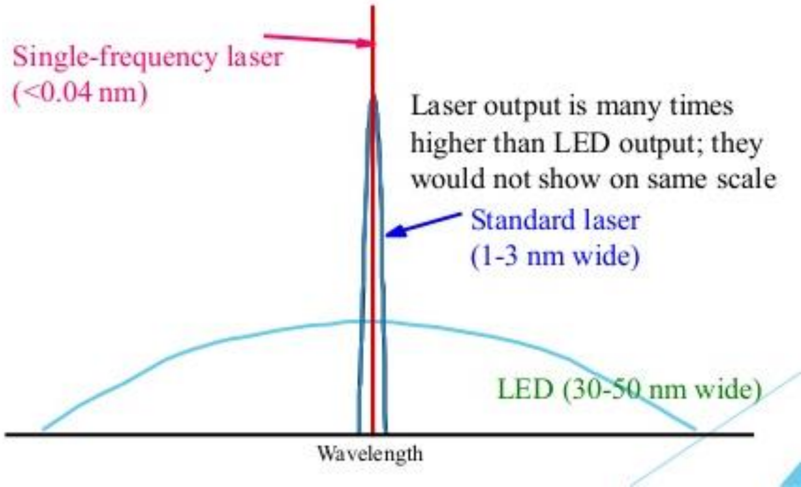
It is necessary to correct the speckle

Experimental arrangement (II)

1. Light source (tunable LASER)

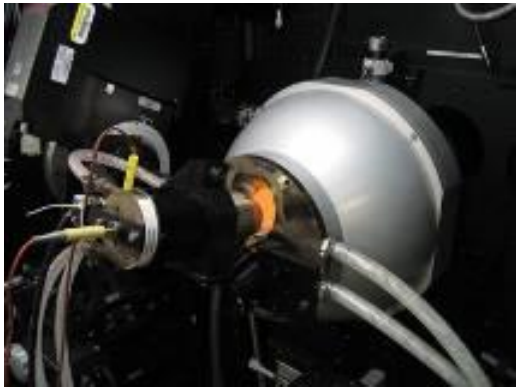


LED vs. laser spectral width



Tunable LEDs?

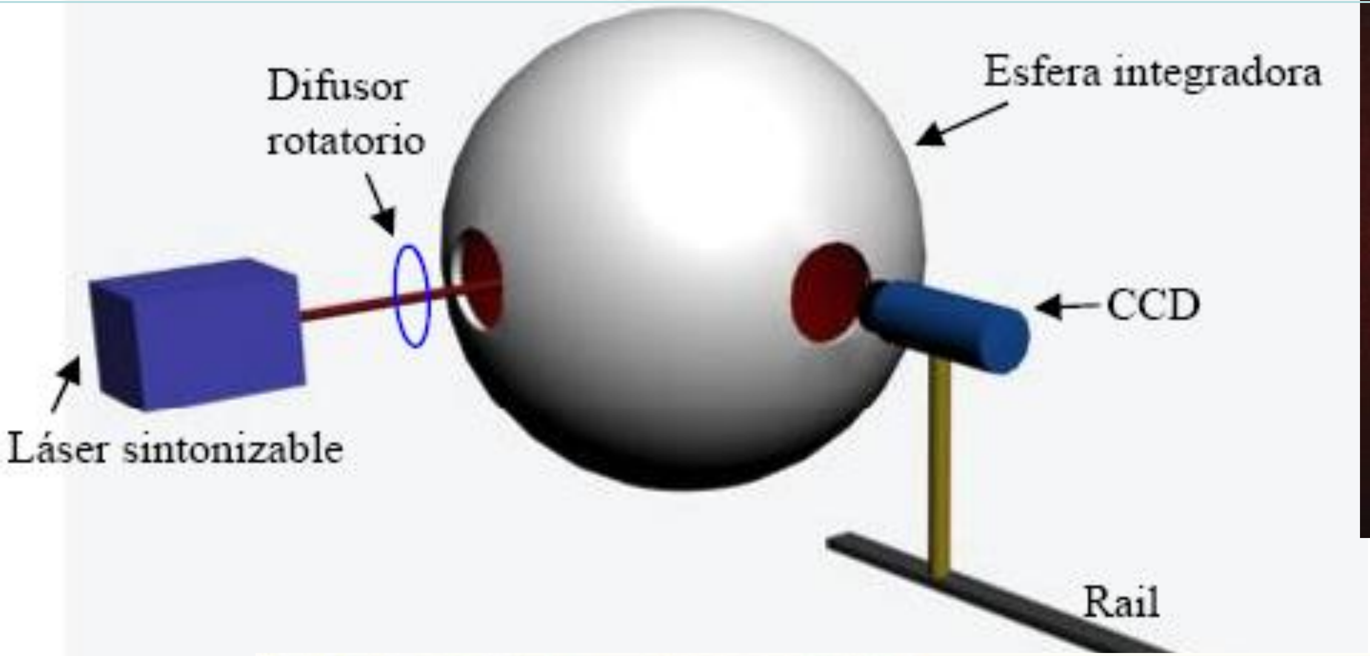
-The Integrating sphere

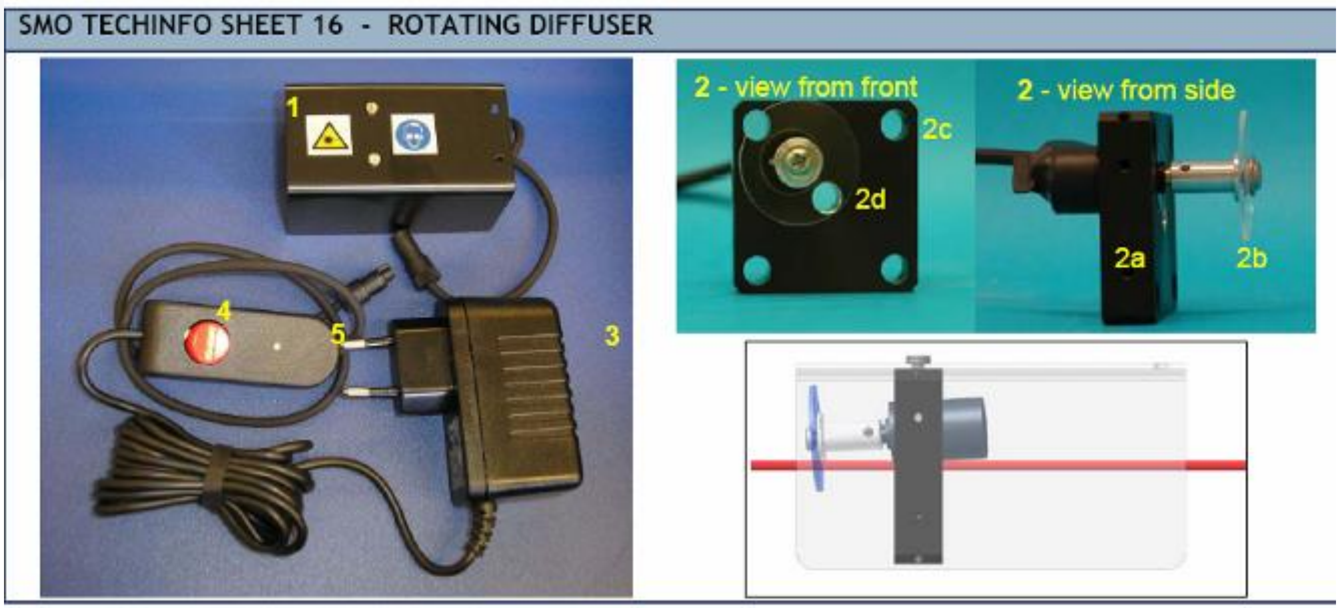


Light spatial homogeneity is essential for spectral sensitivity measurements

-The RGB camera…

And a spectroradiometer for spectral radiance measurements!!


Difusor rotatorio
Esfera integradora
CCD
Láser sintonizable
Rail


SMO TECHINFO SHEET 16 - ROTATING DIFFUSER
1
4
5
3
2 - view from front
2c
2d
2 - view from side
2a
2b

Spectral responsivity measurement:

$$S_\lambda = \frac{\rho_\lambda}{t_{\exp} L_\lambda}$$

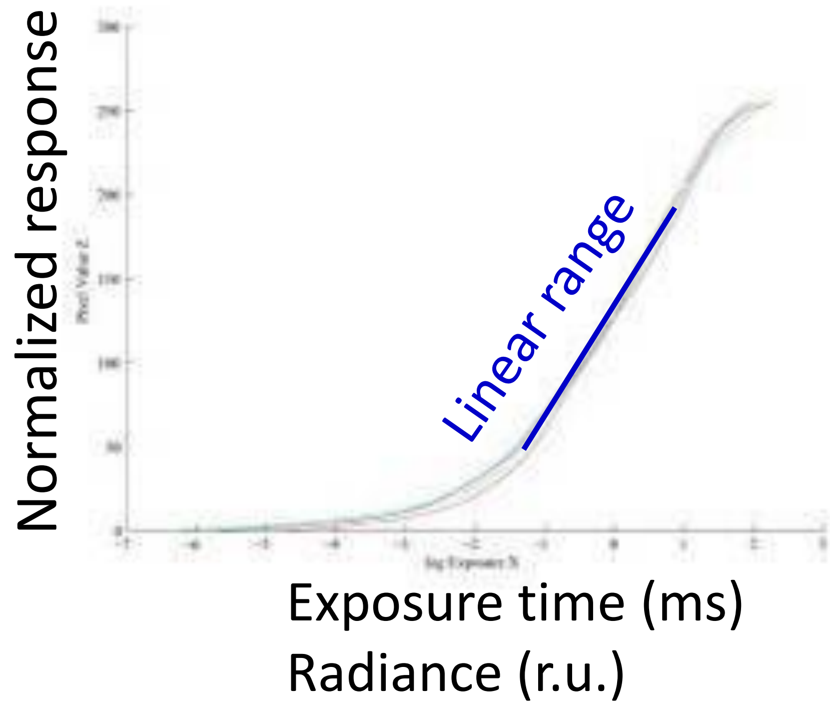
ρ camera responses

$t_{\exp}$ time exposure

L_λ Light impinging on the device

Concerns:

- linearity
- reciprocity
- non uniformity
- noise



$$\rho = k \int_{\lambda_{\min}}^{\lambda_{\max}} L(\lambda)\, R(\lambda)\, O(\lambda)\, T(\lambda)\, S(\lambda)\, d\lambda + n$$

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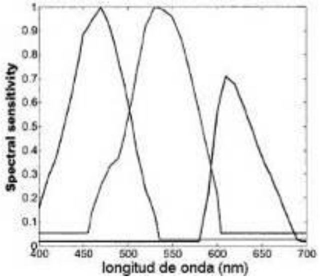
4.1. Sources of noise in image acquisition with a digital camera

4.2. Camera characterization and noise minimization procedures

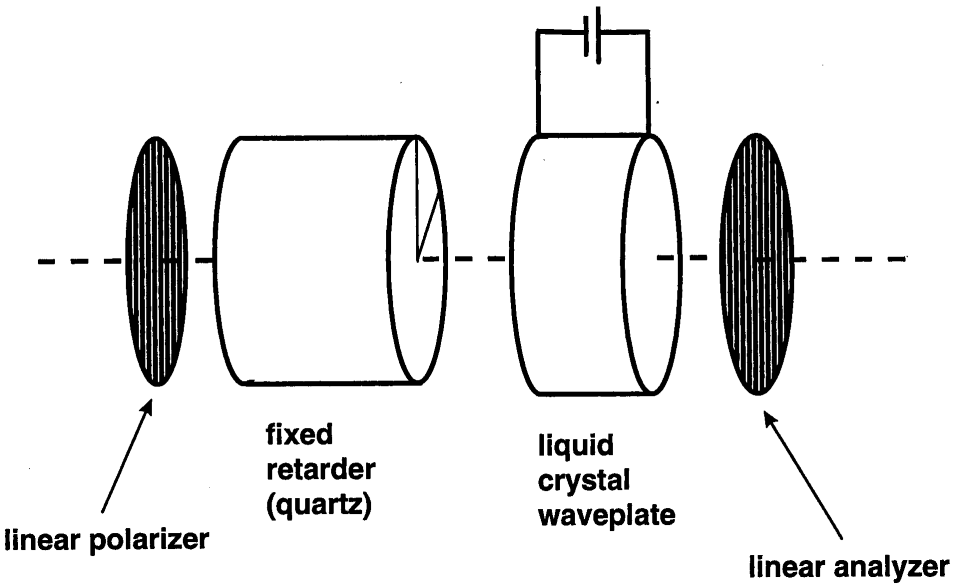


3.1. Direct procedure for a monochrome camera with LCTF

Liquid Cristal Tunable Filter:

Tunable interference filter based on electro-optic effect

$$n = n_0 + aV + bV^2 + \ldots \quad (4)$$



intensity attenuation due to absorption by the polarizer rather than by the filter *per se!!!*

3.1. Direct procedure for a monochrome camera with LCTF

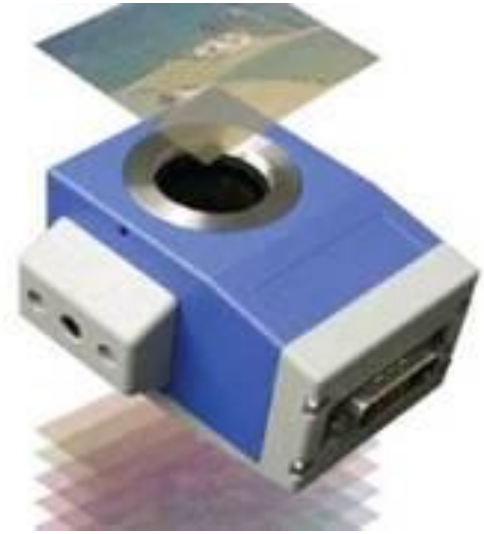
Liquid Cristal Tunable Filter:

VariSpec from CRi

Wavelength range: 400-720 nm

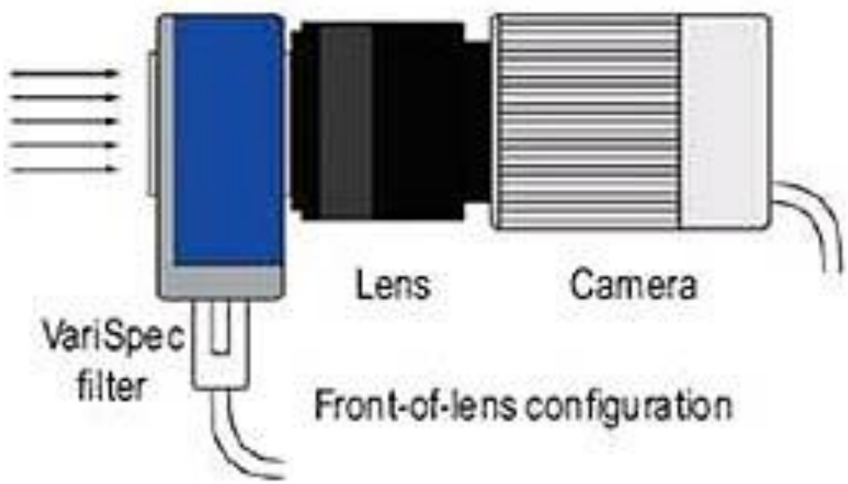
FWHM: 7-20 nm

Spectral resolution: 1nm



- LCTF + monochrome cooled camera arrangement

Image from López_Alvarez's dissertation.



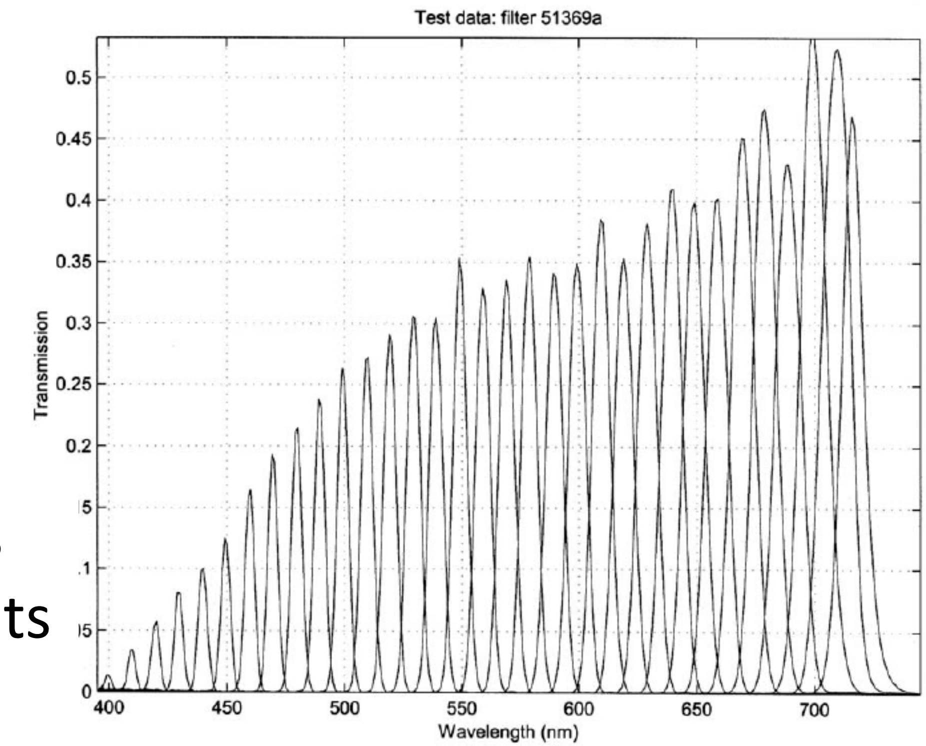
- Experimental device intended for radiance measurements of skylight

- Step 1) LCTF spectral calibration

- Step 2) Monochrome camera calibration with LCTF

Step 1) LCTF spectral characterization: measurements of SPD of light through different peak wavelength selections

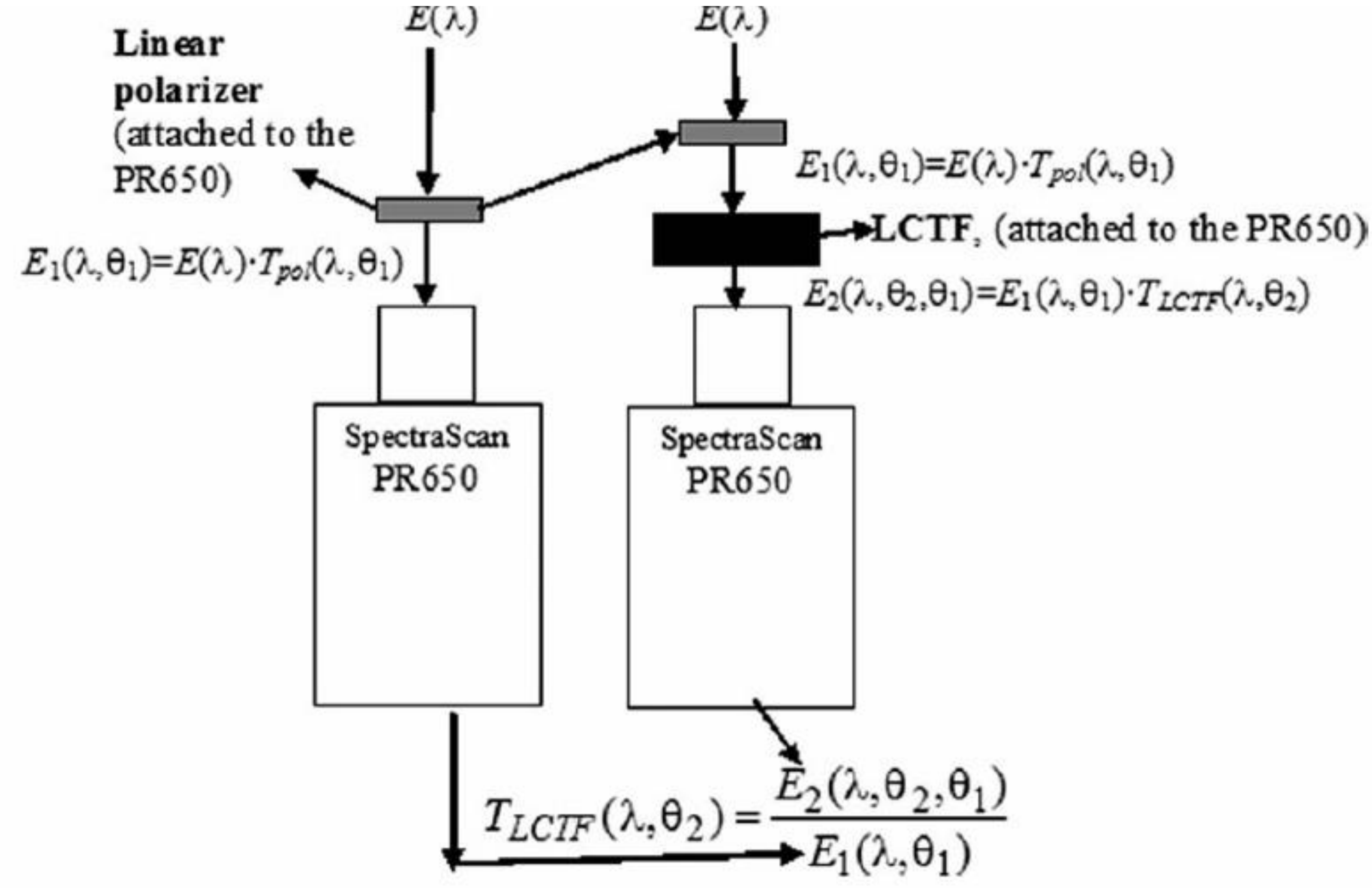
The low-wavelength range transmission is quite reduced



We must assure that light impinges on it being linearly polarized, with its plane of vibration matching the direction described by the polarization transmission line of the LCTF. Otherwise we would perceive intensity attenuation due to absorption by the polarizer rather than by the filter *per se*.

We need a bright light source: clear sky!

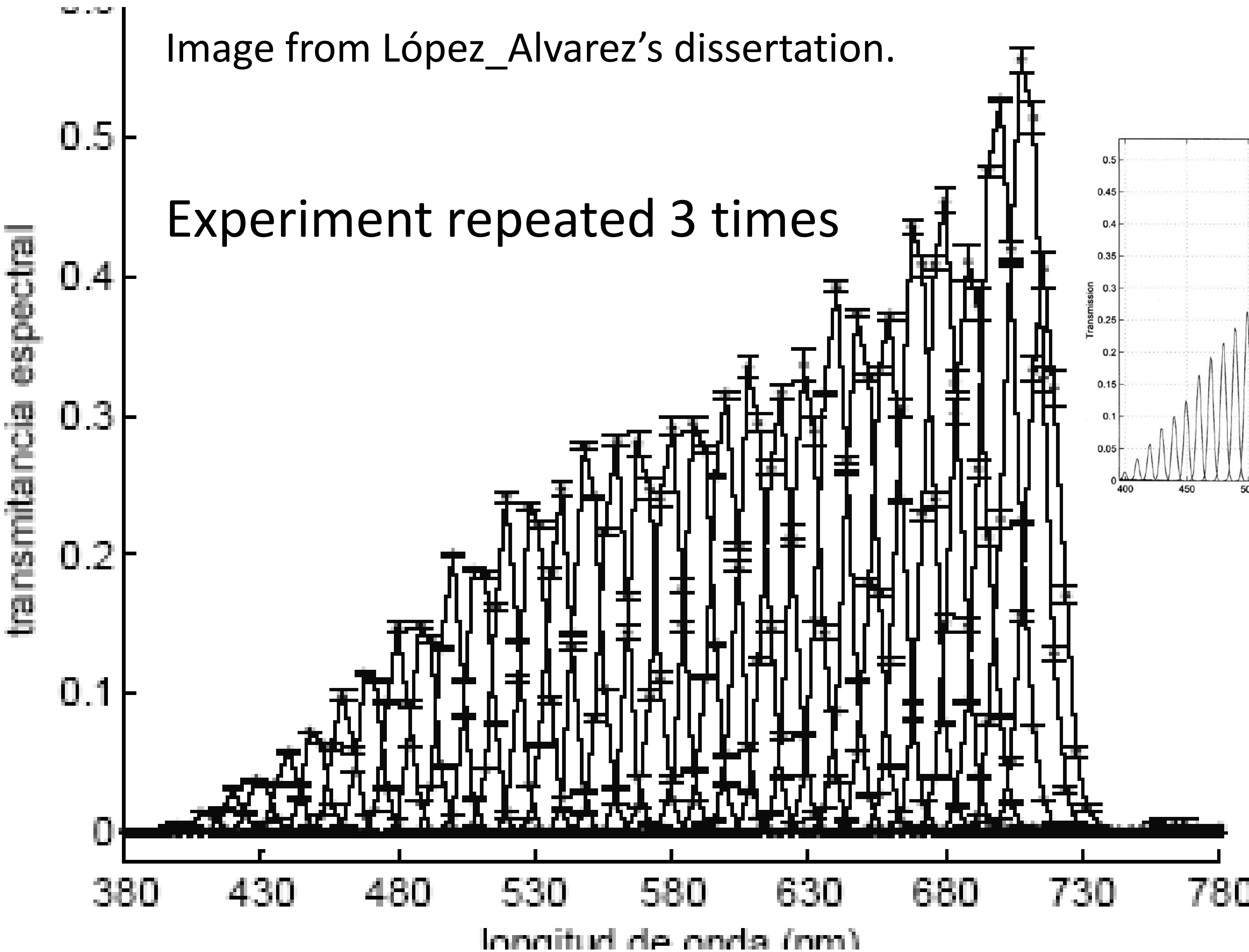
The transmission lines of the polarizer is set to the same angle as the LCTF polarizer

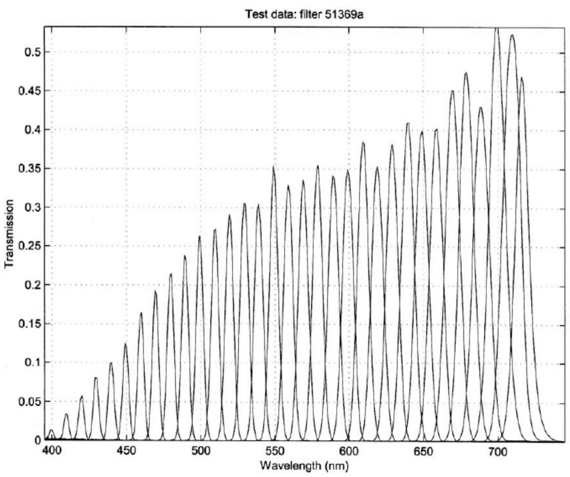


LCTF spectral characterization: experimental results

Image from López_Alvarez's dissertation.

Experiment repeated 3 times





Step 2) Monochrome camera spectral characterization with LCTF

We will treat the noise-sources and noise-correction techniques in section 4

We will use skylight as the source, and the LCTF to select wavelength; radiance is measured with a PR-650

- Responsivity: $$S(\lambda) = \frac{\rho_C}{L(\lambda)\, t_{\exp}} \qquad (5)$$

Little problem: skylight is a partially polarized source of light. So we add a polarizer in front of the PR-650

$$E_1(\lambda,\theta_1) = E(\lambda)T_{pol}(\lambda)T_{pol}(\theta_1)$$

$$E_2(\lambda,\theta_2) = E(\lambda)T_{LCTF}(\lambda)T_{LCTF}(\theta_2)$$

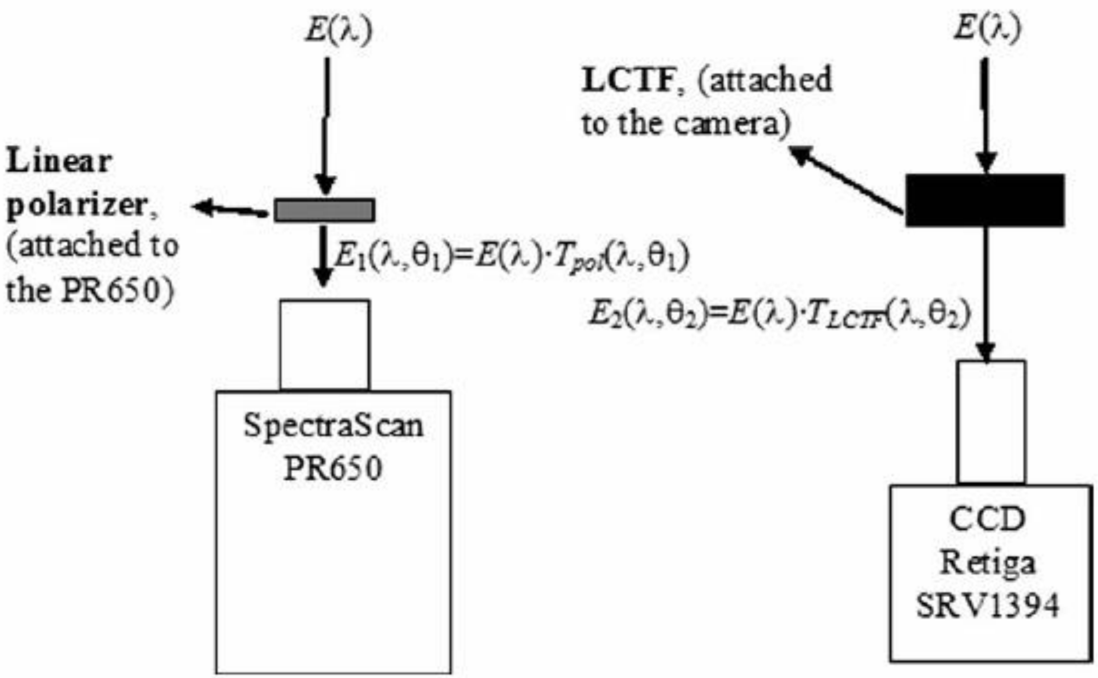
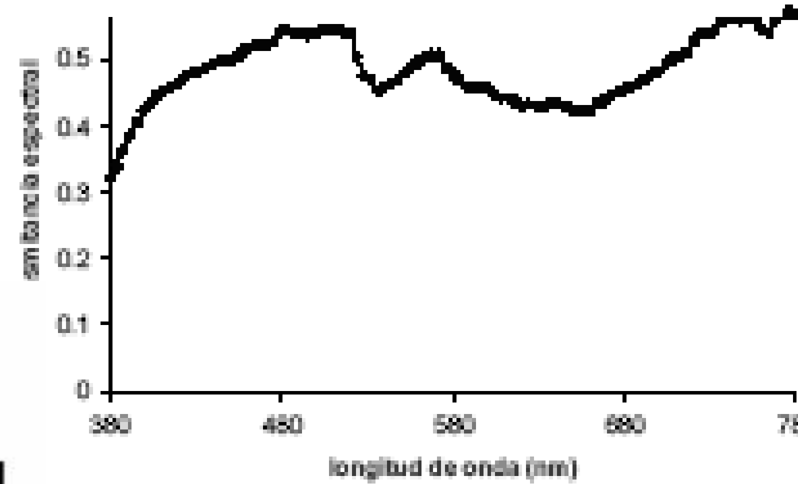


Image from López_Alvarez's dissertation.



$$\theta_1 = \theta_2$$

$$T_{pol}(\theta_1) = T_{LCTF}(\theta_2) \quad (6)$$

$$E_2(\lambda) = \frac{E_1(\lambda)\, T_{LCTF}(\lambda)}{T_{pol}(\lambda)} \quad (7)$$

Experimental results for the spectral characterization

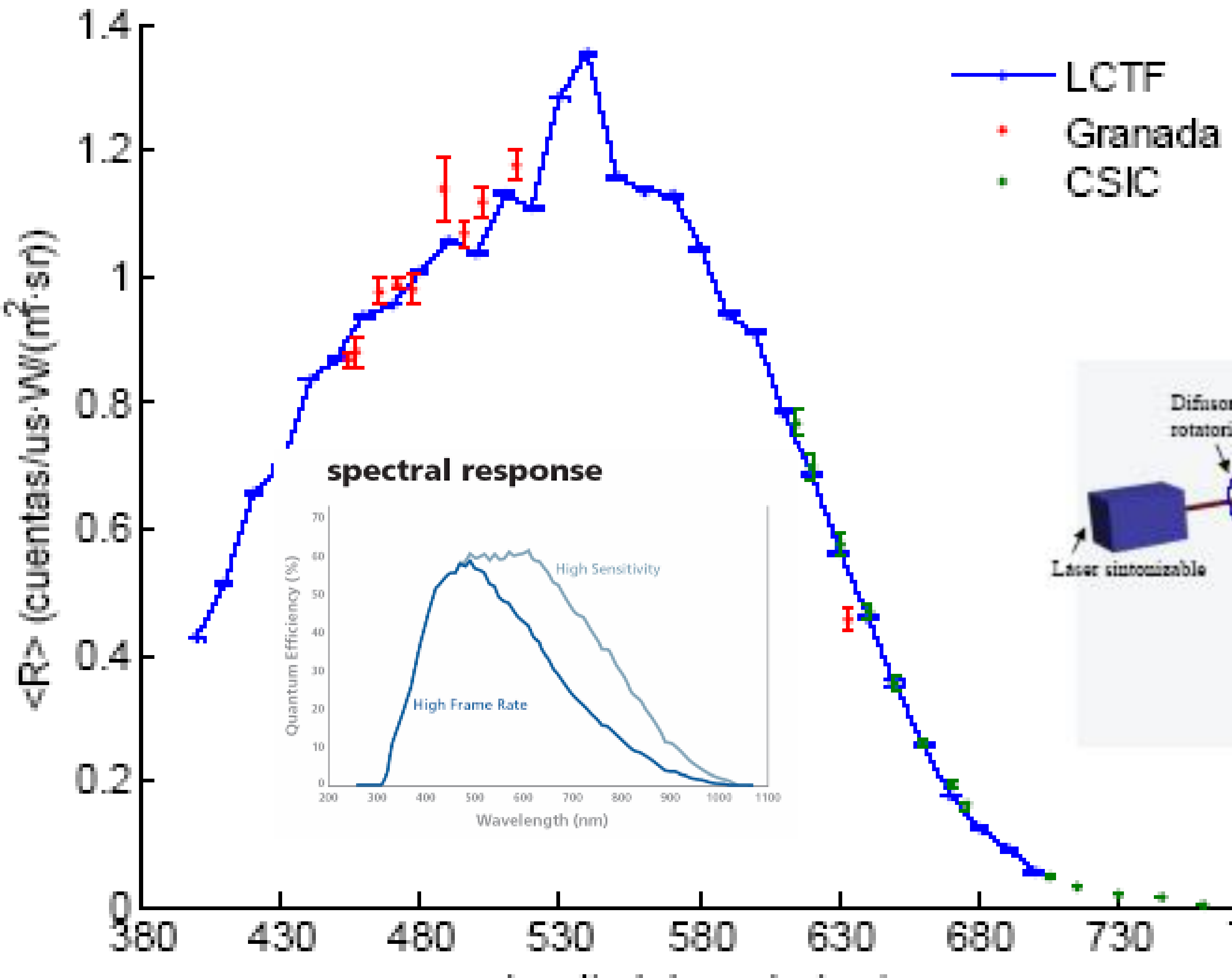
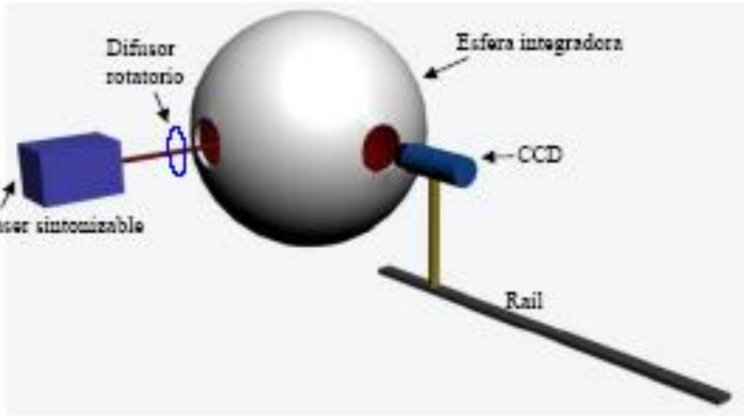


Image from López_Alvarez's dissertation.

Green and red dots: verification by using a tunable laser source and an integrating sphere

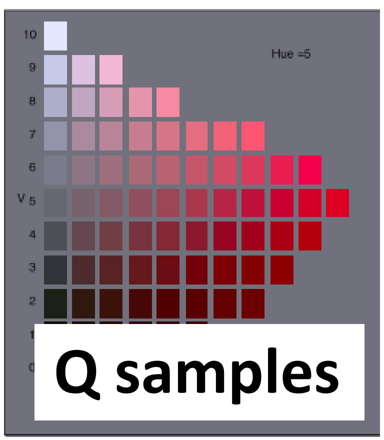


3.2. Indirect procedure (estimation)

General idea: solve the camera response equation using a set of Q known reflectances, a fixed illuminant and the camera responses for the set, from a camera with K channels.

$$E_{PxQ} = LR$$

$$\rho_K = \sum_{n=1}^{P} L(\lambda_n) R(\lambda_n) S_k(\lambda_n) \quad \Rightarrow \quad \rho_{KxQ} = S_{KxP} E_{PxQ}$$

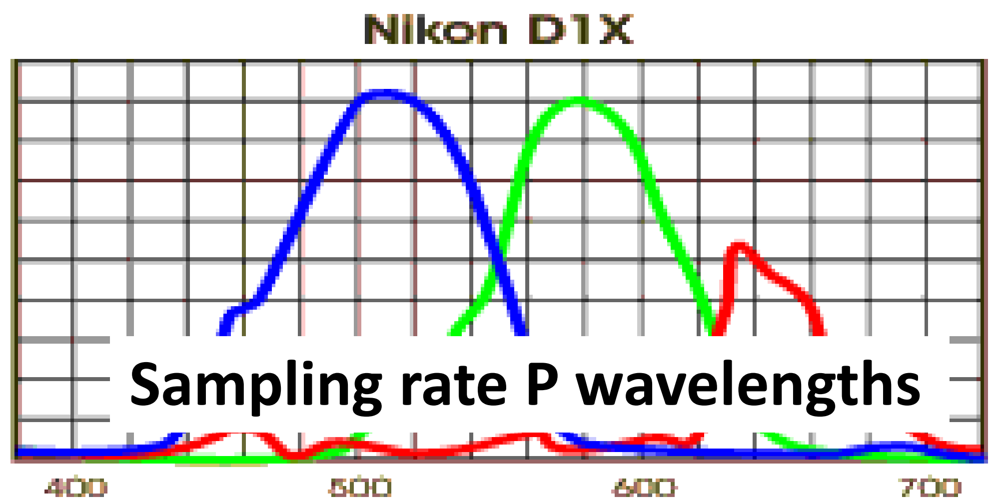


How different the samples should be?

P < Q

P = Q

P > Q



Spectral sensitivities known from the manufacturer?

3.2. Indirect procedure (estimation)

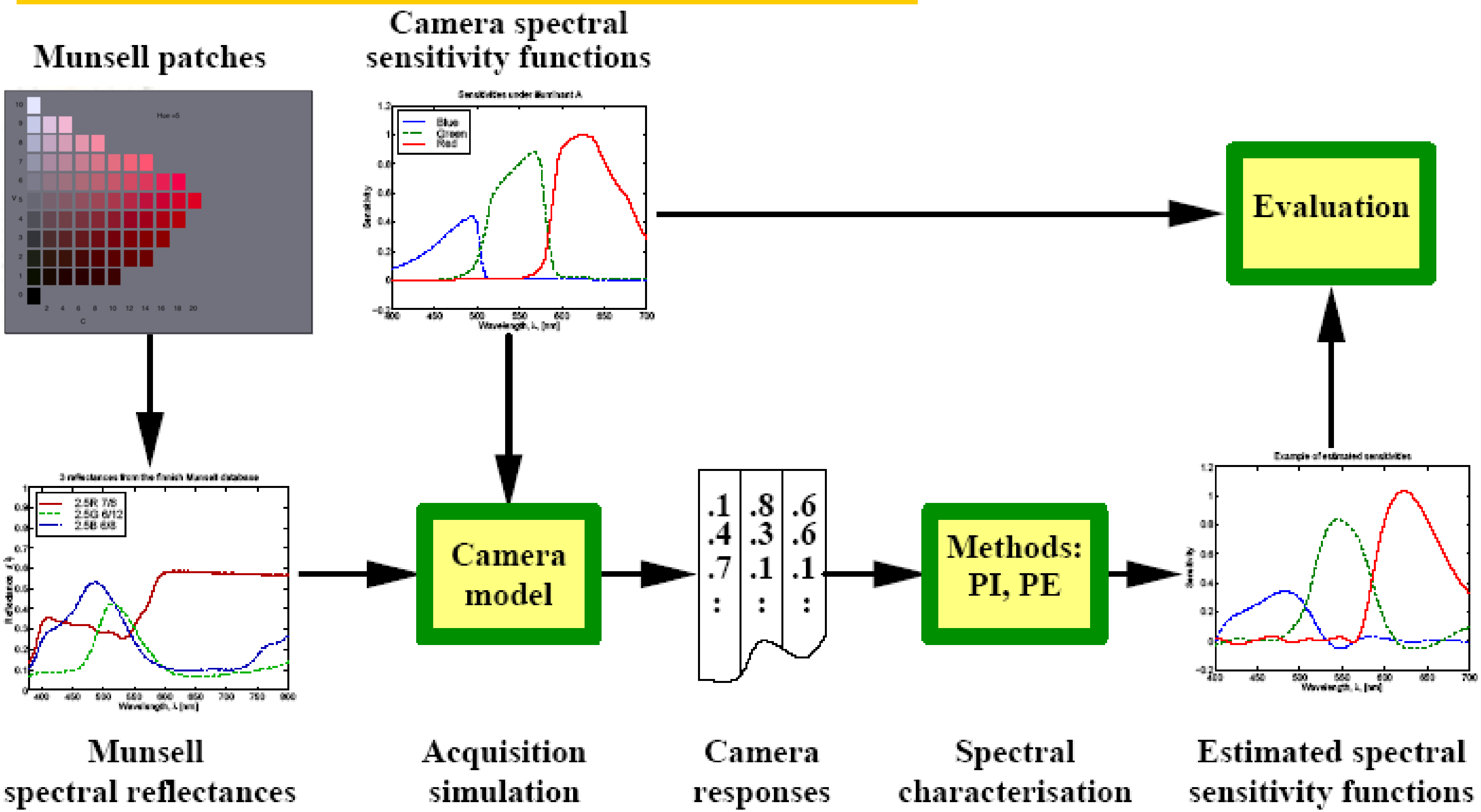


Image from Hardeberg's dissertation.

3.2. Indirect procedure (estimation)

1st method: **Pseudo-inverse** (PI) method or Moore-Penrose

Straigthforward method: ***"Simply"*** by inverting the linear equation

$$\rho_{KxQ} = S_{KxP} E_{PxQ} \qquad \rho = S\,E$$

$$\boxed{S = \rho\, E^{+}}$$

E^{+} denotes the Moore-Penrose pseudo-inverse of E

Which is the code in Matlab to do it?

Theoretically it works well in noise free situations!!!

In the presence of noise…..let's see!

3.2. Indirect procedure (estimation)

2nd method: **Principal eigenvector (PE) method**

$$\left(S_k\right) = \left[VW^-\right]U^t\left(\rho_{k,P}\right)$$

(See section 6.2.2.4 from Hardeberg's book)

Common solution to the inverse problem, based on **singular value decomposition (SVD)**, where **only those components whose singular values are greater than a certain threshold are used**. In this way we reduce the noise sensitivity of the system inversion. This method is also known as the rank-deficient pseudo-inverse.

Using SVD the matrix E_{PxQ} , whose rank is *R,* is expressed as:

$$E = UWV^T$$

U_{PxP} and V_{QxQ} orthogonal matrices (U^TU=I and V^TU=I)

columns of U are the P eigenvectors of EE^T

columns of V are the Q eigenvectors of E^TE

W_{PxQ} matrix with singular values or eigenvalues in its principal diagonal

Which is the code in Matlab to do it?

3.2. Indirect procedure (estimation)

2nd method: **Principal eigenvector (PE) method**

(See section 6.2.2.4 from Hardeberg's book)

The singular values, w_i, *or eigenvalues,* decreases with increasing index

The pseudoinverse of $E = U W V^T$ is $E^+ = V W^+ U^T$

W^+ is a diagonal matrix with entries $1/w_i$ (i=1..R). If w_i are small values, the reciprocal become large, and the solution can become very unstable, and sensitive to small amount of noise.

How to deal with that?

1) **To truncate a number of the smaller eigenvalues**
2) To use regularization (not during this course)

3.2. Indirect procedure (estimation)

2^{nd} method: **Principal eigenvector (PE) method**

(See section 6.2.2.4 from Hardeberg's book)

1) To truncate a number of the smaller eigenvalues

Only the first r<R eigenvalues are taken into account, and only r eigenvectors are used in U and V

Pandora's box

- What is the optimal number of eigenvectors & eigenvalues **r**?
- Which set of reflectance samples do we use?
- How many?
- How do we select them?

3.2. Indirect procedure (estimation)

Which set of reflectance samples do we use for calibration? How many? How do we select them?

- GretagMacbeth ColorChecker
- GretagMacbeth ColorChecker DC

- Esser test chart TE221 - IEC 61966-8

3.2. Indirect procedure (estimation)

(See section 6.2.2.3 and 6.2.2.4 from Hardeberg's book)

Which set of reflectance samples? Munsell

How many? 20

How do they select them? Heuristically, optimally, others?

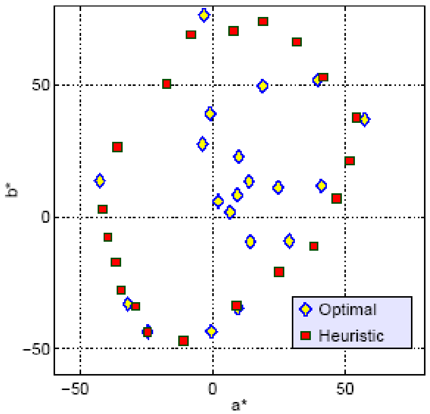
Heuristically: selecting the patch of highest chroma from each one of the 20 hue angle pages of Munsell atlas.

Optimally: iterative process to select a reflectance spectrum which is as different as possible to the others

1st sample: maximum RMS for the first reflectance;

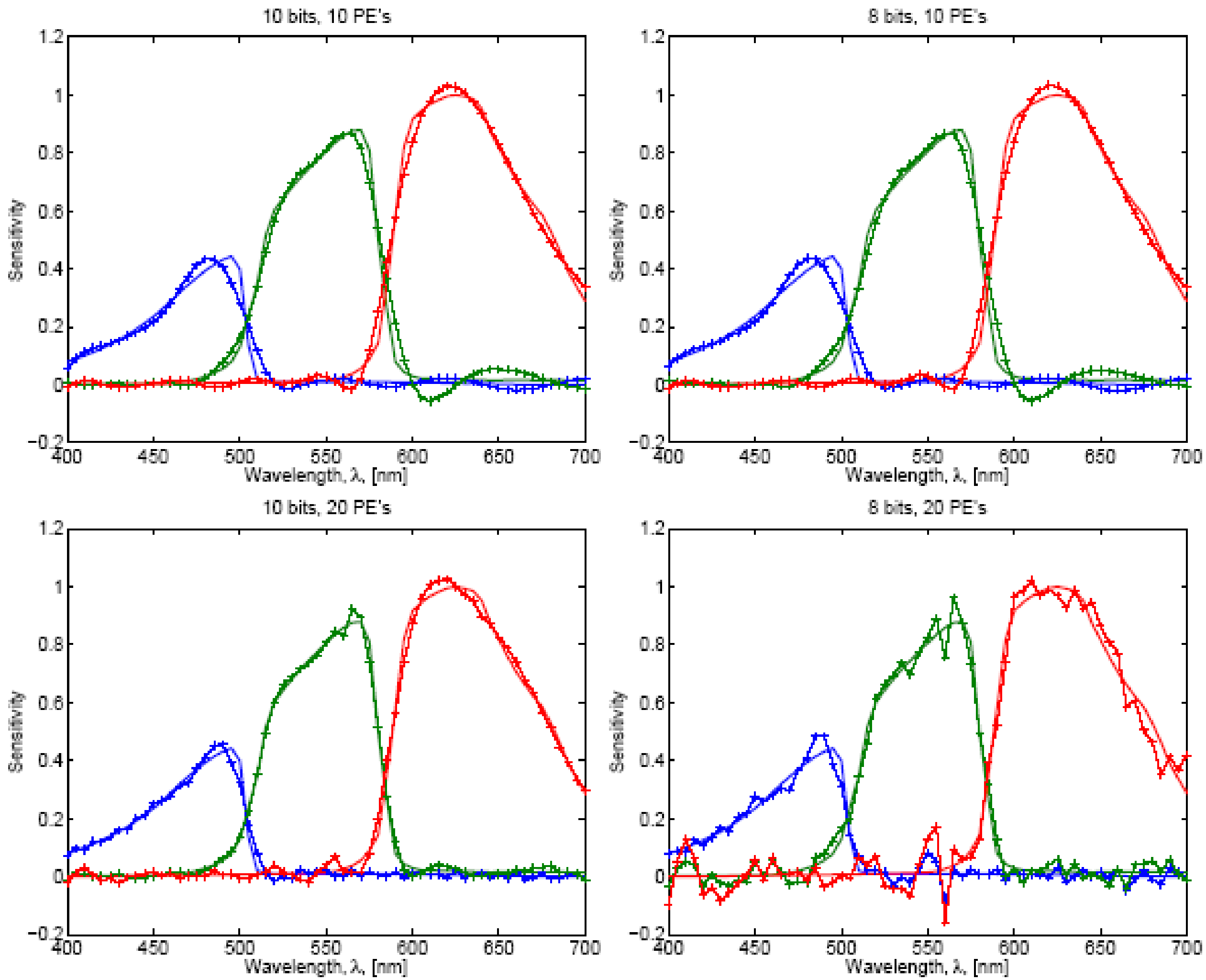
2nd and rest: condition-number minimization

Optimal	Heuristic
7.5 RP 9/2	5 R 5/14
5 R 4/14	10 R 6/12
7.5 Y 8/12	5Y R 7/12
2.5 G 7/10	10 YR 7/12
5 P 2.5/6	5 Y 8/12
10 R 7/12	10 Y 8/12
7.5 RP 6/10	5 GY 8.5/10
2.5 B 5/8	10 GY 7/10
10 P 3/8	5 G 7/10
7.5 R 7/4	10 G 6/10
10 B 6/10	5 BG 6/8
10 Y 8/4	10 BG 6/8
7.5 YR 8/8	5 B 6/8
10 RP 8/6	10 B 6/10
10 R 3/2	5 PB 5/12
7.5 PB 5/12	10 PB 5/10
10 Y 8.5/6	5 P 5/10
10 PB 4/10	10 P 5/12
10 YR 3/1	5 RP 5/12
7.5 YR 6/4	10 RP 5/12



The condition number associated with a problem is a measure of that problem's amenability to digital computation, that is, how numerically well-conditioned the problem is. A problem with a low condition number is said to be well-conditioned

- Results (1): influence of the number of PE used

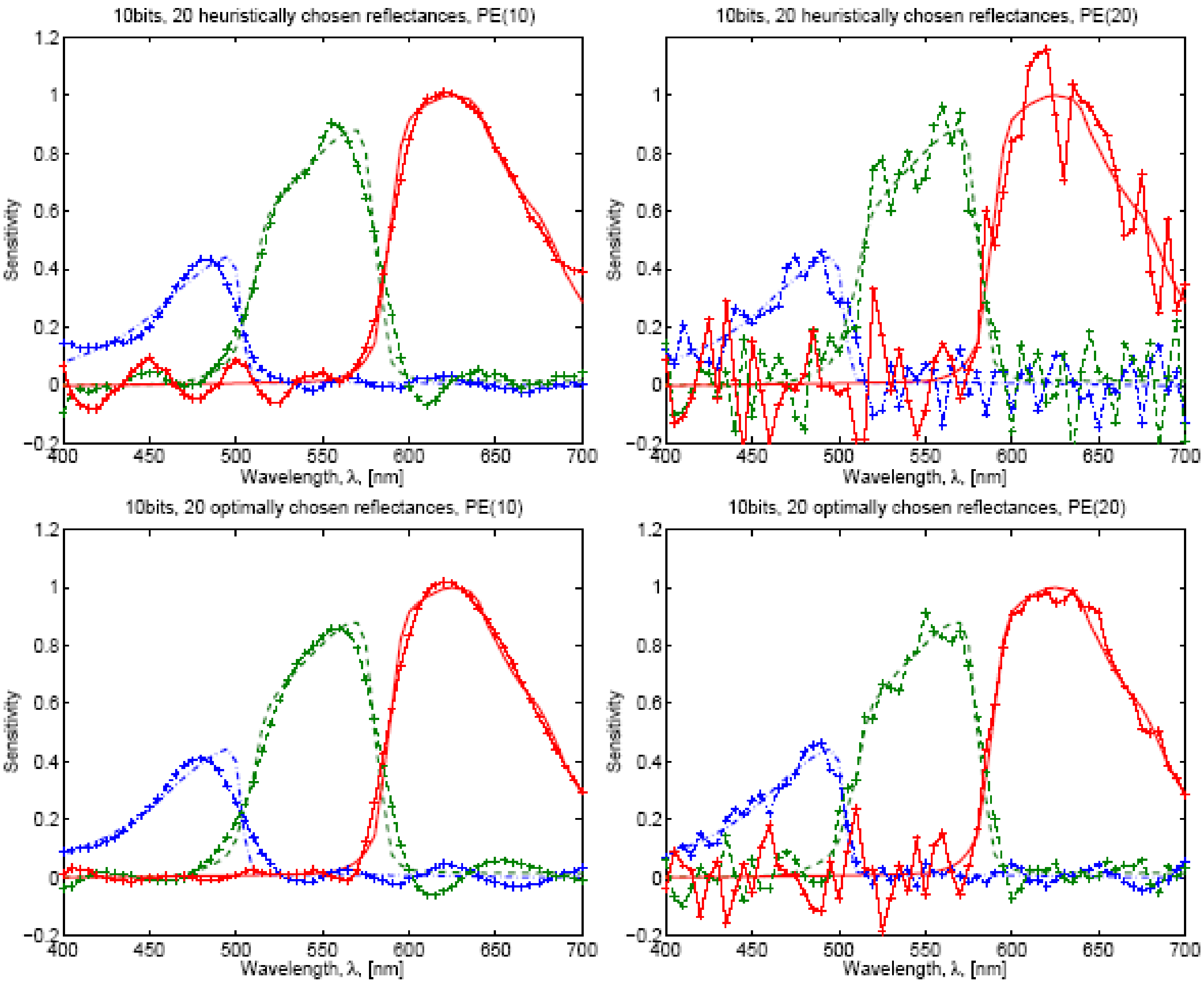


10 eigenvectors offer better results than 20

The higher the noise level, the bigger the influence this parameter has on the results

Image from Hardeberg's dissertation.

- Results (2): influence of the reflectance set used



better with the optimal reflectance set than with the heuristically chosen set

Negative values!!! These results would benefit from the imposition of smoothness and positivity constraints

Image from Hardeberg's dissertation.

Results (3): influence of the method used.

mean RMS error

		8 bit	10 bit	12 bit
All 1269 reflectances	PI	0.25797	0.07752	0.01800
	PE(20)	0.04350	**0.02027**	**0.01796**
	PE(10)	**0.03178**	0.03171	0.03170
20 optimally chosen reflectances	PE(20)=PI	0.19568	0.05365	**0.02498**
	PE(10)	**0.04712**	**0.03821**	0.03772
20 heuristically chosen reflectances	PE(20)=PI	0.40801	0.10726	0.04472
	PE(10)	**0.04734**	**0.04261**	**0.04159**

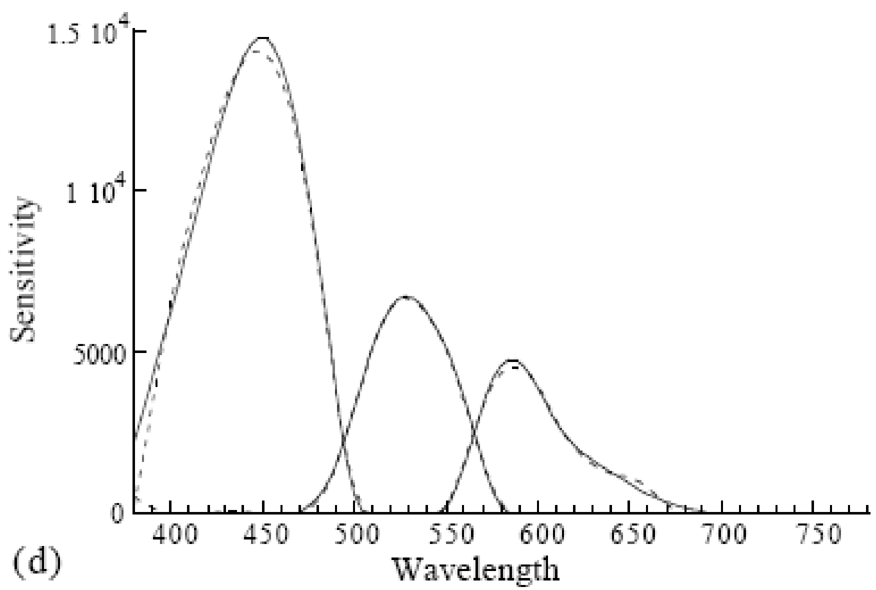
PI is more sensible to noise; PE is better for 10 eigenvectors.
Results improve with higher S/N ratio

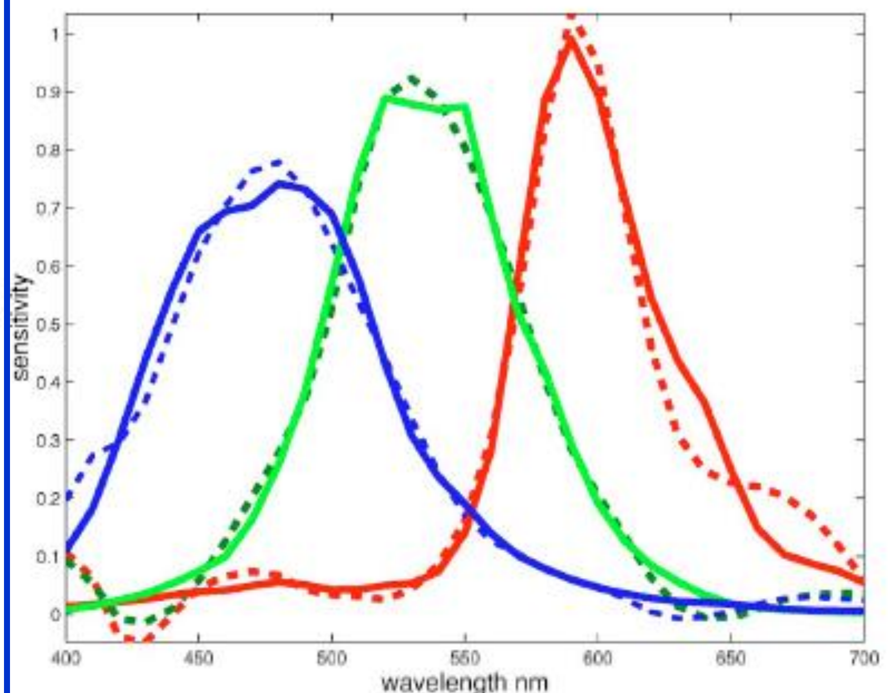
	8 bit	10 bit	12 bit
All	100	100	100
Optimal	148	189	139
Heuristic	149	210	232

Relative estimation errors

The influence of the reflectance set selection gets bigger as noise decreases

- Other alternatives for spectral response function estimation: gamut-mapping (Barnard and Funt,2002), metameric blacks (Alsam and Lenz, 2007), rank-based (Finlayson et al. 2016)…



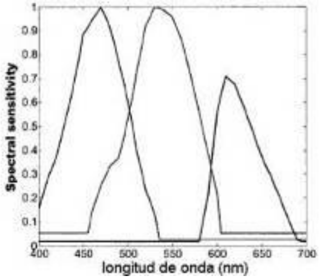


1. **Some basics on image acquisition devices.**
   1.1. Color image capture devices

2. **Experimental measurement of spectral response curves**

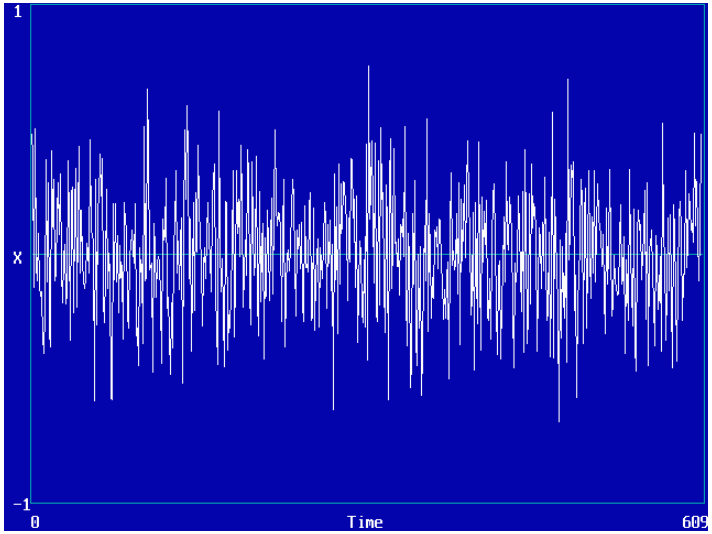
3. **Spectral characterization with color filters**
   3.1. Direct procedure for a monochrome camera with a LCTF
   3.2. Indirect procedure for an RGB digital camera

4. **Sources of noise. How to minimize its influence on the image capture process.**
   4.1. Sources of noise in image acquisition with a digital camera
   4.2. Camera characterization and noise minimization procedures



4.1. Sources of noise in image acquisition devices

Noise: a perturbation added to the signal



Classification :

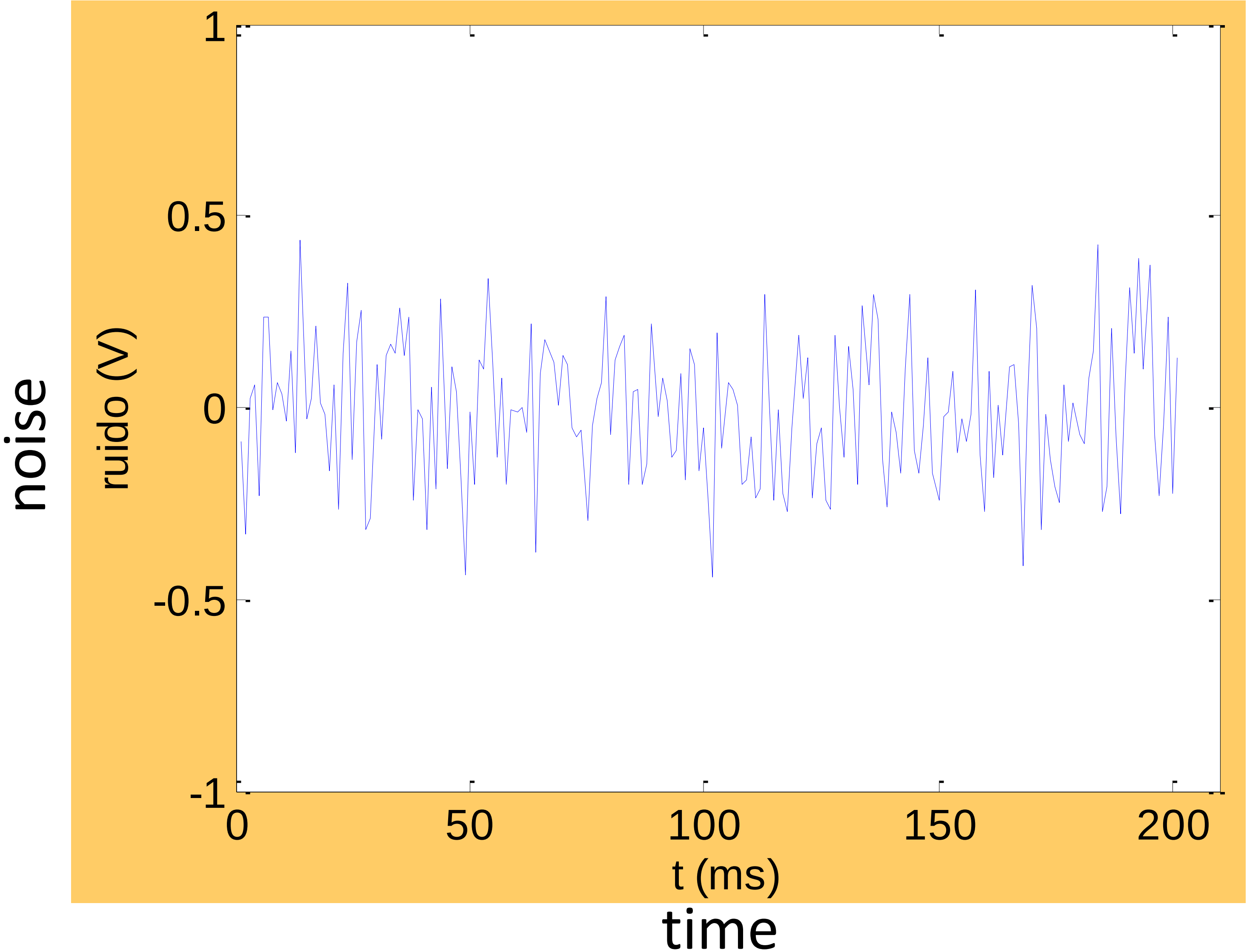
Origin: interior or exterior
Magnitude: high or low level
Statistics: Gaussian, Poisson, uniform
Frequency: white, 1/f.
Nature: thermal, quantization, etc

- Signal to noise ratio (SNR):

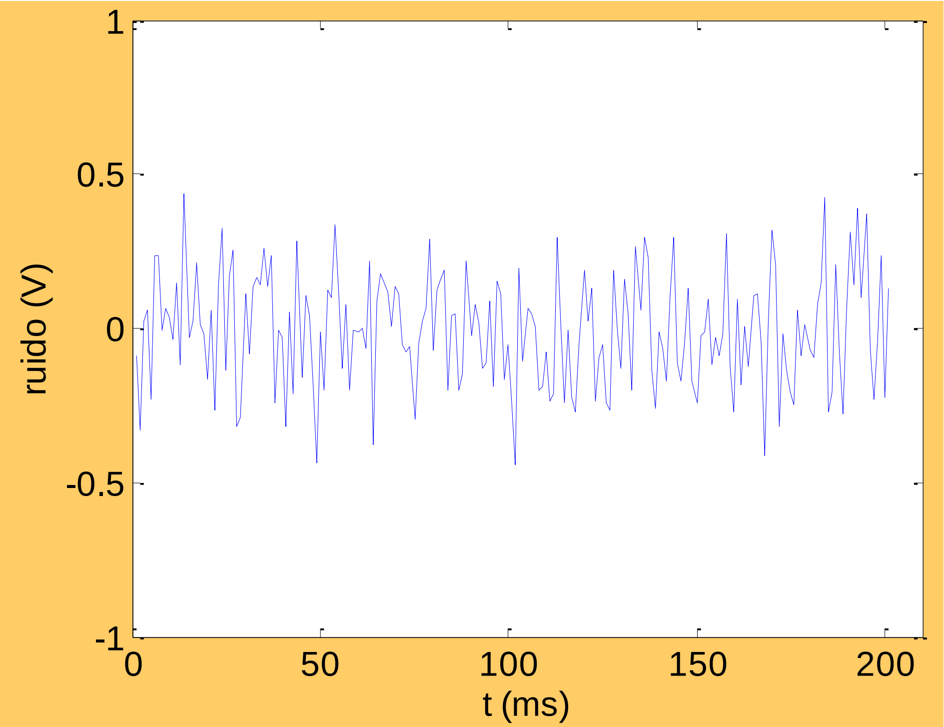
$$SNR_{dB} = 10\log\left(\frac{S}{N}\right) = 10\log\left(\frac{P_{signal}}{P_{noise}}\right) = 20\log\left(\frac{V_{signal}}{V_{noise}}\right)$$

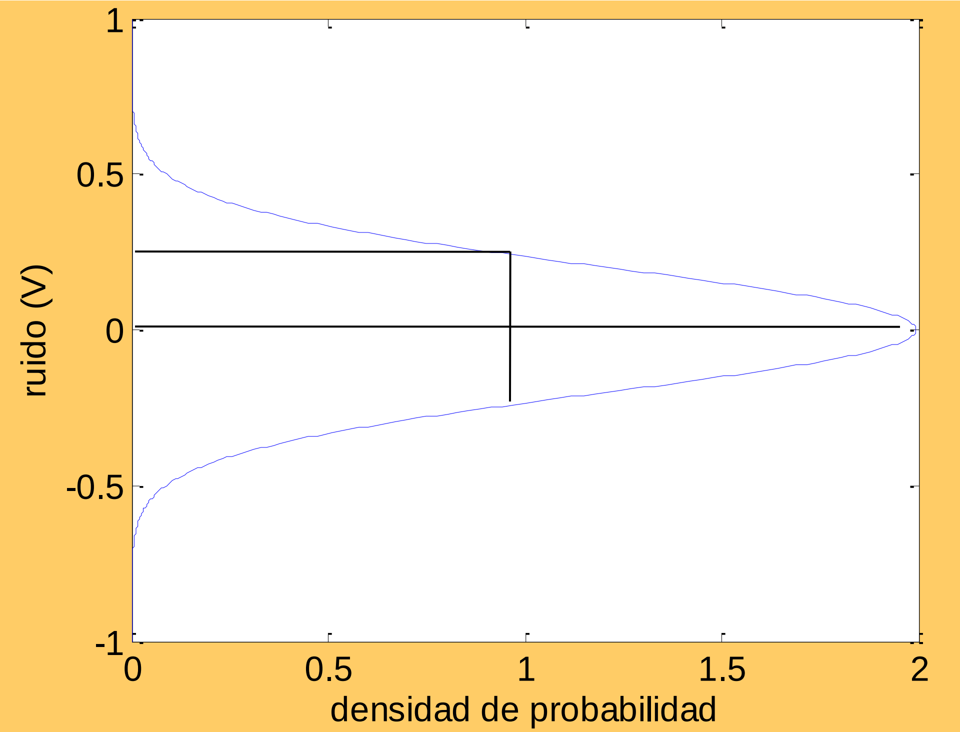
CHECK that 1%, 3%, 5% errors correspond to 40dB, 30dB and 26dB respectively

- Example of noise. What about it statistics?



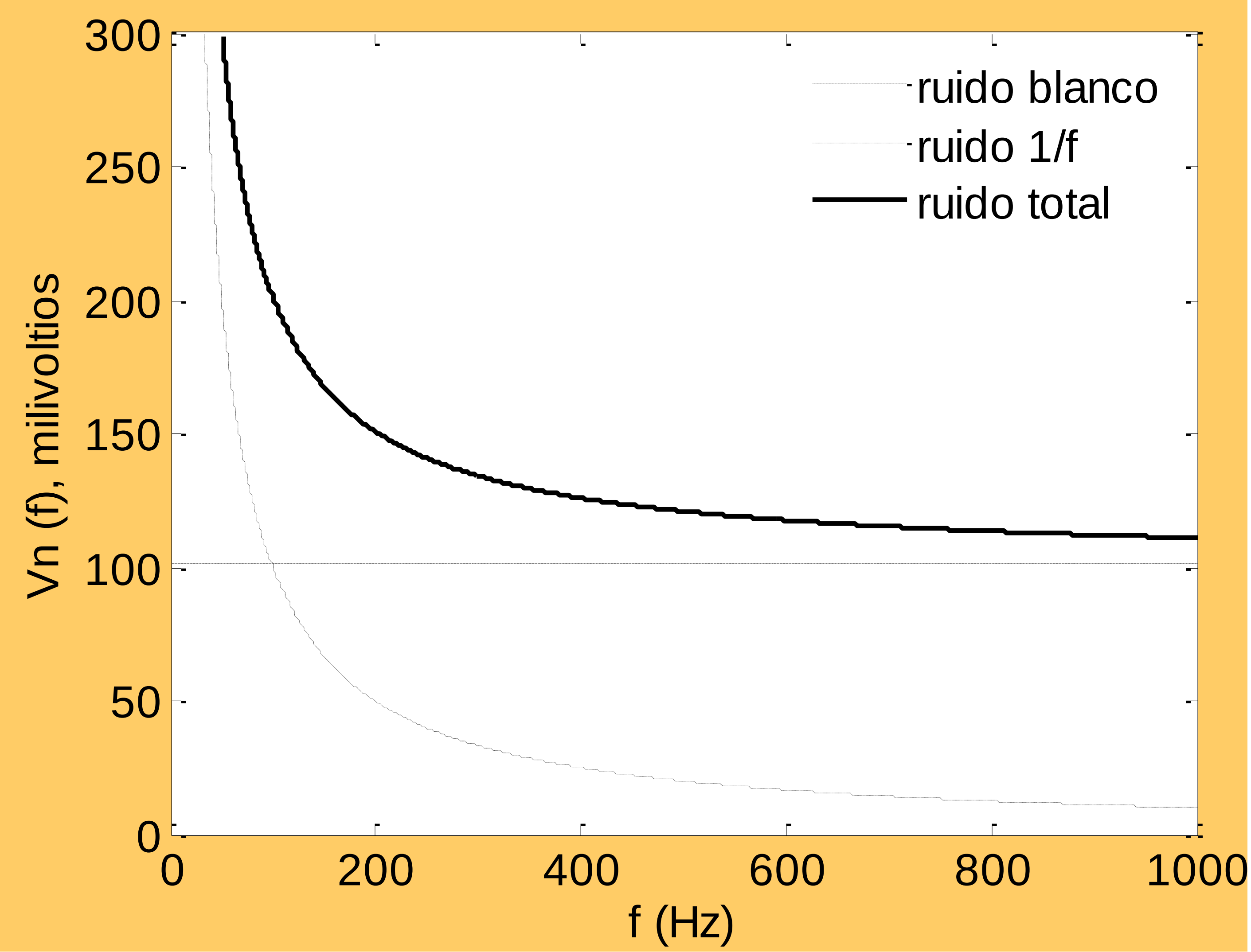
- Example of Gaussian noise





mean value 0, FWHM value 0.2 V (rms value)

Typical variability with signal frequency



Noise according to its nature in digital image acquisition

1) DC (dark current noise): constant, dark-current, easy to eliminate. It is due to the current or voltage offset present at the entrance of the readout amplifiers

Mostly because **thermal noise** triggers a false event in the detector

–

How many DC images to eliminate?

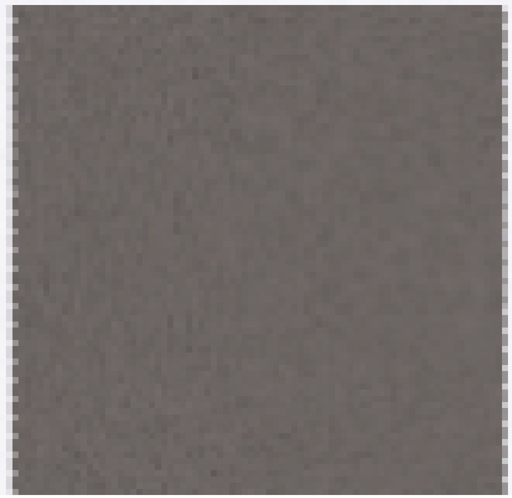
–

Take any DC image when you change any parameter

Depends on integration time (in a non linear way)! (at high exposure times DC becomes a nuisance). But fortunately is pixel specific. Some pixels have low dark noise, some have specially high dark noise (know as "hot" pixels)

Subtract dark current noise

-



2) Thermal noise (or Johnson noise)
3) Shot noise
4) Flicker noise
5) Quantization noise (read-out noise)
6) others????

AVERAGING to minimize noise?

Random events related to the quantal nature of light's interaction with matter follow a Poisson distribution, which means that the standard deviation equals the square root of the average.

Solutions: mainly averaging. Signal to noise ratio (SNR), quotient of the average and the std, is equal to the square root of the signal

$$SNR = \frac{average}{std} = \frac{N}{\sqrt{N}} = \sqrt{N}$$

Averaging 100 images will increase SNR by a factor of 10. The cost may be too high!

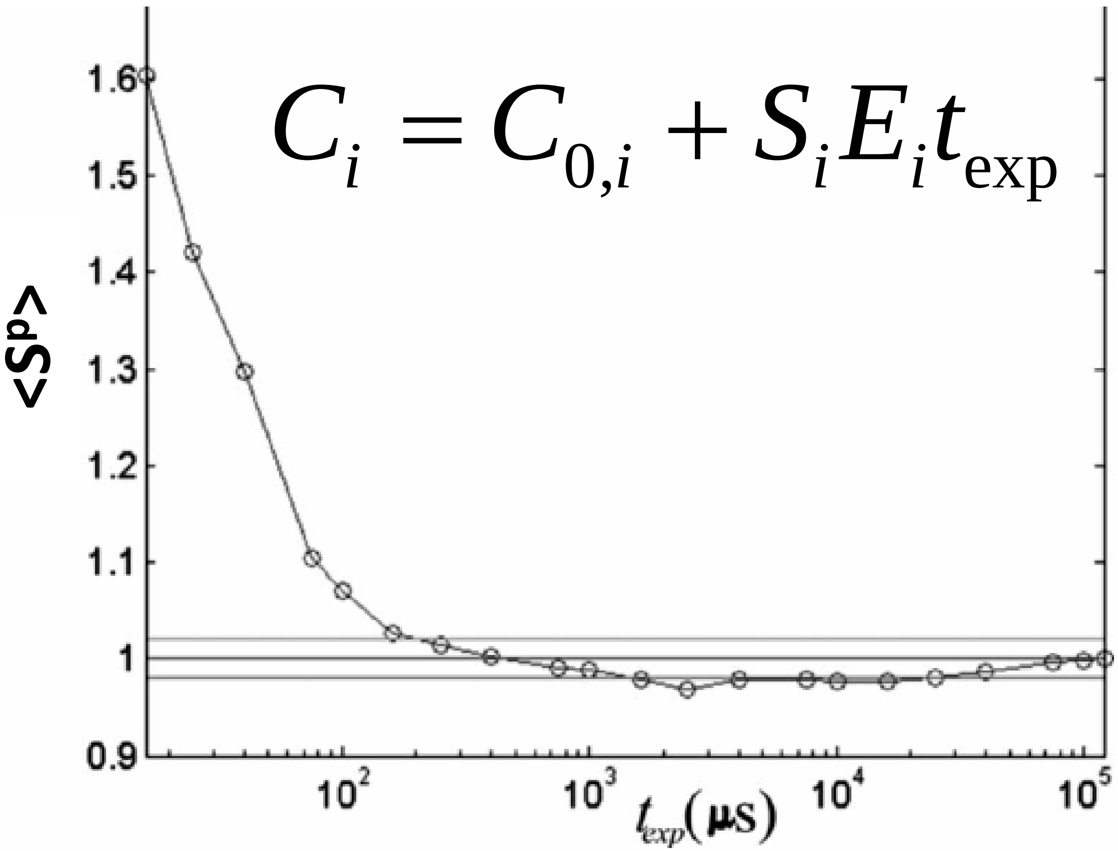
3) Reciprocity law: response do not vary if the product radiance by exposure time is constant. We study the dependence of normalized camera responses (without dc-noise) with exposure time.

$$C = S\ E\ t_{\mathrm{exp}}$$

3) Reciprocity law: response do not vary if the product radiance by exposure time is constant. We study the dependence of normalized camera responses (without dc-noise) with exposure time.

$$C_i = C_{0,i} + S_i E_i t_{\exp}$$

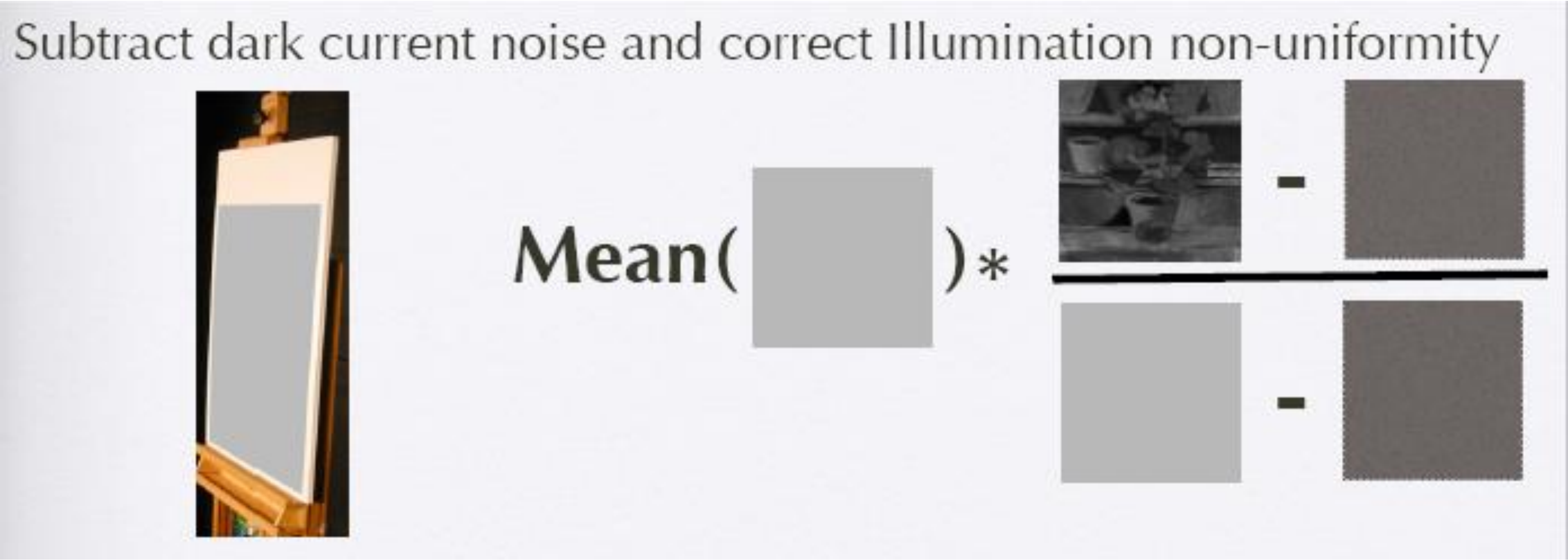
$$\frac{\overline{C_i - C_{o,i}}}{t_{\exp}}$$



In this example: Reciprocity is maintained for $t_{\exp} > 4$ ms

Variation in responsiveness is below 2%

4) Spatial Non-uniformity. Usual correction by acquiring the image of a uniform surface.



What about outdoors? For instance: drones?

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