Computational Colour and Spectral Imaging

“Advanced Colour and Spectral Imaging”

Chapter 2: What is a spectral image?

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

UNIVERSIDAD DE GRANADA

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

Some motivating questions for Chapter 2…

- Do spectroradiometers or spectrophotometers take multispectral images?
- What is the difference between a spectral image, a multispectral image and a hyperspectral image?
- Imagine we change our cornea or our lens by a prism? Would we "see" spectra?
- How many dimensions a sensor should have to take a multispectral image?
- How many different types of cones we should have to have spectral vision?

Find the best solution for:

Task 1: to measure the color and spectrum of the light from the moon?

Task 2: to measure the color and spectrum of the rainbow?

1. **Measuring tristimulus values: colorimeters.**
    1.1. A curious fact...
    1.2. The tristimulus colorimeter
2. **Measuring spectral radiance: spectroradiometers**
    2.1. Optic fiber vs conventional optics
    2.2. CCD vs CMOS
    2.3. Errors
    2.4. Commercial examples
3. **Measuring spectral reflectance: spectrophotometers.**
    3.1. How does it work?
    3.2. Commercial examples
4. **Sources of error: sampling rate and others**
    4.1. Sampling interval
    4.2. Optical resolution and accuracy
    4.3. Additional sources of error
5. **Future evolution of spectral measurement systems: multispectral devices.**

How does a "colorimeter" work?

Colorimeter using google or wikipedia?

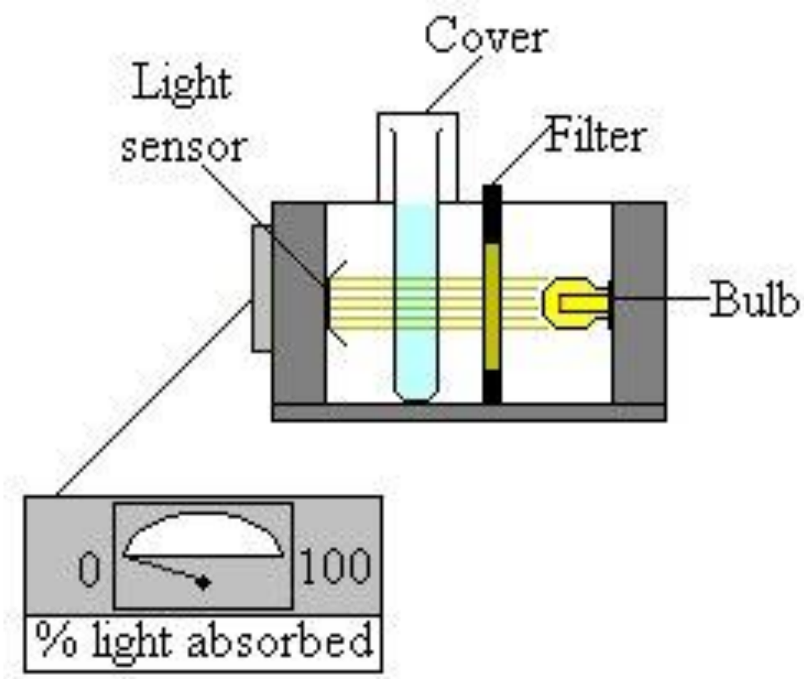
$$A = \varepsilon c l$$

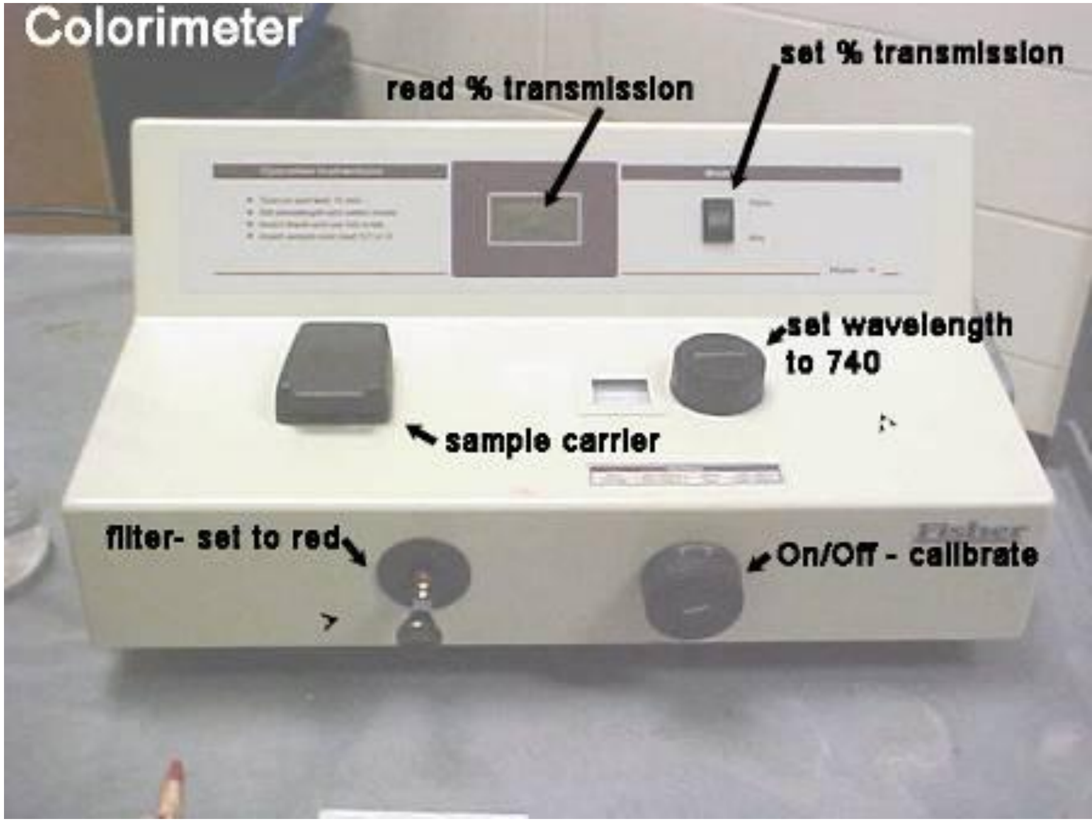
Beer-Lambert law

epsilon=molar absorptivity

How does a "colorimeter" work?

"colorimeter": an instrument working by making color comparisons of transmitted light through solutions for selected wavelengths to a standard sample. Used in chemistry analyses, medicine, etc…

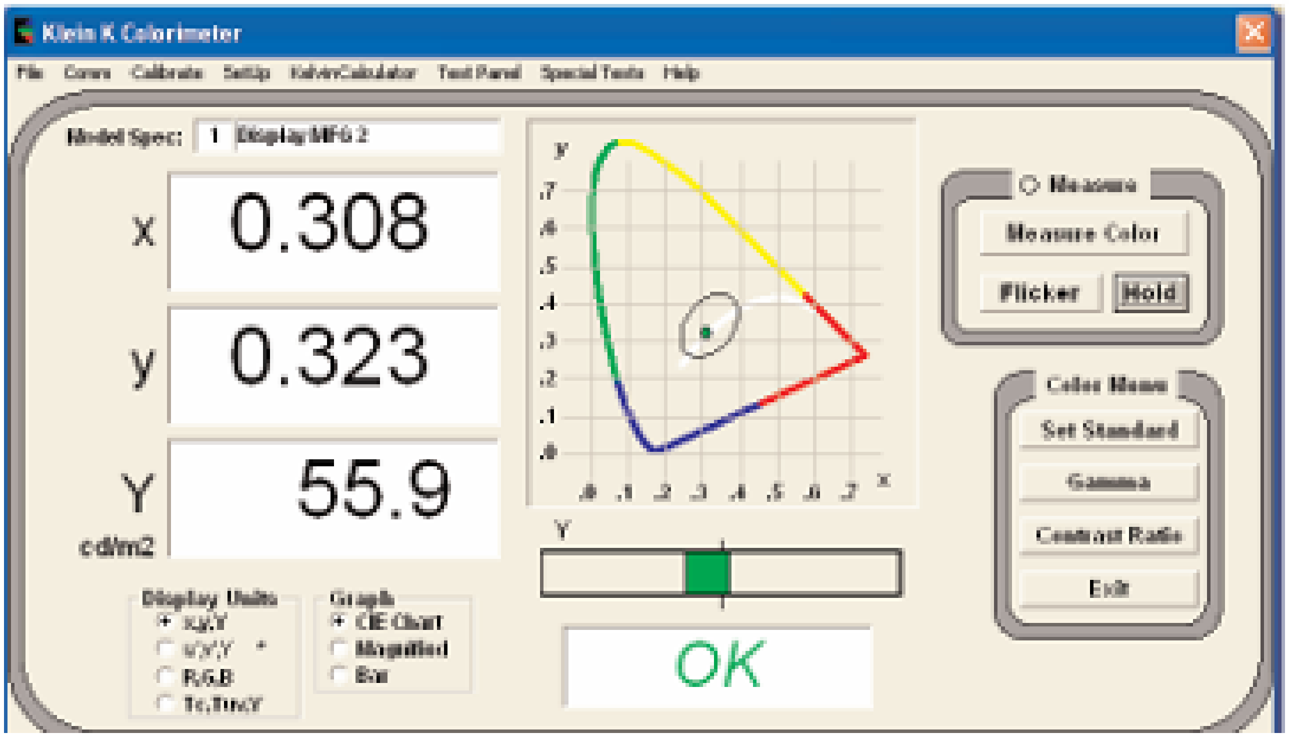




How does a “real” colorimeter work?

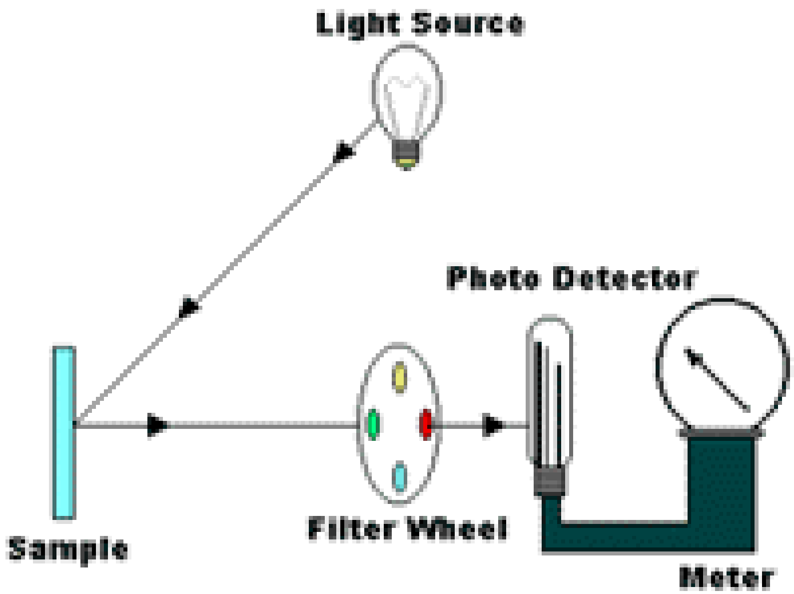
How does a colorimeter work?

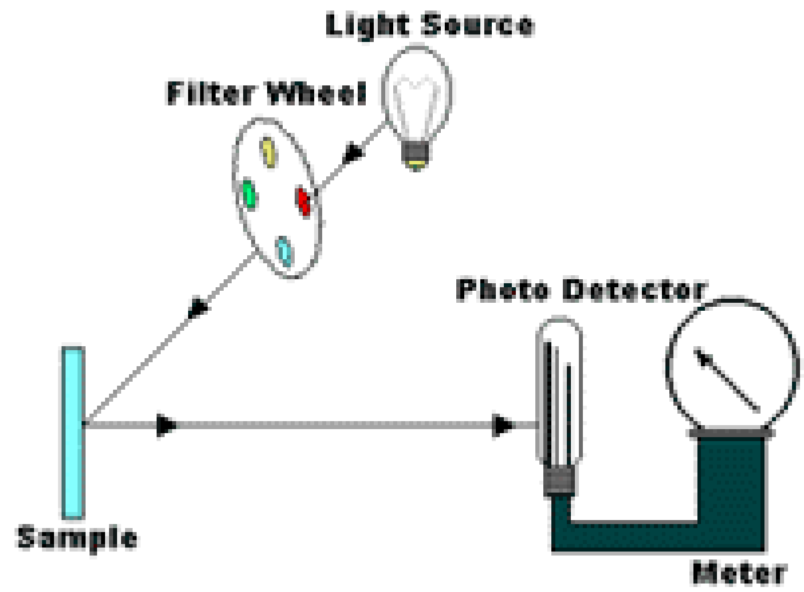
1. Bowels of a typical colorimeter
2. Requirements of the different parts
3. Operation principles



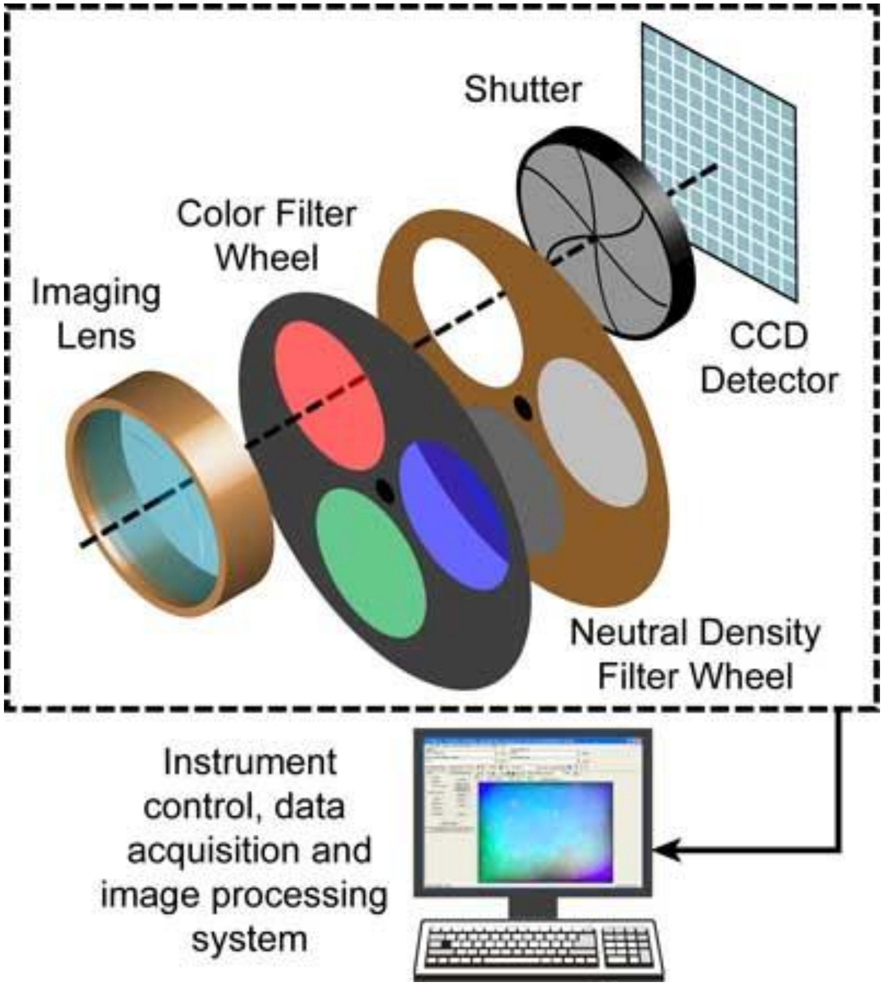
How does a colorimeter work?

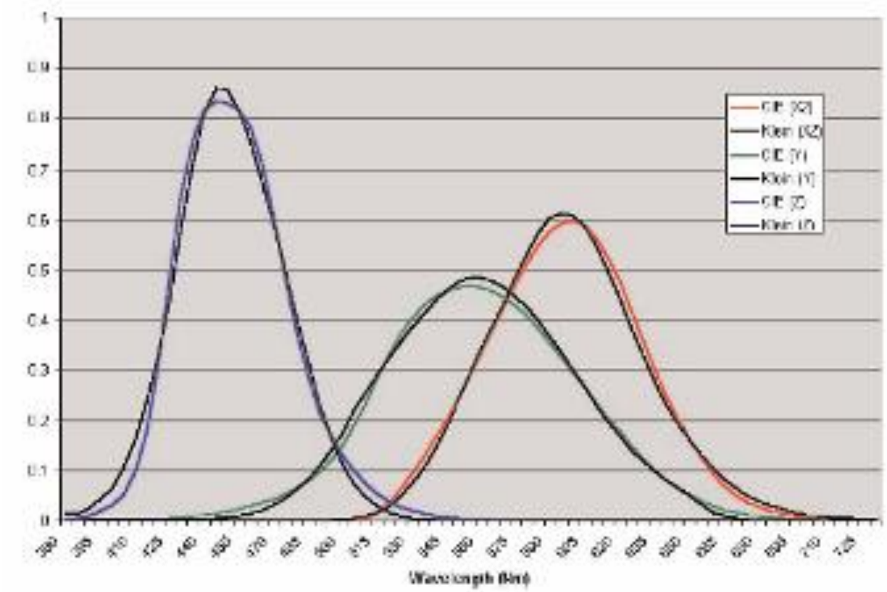
The main idea is making light go through an array of color filters and measure total transmitted radiance with a photodiode.





How does a colorimeter work?





(actual X. Y. Z. filter data)

Luther's condition!!

Why 4 filters instead of 3?

Device's response model

- 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 c Final response

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

assuming linear opto-electronic transfer function!!!

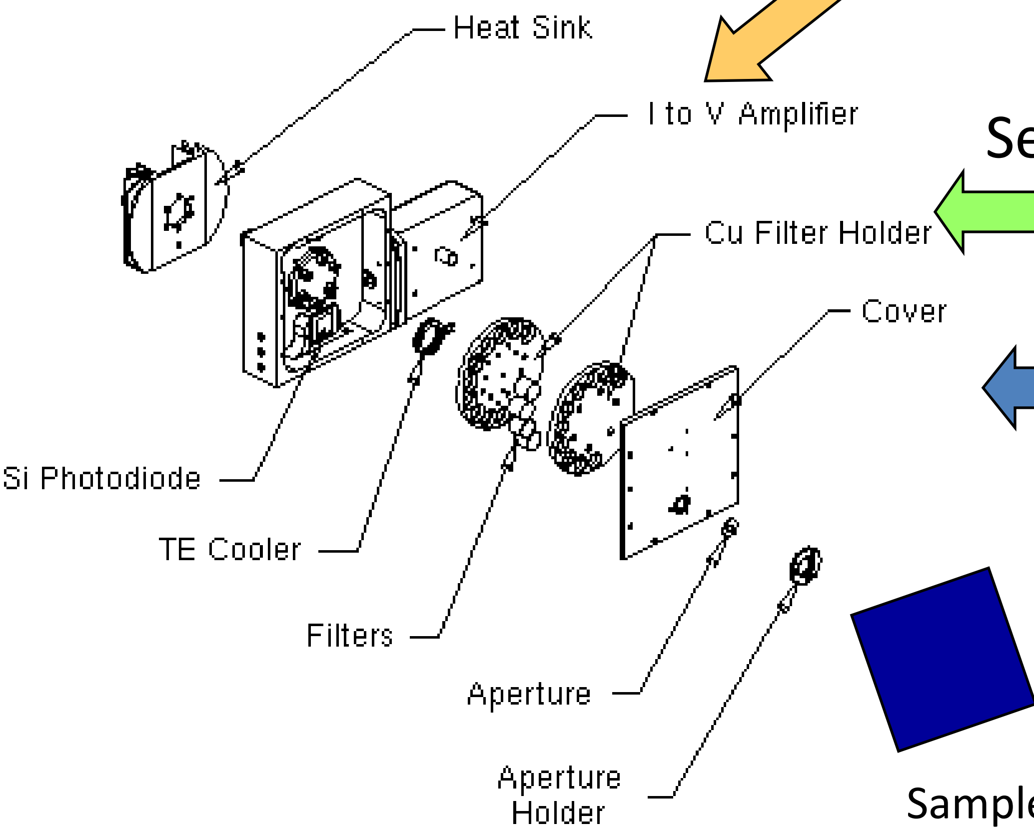
$$c = \int_{\lambda_{\min}}^{\lambda_{\max}} L(\lambda)\, R(\lambda)\, O(\lambda)\, T(\lambda)\, S(\lambda)\, d\lambda$$

$$\boxed{c_i = \sum_{\lambda} L(\lambda)\, R(\lambda)\, T(\lambda)\, S(\lambda)\, \Delta\lambda}$$

Third stage $L(\lambda)\, R(\lambda)\, T(\lambda)\, S(\lambda)$

Second stage: $L(\lambda)\, R(\lambda)\, T(\lambda)$

First stage: $L(\lambda)\, R(\lambda)$



Sample

Usually it is made more or less portable…

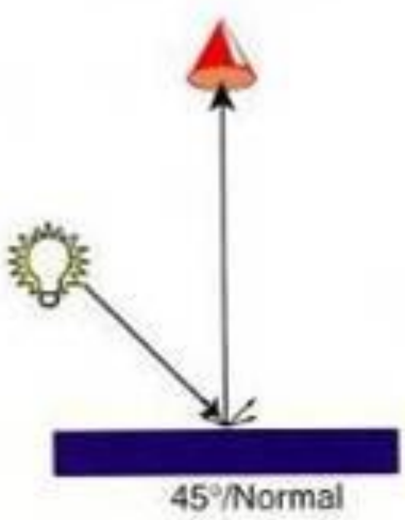
- Direct contact with the sample
- Integrated optics to allow to work at a distance from the samples

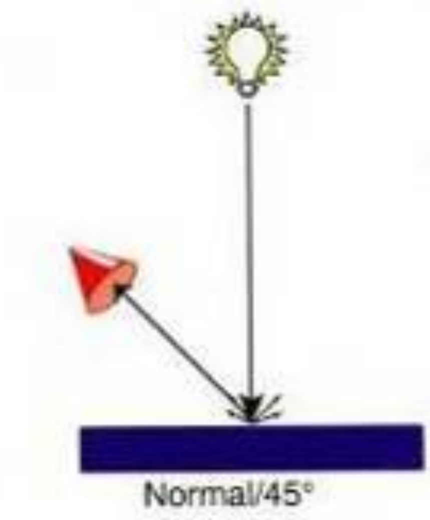
Or even specifically designed for some applications
(device calibration)...

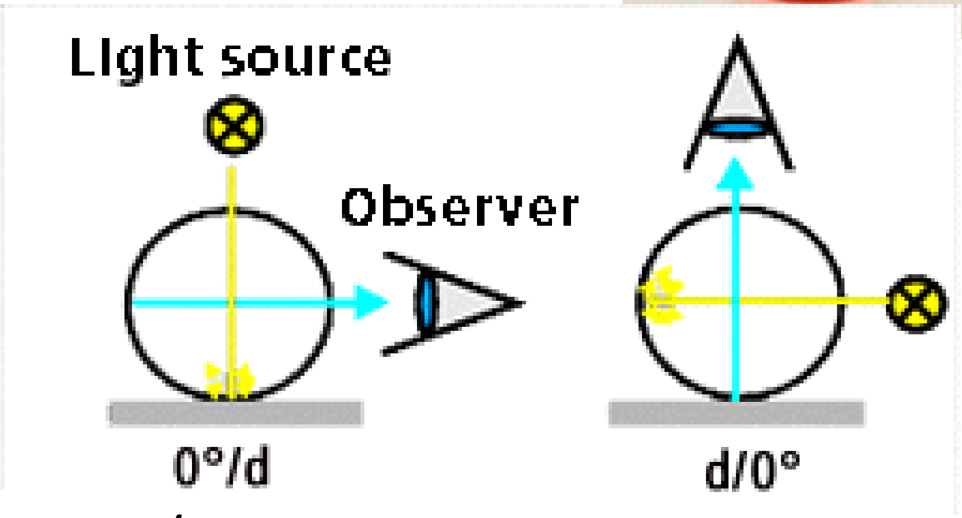
Specification Sheet example: K-80 from KLEIN INSTRUMENTS:
http://www.kleininstruments.com/s/02-0093-01-K-80-SpecSheet.pdf

For the measurement to be complete, illumination source, observer or field size and geometry must be specified

Some instruments use diffuse standard geometries







-Examples: 12 mm window D65-45/0
3 mm window D65-0/45, 2° obs

- Some recent developments.

1) LED-based colorimeter, offering color difference calculations and nearest-neighbor identification for standard sets.

L_i: reflected intensity from sample for LED i

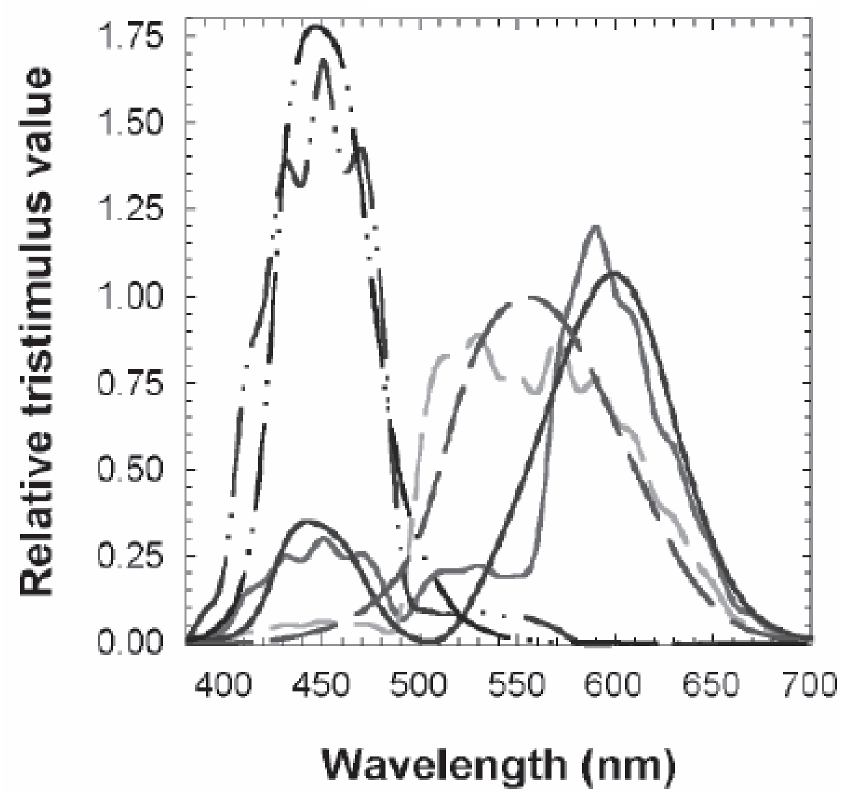
$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{pmatrix} \begin{pmatrix} L_1 \\ L_2 \\ L_3 \end{pmatrix}$$

Some recent developments.

Using a color digital camera as colorimeter? (project in Applied Advanced Colorimetry)

a) spectral characterization of the digital camera and its CMFs

b) Finding the relation between RGBs and XYZ for unknown illumination conditions



What is a spectroradiometer?

- Instrument used to measure spectral radiance (not only):

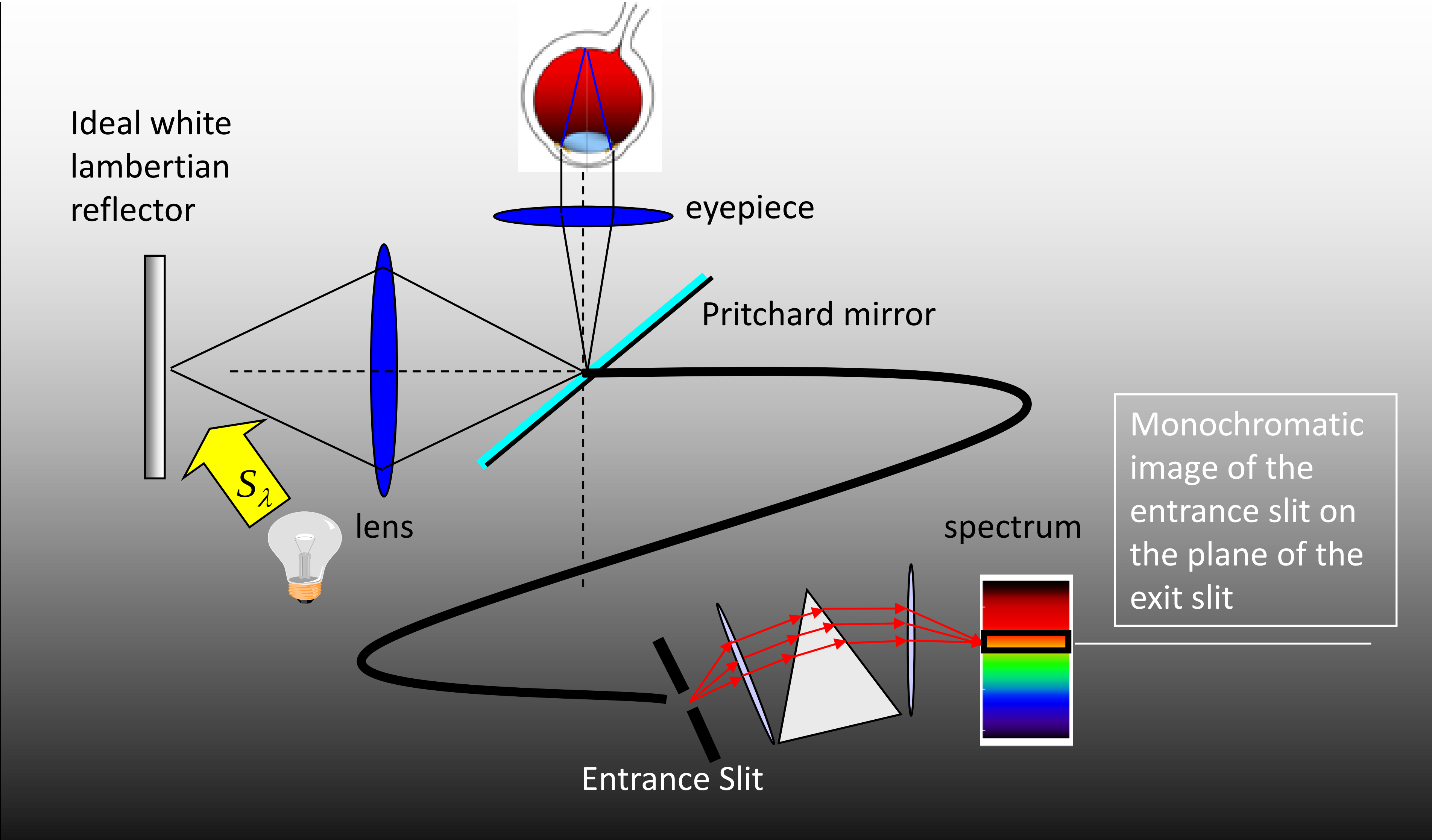
Measures by sampling spectral radiance at multiple wavelengths in the visible or IR-UV regions

Measurements at a distance from the sample (do not have illumination system included in the instrument)

Usually: some optics make part of the instrument to focus the sample into the internal measure spot

Operation principles… How does it work?

Operation principles… How does it work?



Optic fiber vs conventional optics

Different approaches: optic fiber vs conventional optics

Fiber-based devices usually work at shorter distances from the samples

Lambertian surface= perfect diffuser

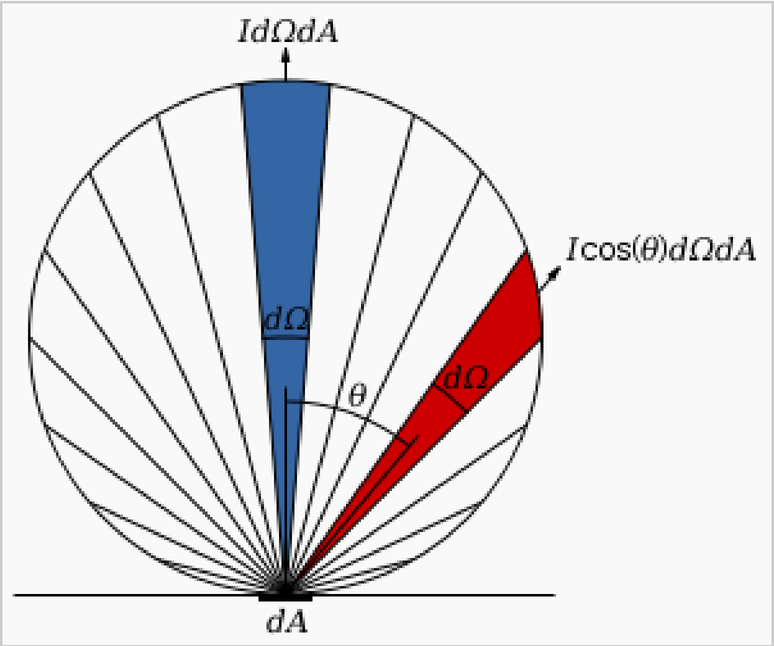


Figure 1: Emission rate (photons/s) in a normal and off-normal direction. The number of photons/sec directed into any wedge is proportional to the area of the wedge.

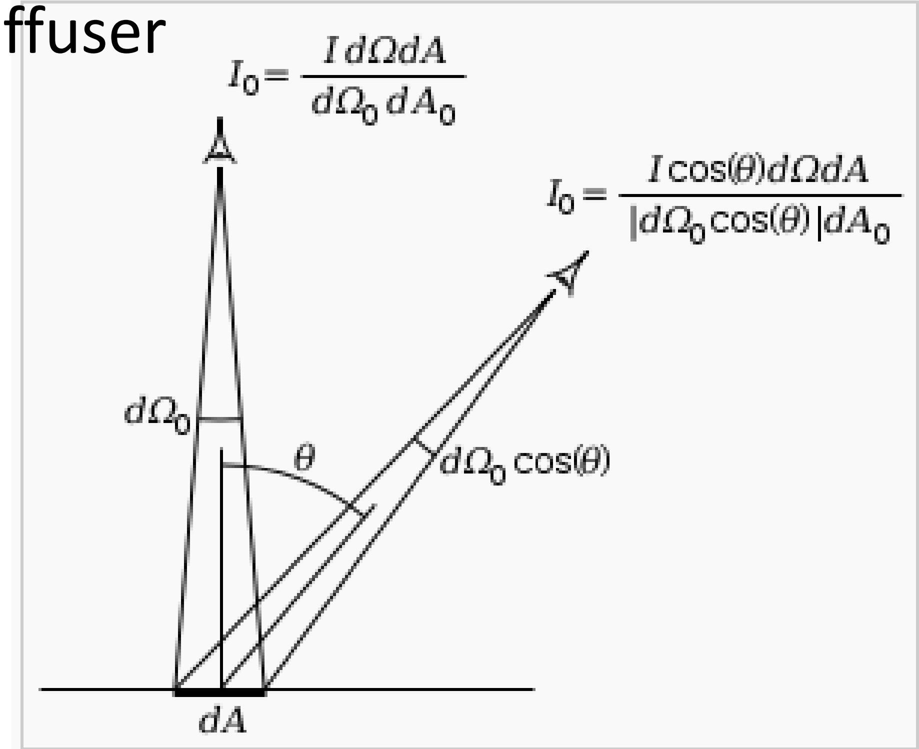
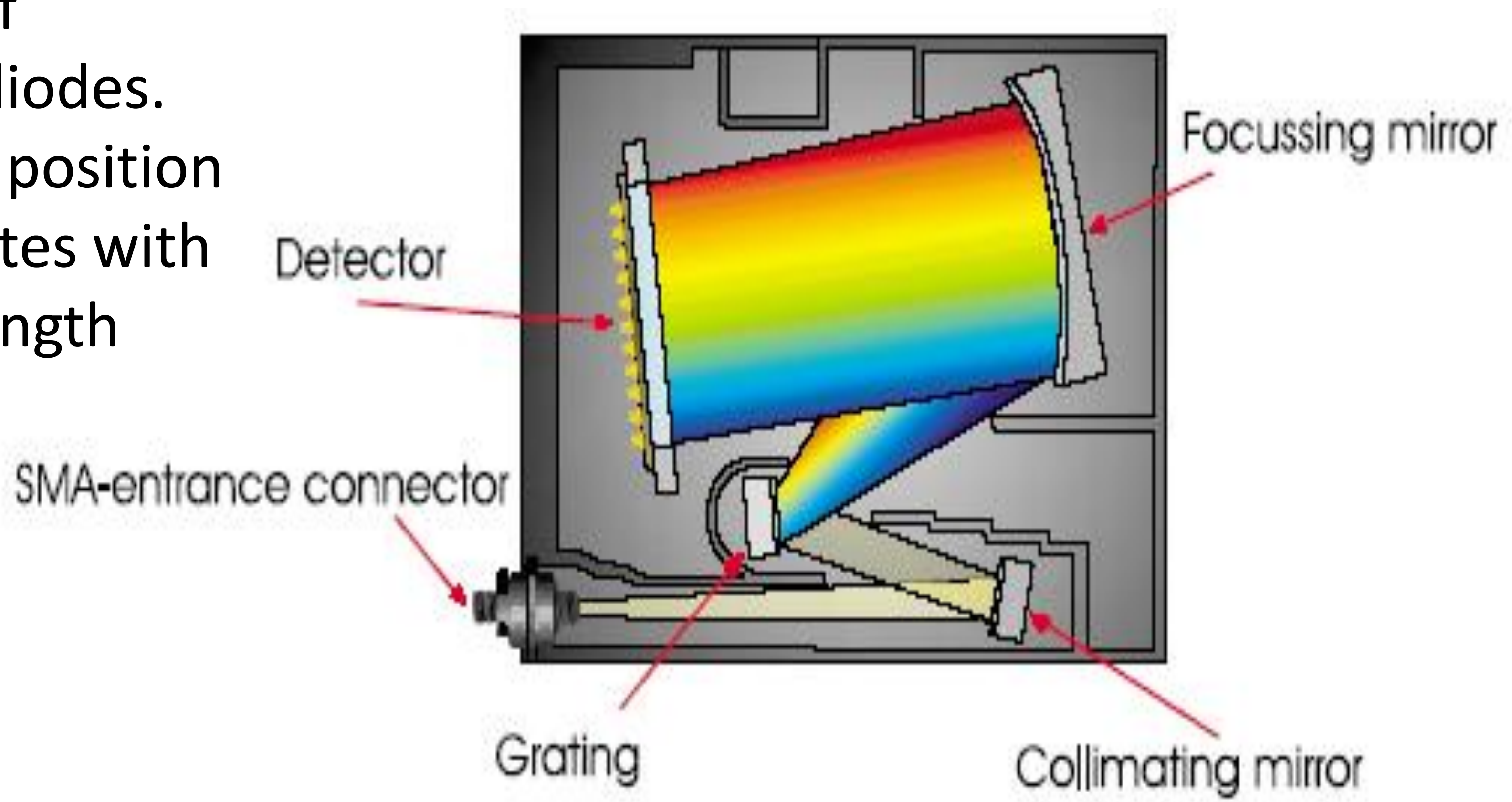


Figure 2: Observed intensity (photons/(s·cm^2·sr)) for a normal and off-normal observer; dA_0 is the area of the observing aperture and $d\Omega$ is the solid angle subtended by the aperture from the viewpoint of the emitting area element.

Perfect difusers have equal luminance along any direction of viewing. the apparent brightness of the surface to an observer is the same regardless of the observer's angle of view. More technically, the surface luminance is isotropic.

The detector is an array of photodiodes. Spatial position correlates with wavelength

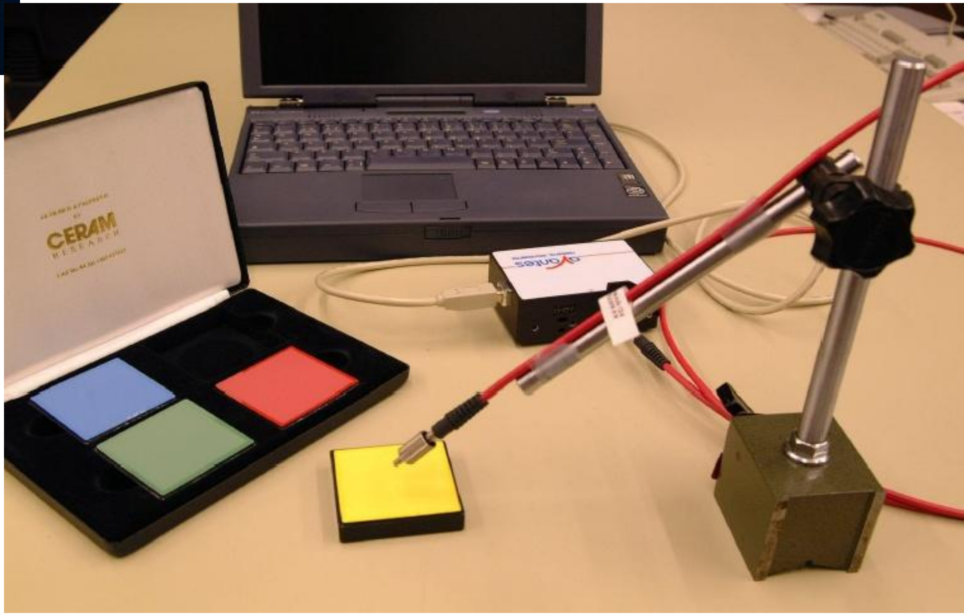
Image courtesy of AVANTES Inc.

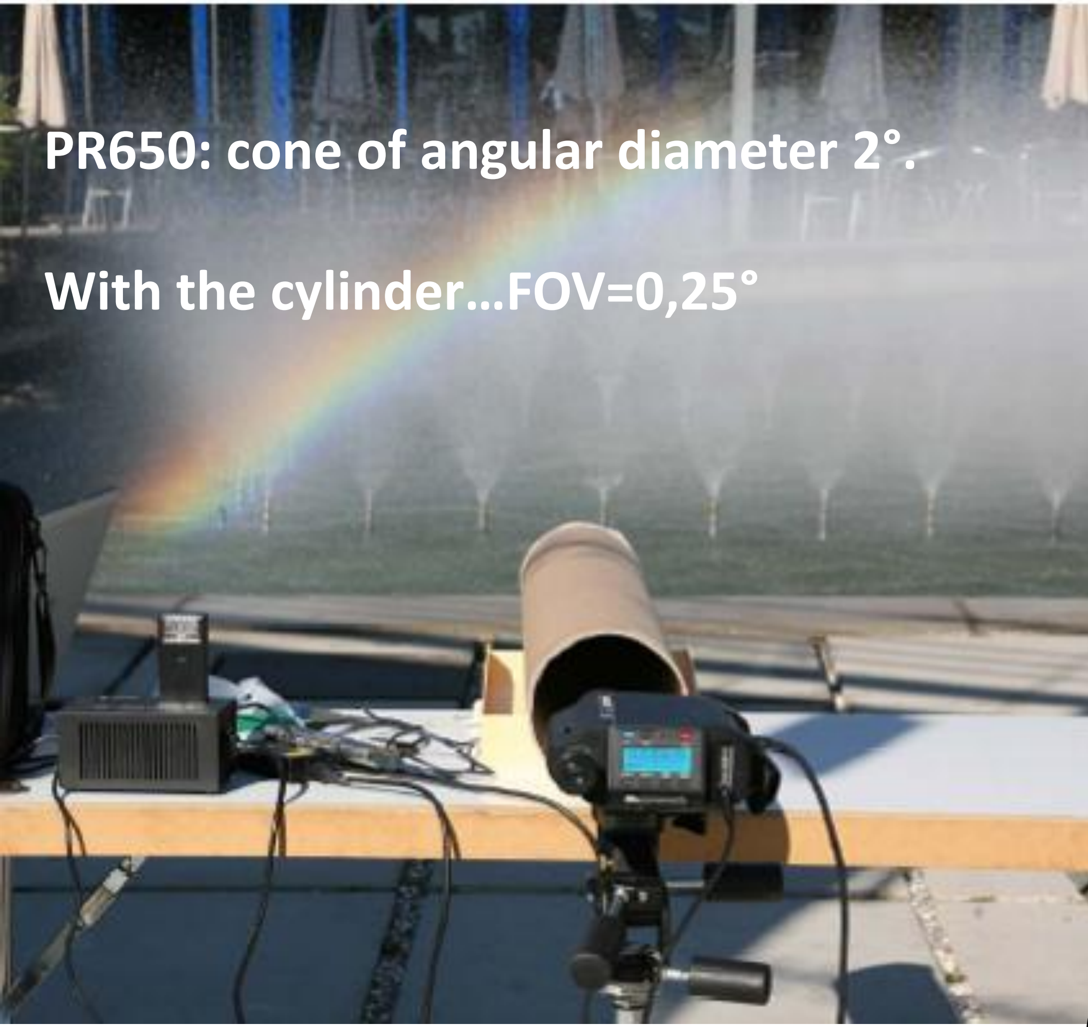


Usually, the spectrum is obtained by a reflection diffractive grating

Conventional optics devices: typical field sizes from 1°-2° to 1/8 deg. Macro accessories if working at shorter distances is needed (from 28 mm).

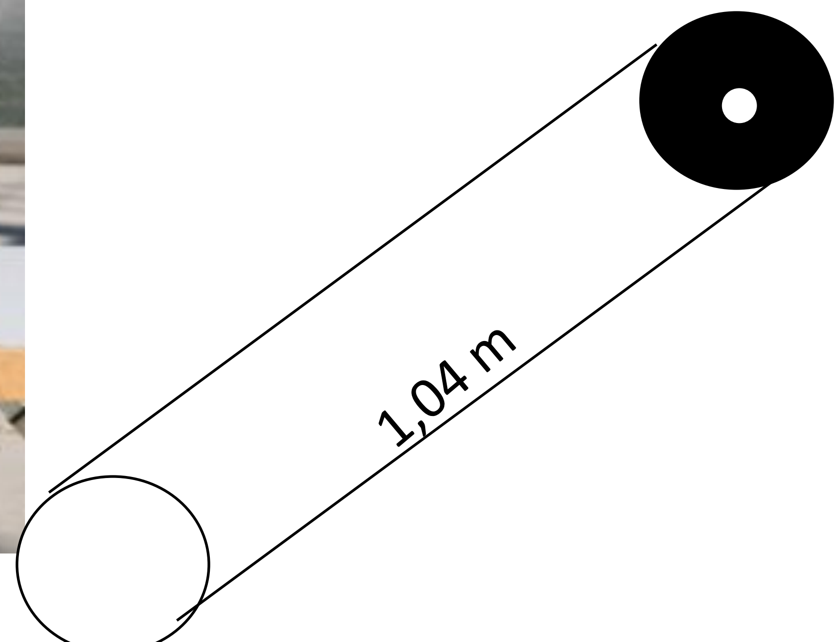
-Fiber-based devices: small aperture lens as accessories, typical field sizes of 1 deg.





From Gedzelman and Hernández-Andrés, Applied Optics, 2009

Hole diameter = 0,4cm

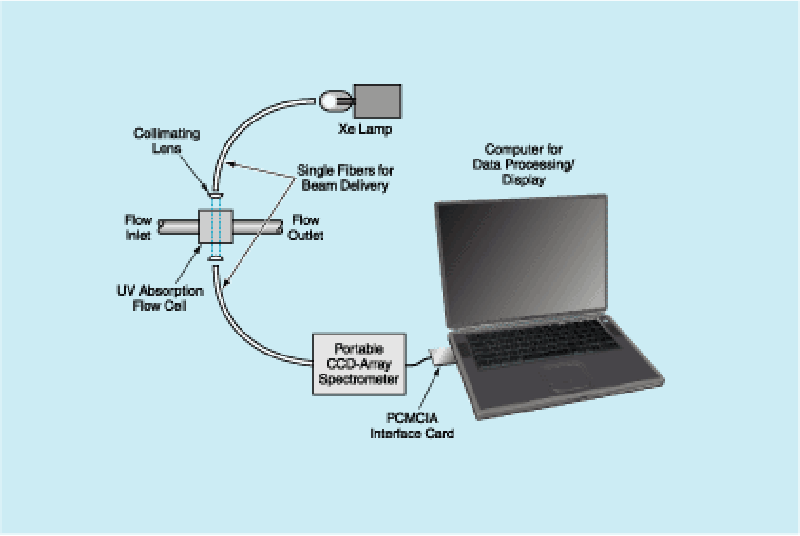


The optic fiber approach: more details

- The fiber (low absorption silica) is used to transport light from the sample to the optical bench of the spectrometer.

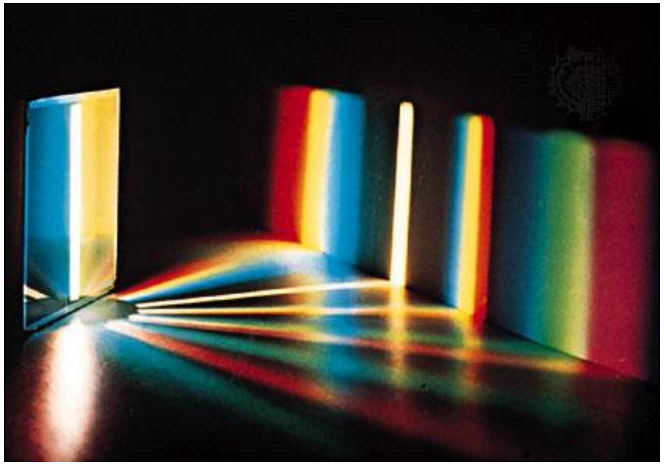
- Advantages: flexibility, modularity, low cost.

- Directionality and field size not easy controlled.



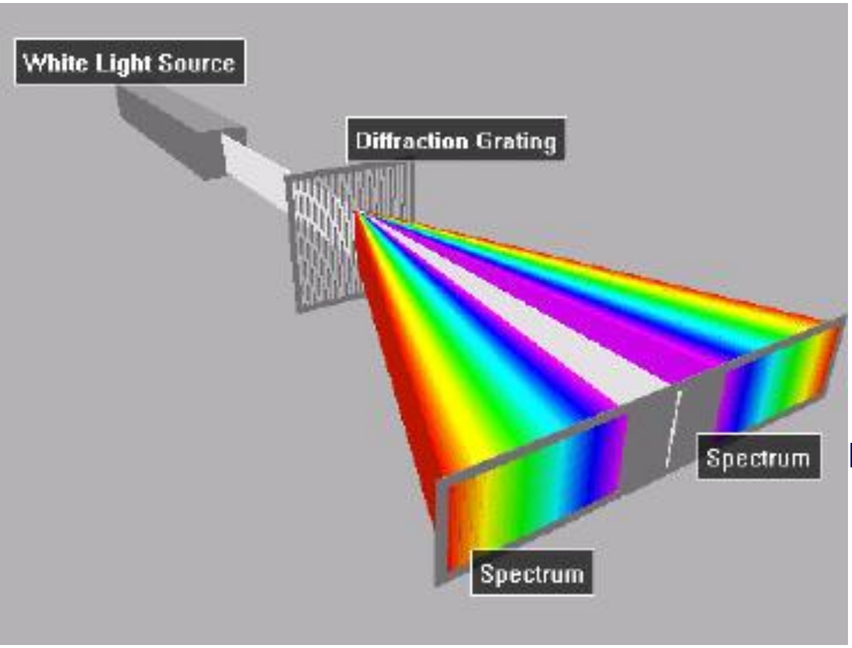
INSTRUMENT FEATURES:

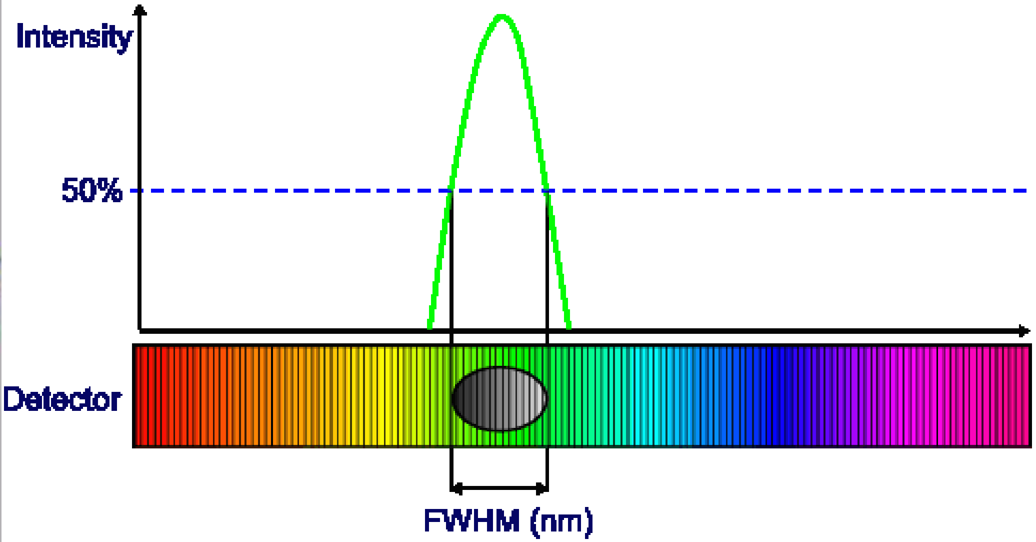
-**Wavelength range**: variable according to fiber, grating and sensor selection. Indicative: 200 nm-2500 nm (not in one instrument!)



- **Optical resolution**: the optical resolution is defined as the minimum difference in wavelength that can be separated by the spectrometer. For separation of two spectral lines it is necessary to image them at least 2 array-pixels apart.

-**Optical resolution**: variable according to grating selection.
Indicative: 600 -2400 lines/mm (VIS).
- Slit sizes from 10 to 500 microns (typical values, for the Avantes instruments).
Resolutions: 0.8-0.04 nm (10 microns slit size)





CCD vs CMOS

See Assignment #2

Describe how a CCD works, defend the pros of CCDs, describe the main features, …
Do the same for CMOS.

Clues: linear response, noise, dynamic range, uniformity, price, A/D conversion, quantum efficiency, spectral sensitivity, power consumption, response time, frames per second, blooming effect, compactness, signal out of pixel, signal out of chip, signal out of camera, fill factor, amplifier mismatch, etc

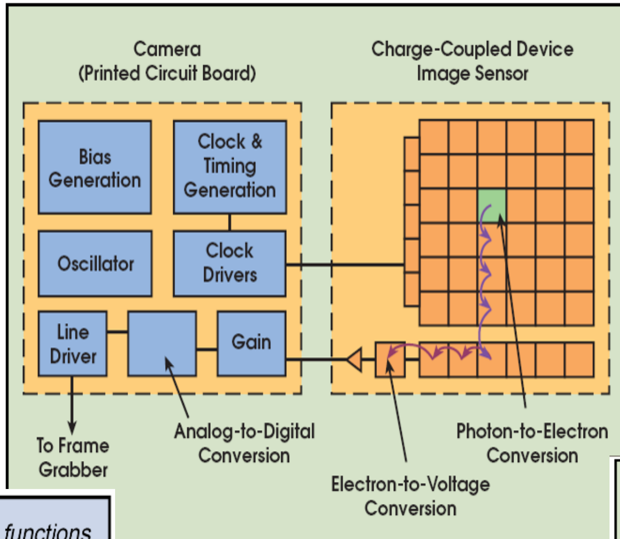


Figure 1. *On a CCD, most functions take place on the camera's printed circuit board. If the application's demands change, a designer can change the electronics without redesigning the imager.*

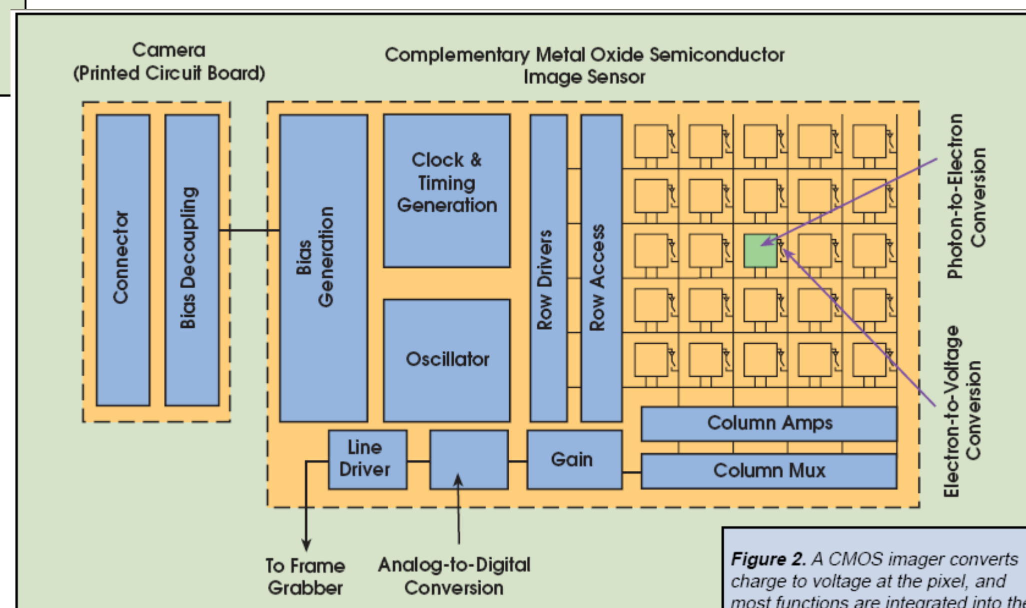
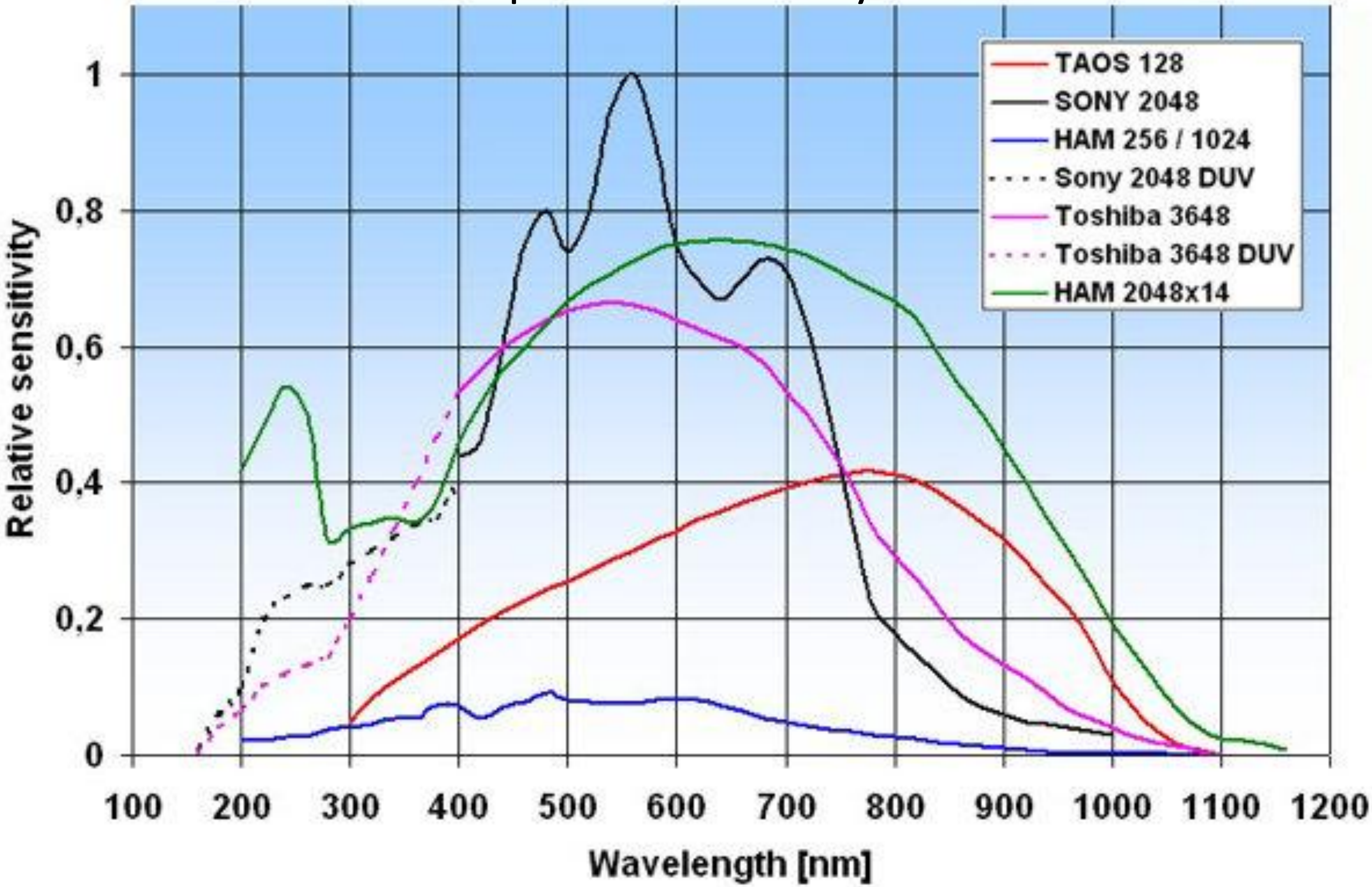


Figure 2. *A CMOS imager converts charge to voltage at the pixel, and most functions are integrated into the chip. This makes imager functions less flexible but, for applications in rugged environments, a CMOS camera can be more reliable.*

• **Uniformity**, the consistency of response for different pixels under identical illumination conditions.

ufacturers have invested considerable effort in suppressing dark nonuniformity, it is still generally

Detector spectral sensitivity curves.



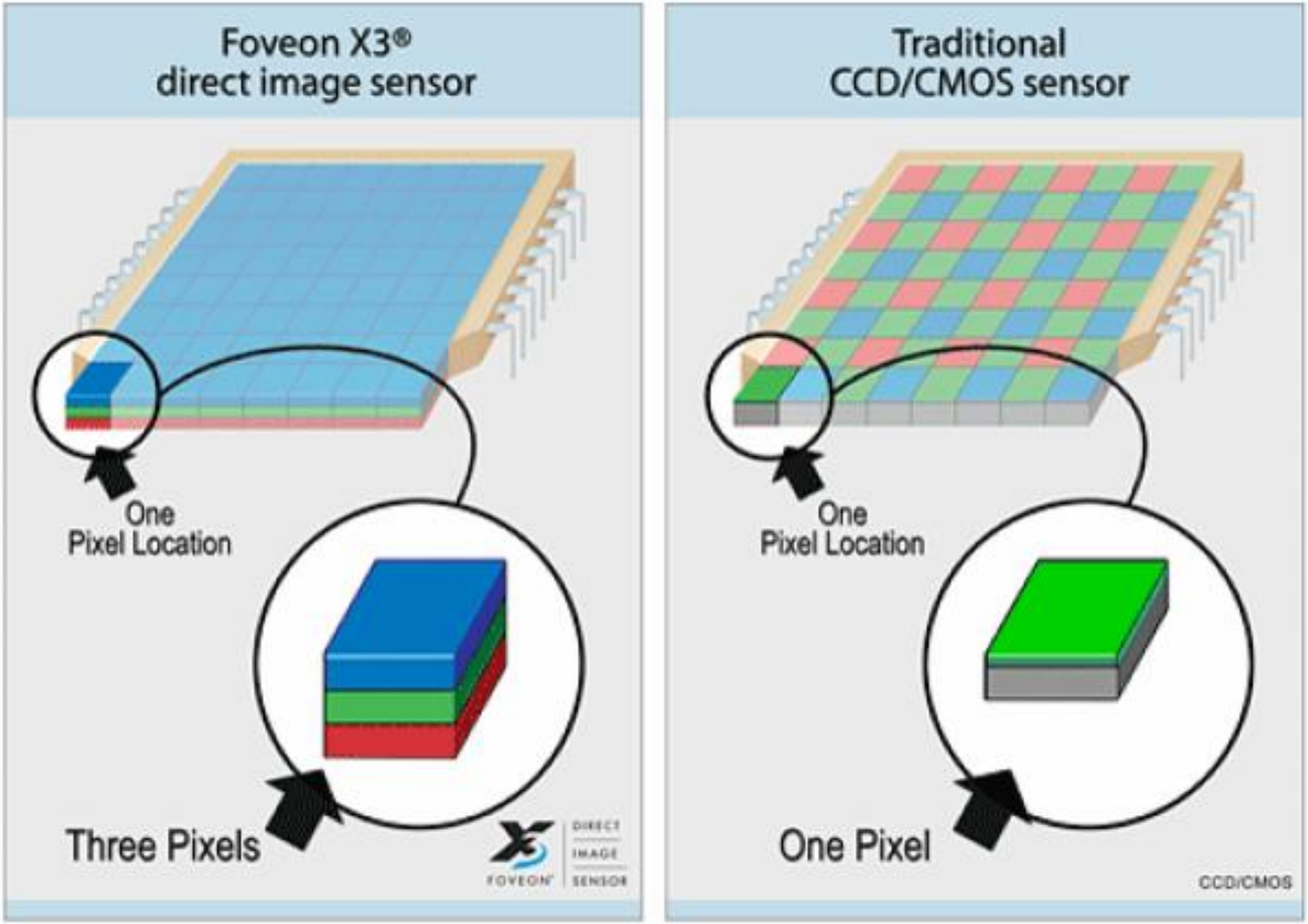
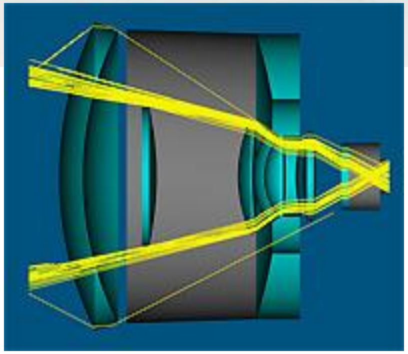
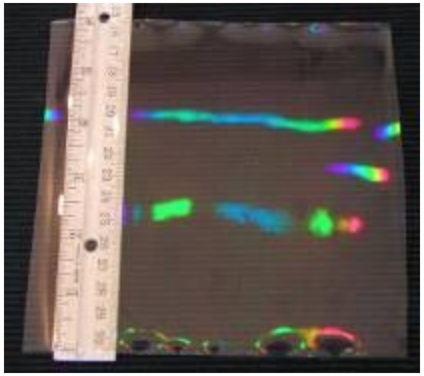


Figura 2.4. Estructura del sensor Foveon X3 y del pixelado clásico de Bayer.

Errors

-Stray light and second-order effects.





-Stray light: radiation non intended to be detected that activates a signal at a detector element.

-Sources and solutions:

1) Ambient light

-Encasing in a light-tight housing

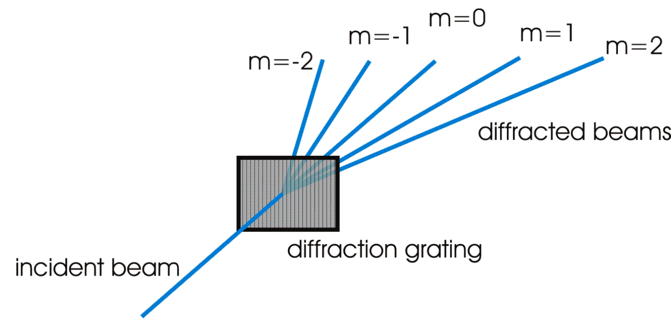
2) Scattered light from mirrors and grating

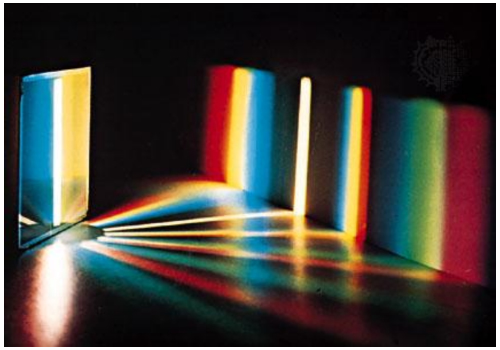
-Use of holographic diffraction gratings

-Example of one instrument: Stray light performance: <0.05% (600nm).<0.1% (250nm)

-Second-order effects.

- Caused by the 2nd order diffracted beam (low groove frequency gratings)





-Solution: limiting light to the non-overlapping region of the spectrum for the grating

-This is usually done by installing long-pass filters in the entrance slit or order-sorting coatings in a window in front of the detector.

Commercial examples

Ex. 1) PR-670 from Photoresearch

• 256 elements array photodetector with 1.56 nm per pixel

• 4 apertures from 1 to 1/8 deg.

• accessories for reflectance and LED-source characterization

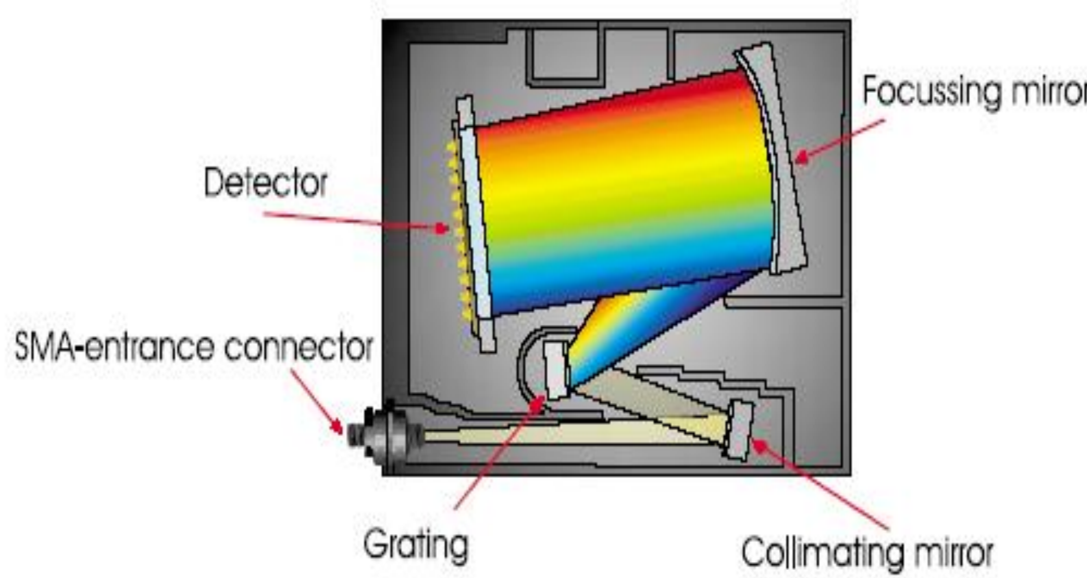
Commercial examples

Ex. 2) USB2000 from Ocean Optics

Physical	
Dimensions:	89.1 mm x 63.3 mm x 34.4 mm
Weight:	190 grams
Detector	
Detector:	Sony ILX511 linear silicon CCD array
Detector range:	200-1100 nm
Pixels:	2048 pixels
Pixel size:	14 µm x 200 µm
Pixel well depth:	~62,500 electrons
Sensitivity:	75 photons/count at 400 nm; 41 photons/count at 600 nm

Commercial examples

Ex. 2) USB2000 from Ocean Optics

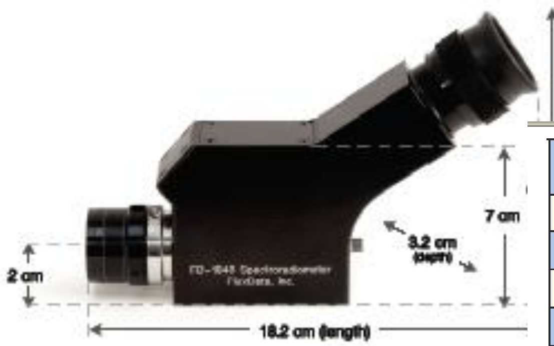


Spectroscopic

Wavelength range:	Grating dependent
Optical resolution:	~0.3-10.0 nm FWHM
Signal-to-noise ratio:	250:1 (at full signal)
A/D resolution:	16 bit
Dark noise:	50 RMS counts
Dynamic range:	2 x 10^8 (system); 1300:1 for a single acquisition
Integration time:	1 ms to 65 seconds
Stray light:	<0.05% at 600 nm; <0.10% at 435 nm
Corrected linearity:	>99.8%

Commercial examples

Ex. 3) FD-1840 from FluxData



- Hand-held, small
- No moving parts
- Possibility of use in display calibration for LCDs and plasma

Model	FD-1840QE	FD-1840+
Wavelength Range	385-765nm	380-1000nm
Measuring Aperture(s)	1.0° standard, 0.5°, 1.5°, 2.0°, 2.9°, 4.4°, 7.3° lens options available	
Measuring Distance / Area	150mm - Infinity / 2.61mm (with 1.0° lens)	
Eyepiece Field of View	15° FOV (with 1.0° lens)	
Luminance Sensitivity / Accuracy	0.02 cd/m² / ±2% (for Illuminant A)	TBD
Color Accuracy	CIE 1931 x,y ±0.0015 (for Illuminant A)	
Measuring Capabilities	Spectral Radiance, Luminance, Spectral Irradiance, Illuminance, Spectral Radiant Flux, Radiant Intensity, CCT, XYZ, L*a*b*, L*u*v*	
Spectrometer / Detector	Ocean Optics QE65000 / Hamamatsu S7031-1006	Ocean Optics USB 2000+ / Sony ILX511
Pixels	1024 x 58	2048
Optical Resolution	0.92nm (FWHM)	1.33nm (FWHM)
Signal-to-Noise Ratio	1000:1 (at full signal)	250:1 (at full signal)
A/D Resolution	16 bit	
Dark Noise	3 RMS counts	3.2 RMS counts
Integration Time	8 ms to 15 minutes	1 ms to 65 seconds
Power Consumption	3.5 A @ 5 VDC (with TE cooling)	90 mA @ 5 VDC
Maximum Data Transfer Speed	Full scans to memory every 7 ms with USB 2.0	Full scans to memory every 1 ms with USB 2.0
Inputs / Outputs	10 onboard digital user-programmable GPIOs	
Temperature & Thermoelectric (TE) Cooling	Set in software from -15° C to 50.0° C (max 40° C below ambient). Stability of ±0.1 °C reached in <2min.	N/A
Operating Systems	Windows, Mac OS X and Linux	
Standard Accessories	Carrying case, USB-cable (2m), Data processing software, Optical Fiber (2m)	
Spectrometer Dimension / Weight	182×110×47mm / 1148g	89×63×35mm / 224g

What is a spectrophotometer?

- Instrument used to measure spectral reflectance (sometimes transmittance too)

Measures by sampling spectral radiance at multiple wavelengths in the visible or IR-UV regions (and discounting the illuminant afterwards to obtain reflectance or transmittance)

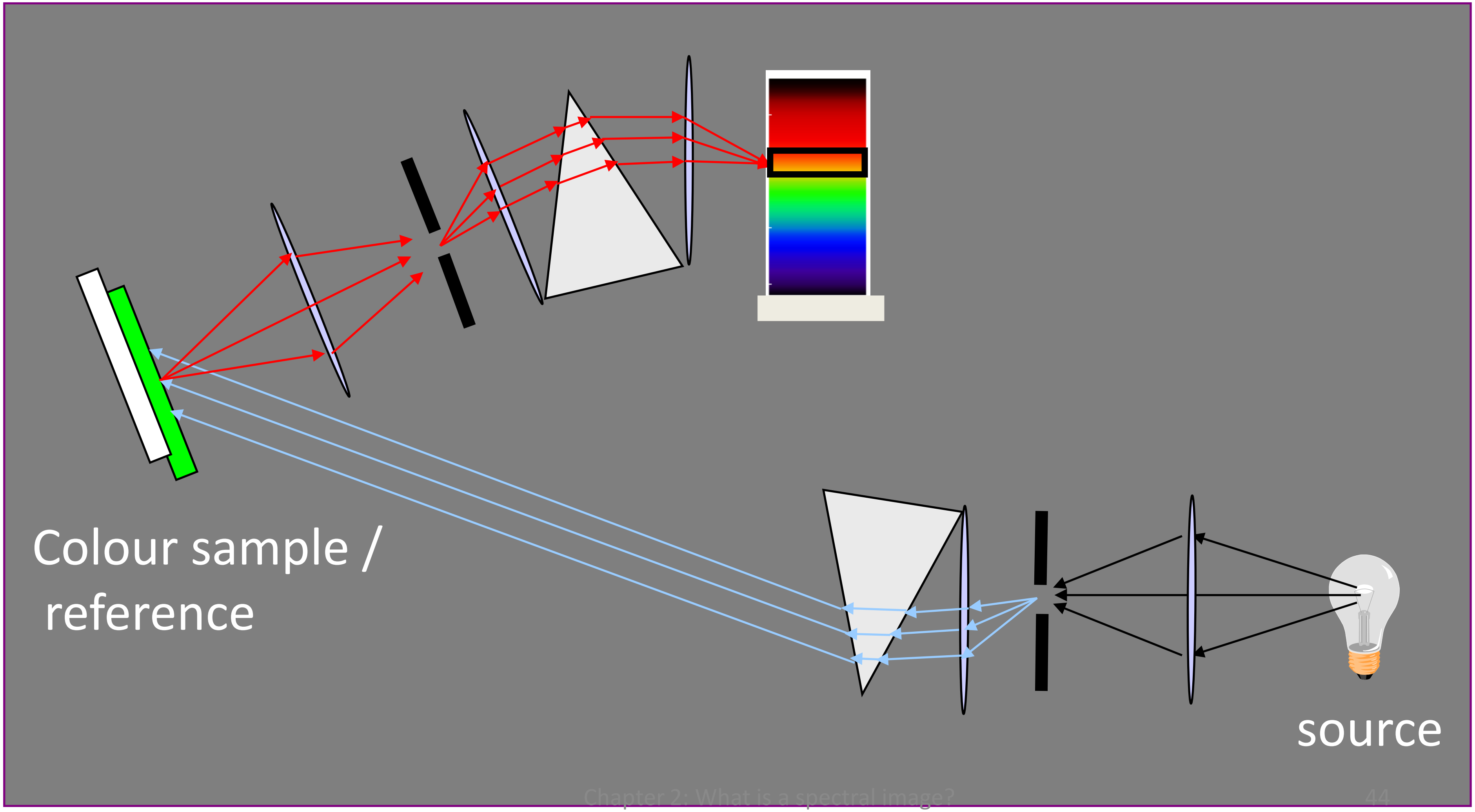
Measurements in close contact with the sample (they implement an illumination system)

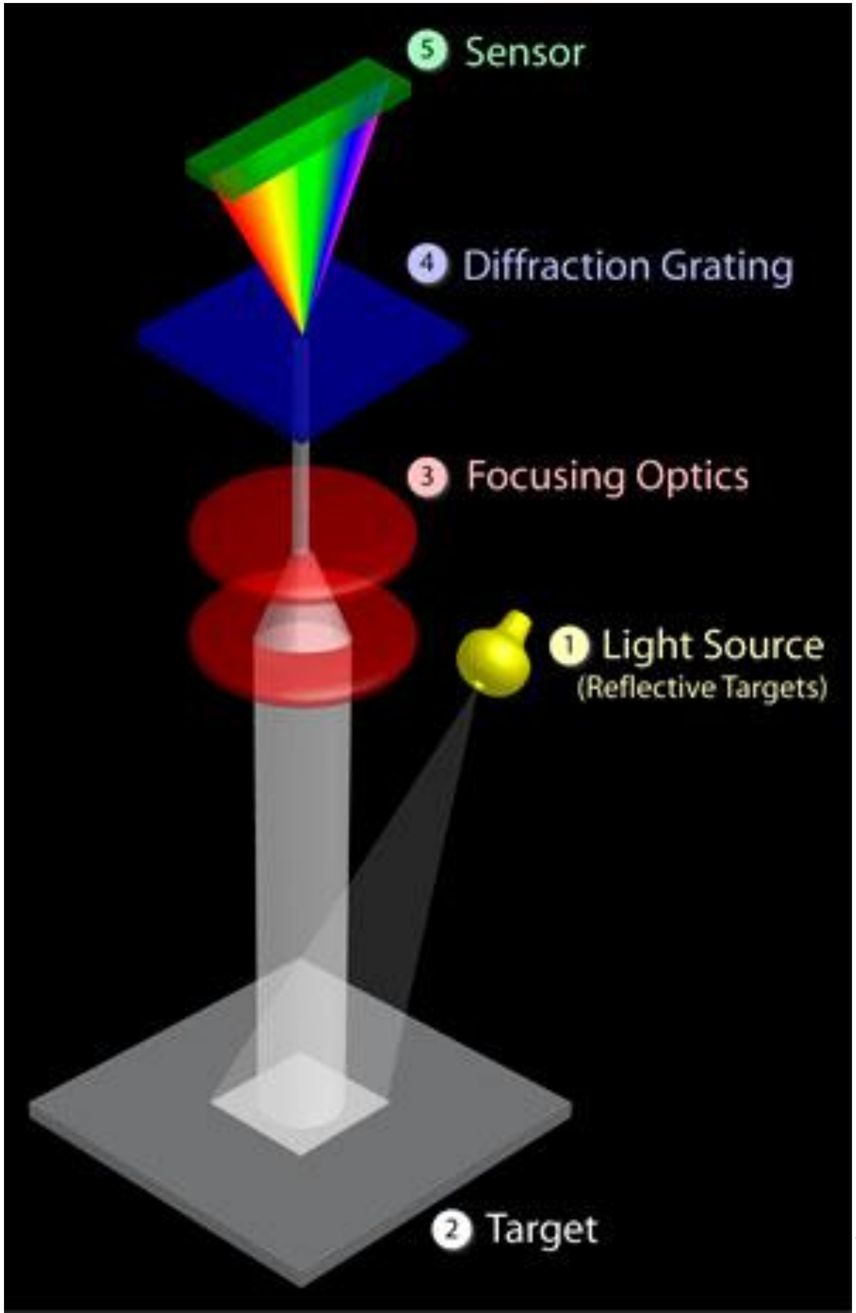
What is a spectrophotometer?

How does it work?

What is a spectrophotometer?

How does it work?

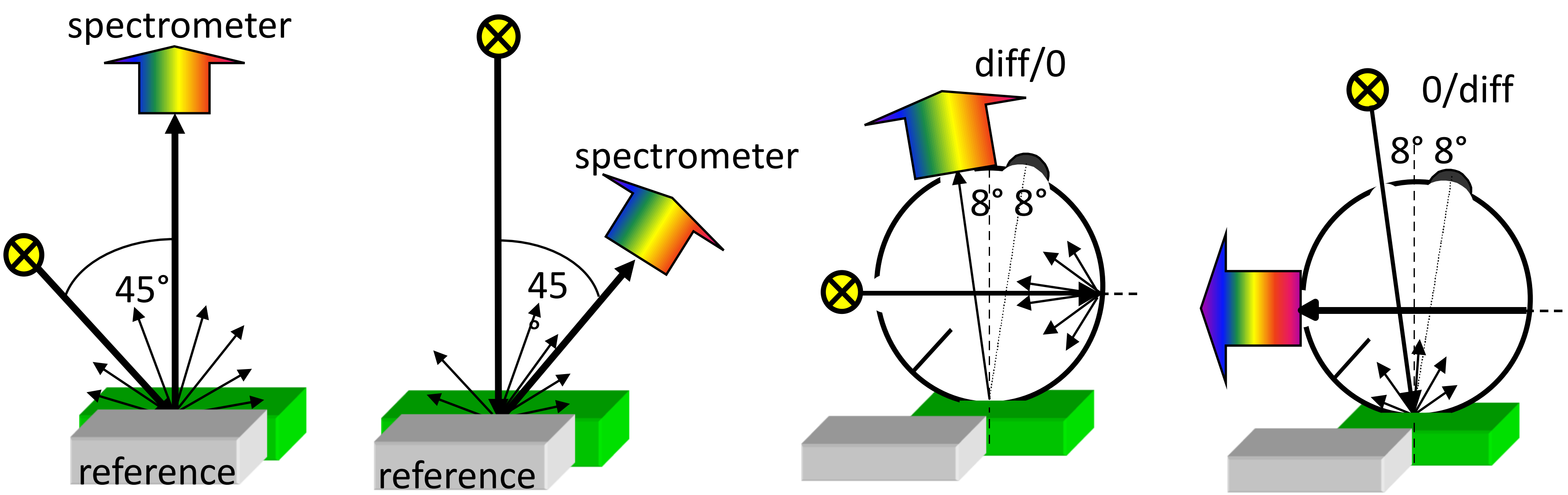




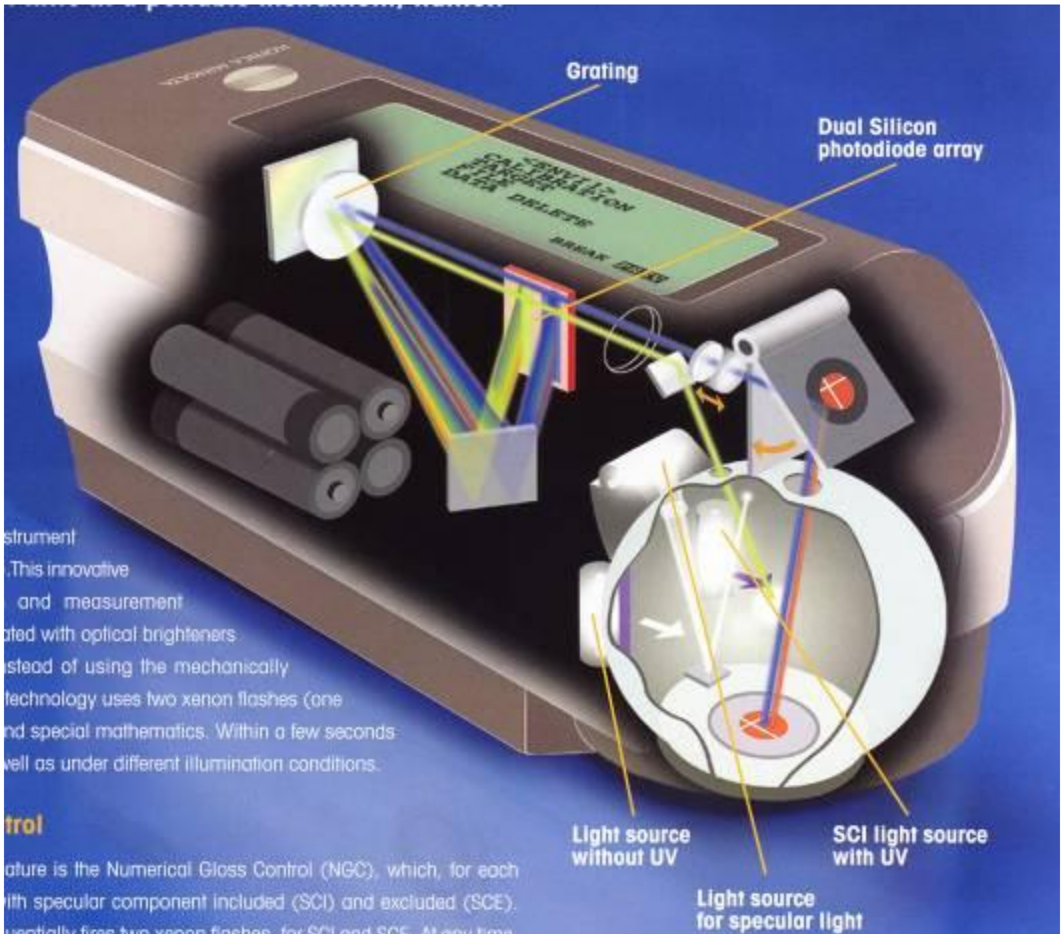
-There may be a reflection or transmission grating (depending on the design and the instrument size)

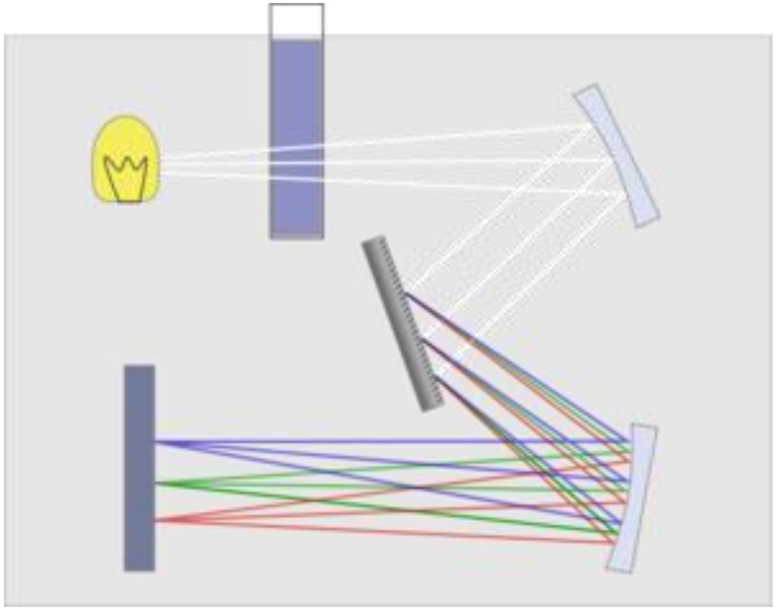
-It can contain also one or more light sources (depending on spectral range or measurement set-up for specular or diffuse reflection)

-Standard geometries: 0/45 or 45/0 (also diffuse geometries)

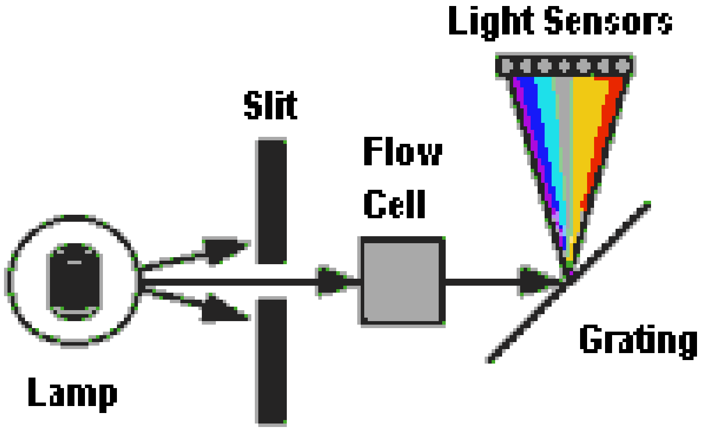


- Two main different approaches. Portability-reflectance (more rarely transmittance) vs non portable high-precision-reflectance-transmittance

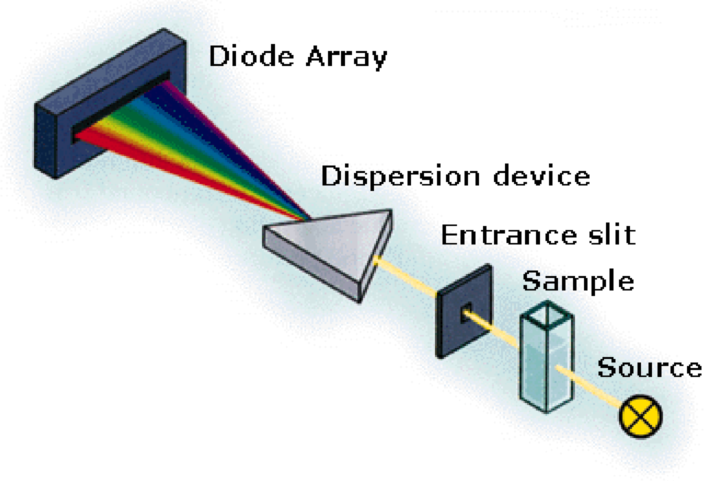


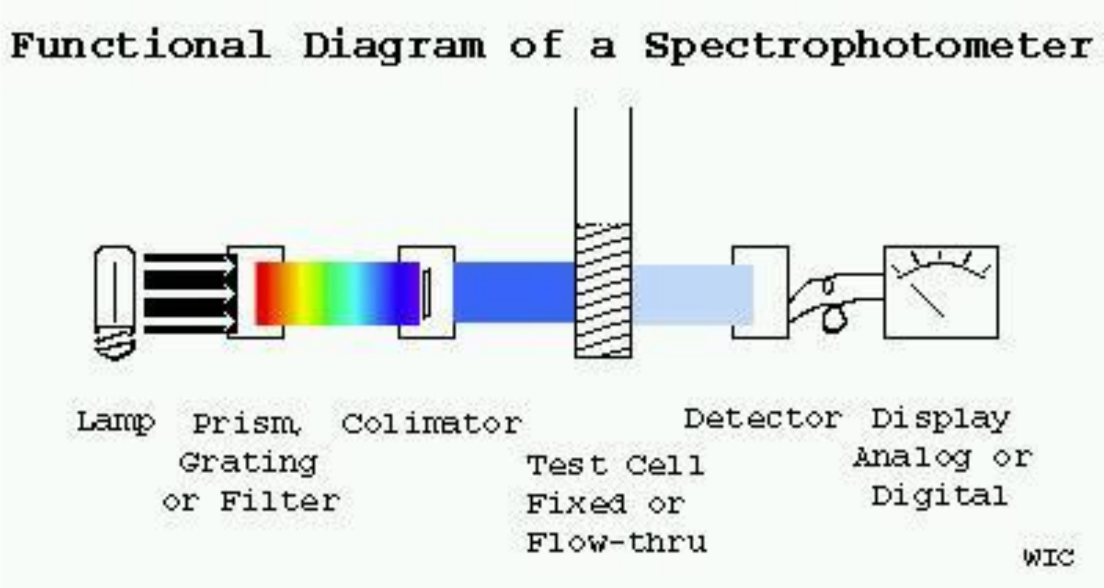


-Portable spectrophotometer for transmission measurements (including sample holder)



- Two main different approaches. non portable high-precision- reflectance-transmittance





-The grating can be placed before or after the sample (monochromator vs radiometer)

- The fiber approach. Is it really a spectrophotometer?

-Its manufacturers say it's a "spectrometer"

-It can be used to measure reflectances (by discounting the illumination source) and including some accessories for sample holding and calibration.

Colorimeter vs. spectrophotometer

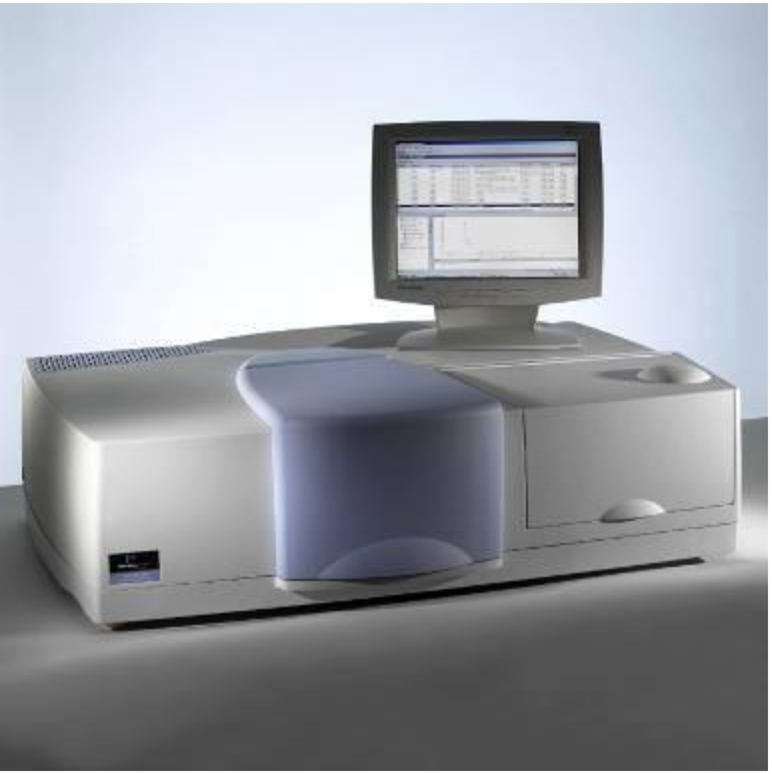
Colorimeter	Spectrophotometer

Colorimeter vs. spectrophotometer

Colorimeter	Spectrophotometer
-Measurements directly related to psychophysical data (tristimulus values)	-spectral measurements (it may provide tristimulus and color coordinates but it is not its main objective)
- Sensor and simple data processor	- Sensor and more sophisticated data processor (PC or similar)
- Broad band spectral filters	- Gratings (narrow band spectrum)
- Fixed settings (simple instrument)	- Variable settings (complex instrument)

Commercial examples

Ex. 1) Lambda series from Perkin Elmer

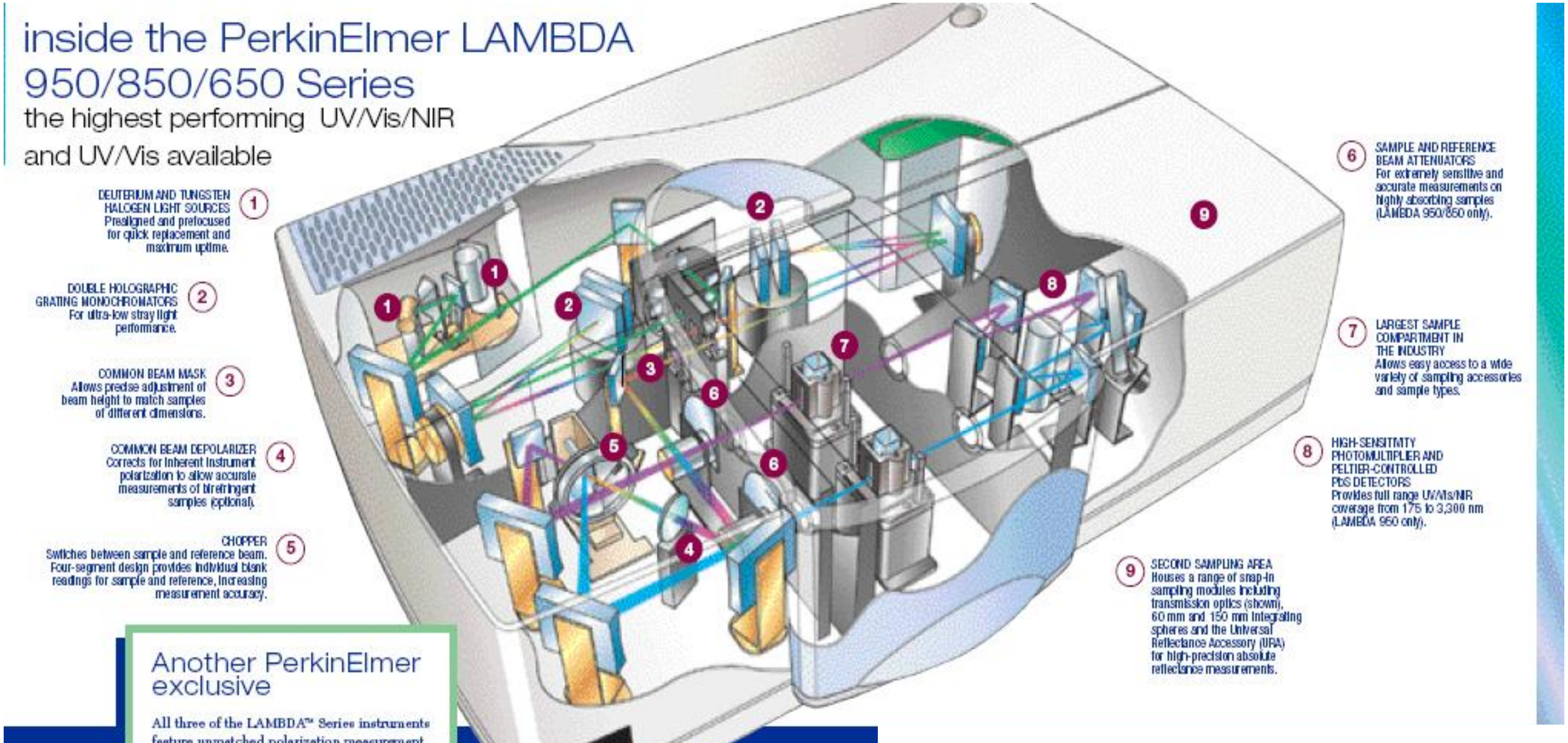


- High performance and optical resolution

- Reflectance or transmittance (with accessories)

- Not quite cheap…

Ex. 1) Lambda series from Perkin Elmer



1) Light sources
2) Double holographic transmission gratings
4) Depolarizer
5) Rotating mirror

6) Intensity attenuators
7) Sensor
8) Photomultiplier
9) Accessories for reflectance measurement

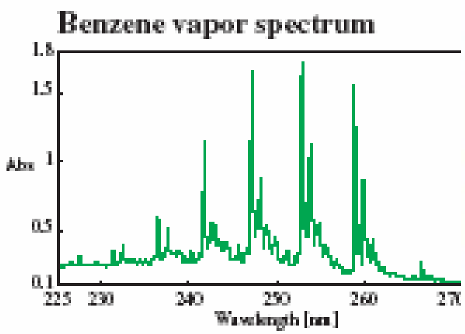
Ex. 2) V-650 from JasCo

V-630 General-purpose UV-Vis

- Double-beam spectrophotometer with single monochromator
- Silicon photodiode detectors
- Range 190 to 1100 nm
- Fixed bandpass of 1.5 nm
- High-speed scanning up to 8,000 nm/min
- IQ Accessory and IQ Start provide simplicity and ease of use
- USP, EP and JP compliant instrument validation software

V-650 High resolution UV-Vis

- Linearity up to 4 absorbance
- Range 190 to 900 nm
- Variable bandpass to 0.1 nm



-Mainly for transmittance (absorptance) measurements

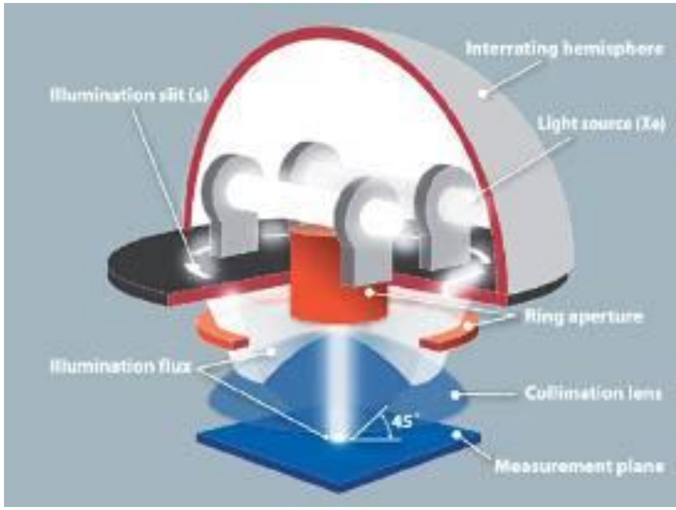
-Monochromator approach

Ex. 3) CM-2500C from KonicaMinolta

-Only for reflectance measurements

-45/0 geometry incorporated in the device illumination system (annular illumination)

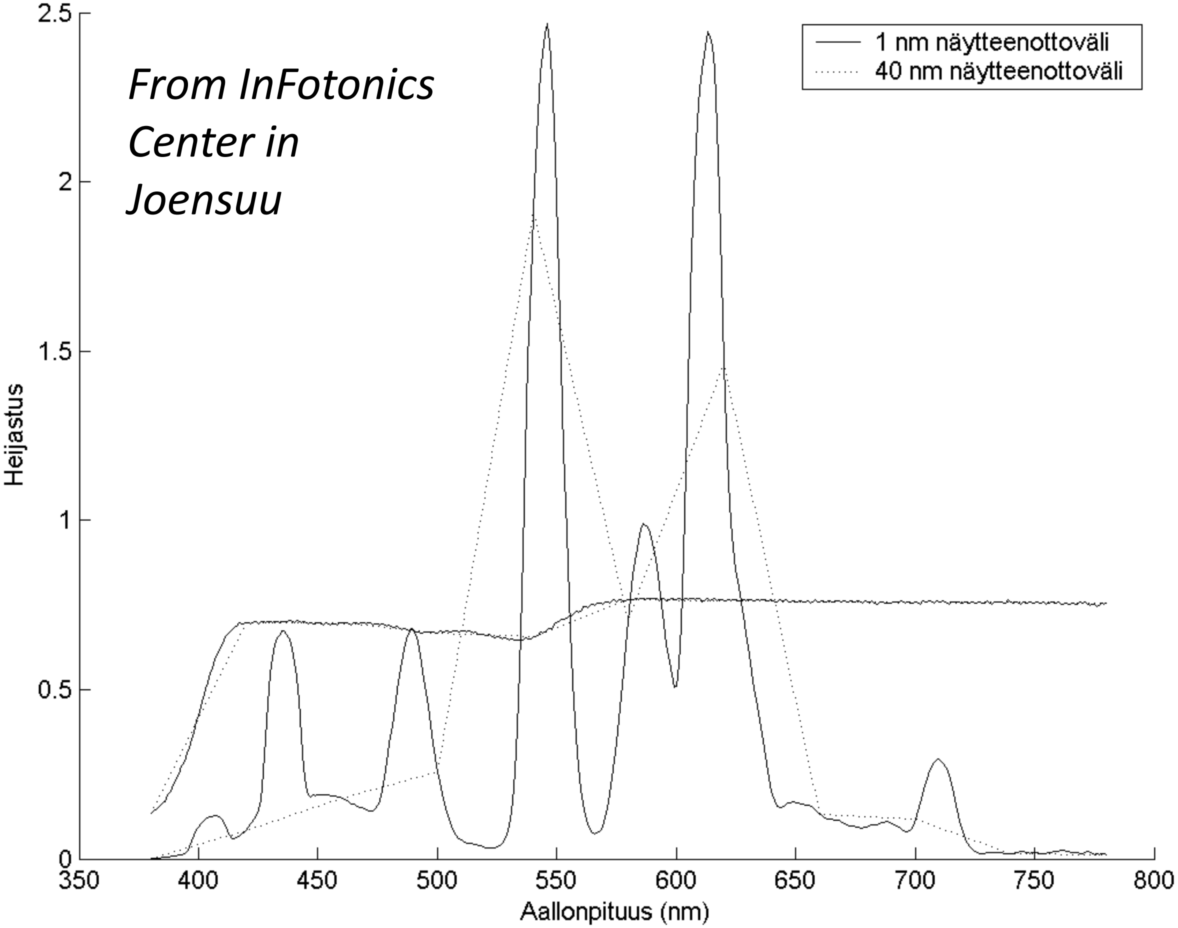
-Restricted wavelength range and spectral resolution

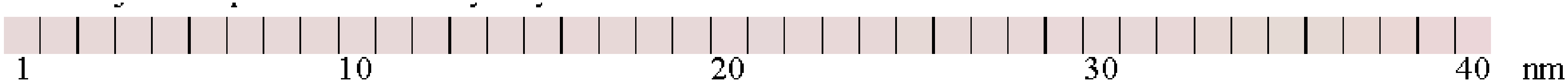


Sources of error….

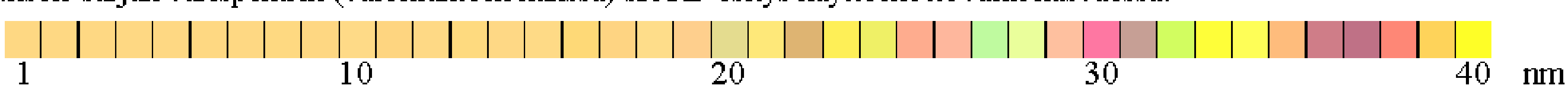
4.1. Sampling interval

From InFotonics Center in Joensuu





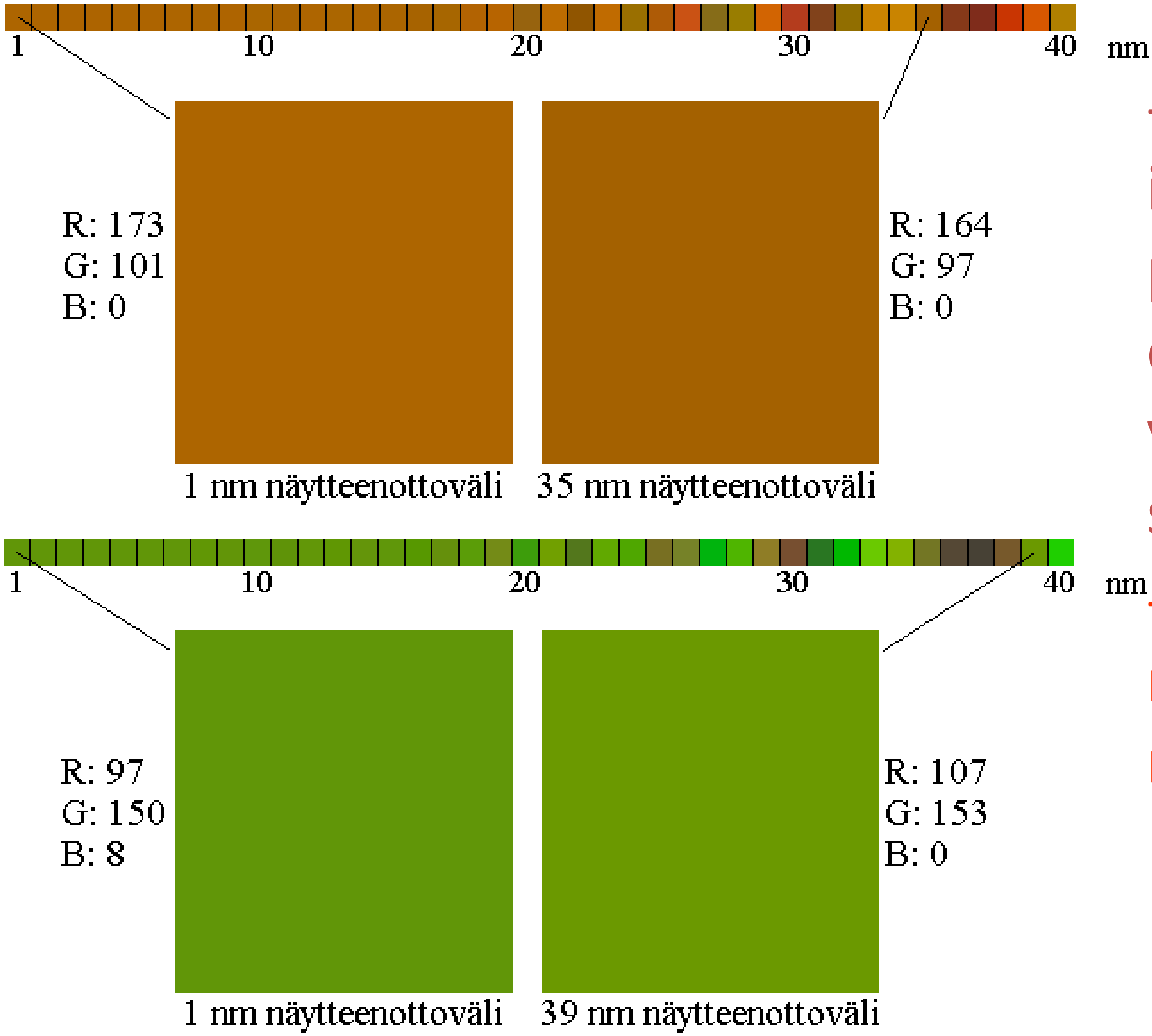
Munsell-sarjan värispektrin (valonlähteen kanssa) sRGB-esitys näytteenottovälin kasvaessa:



-The sampling interval must be selected according to the form of the spectral signal being measured

-For flat or nearly flat reflectances or SPDs, the influence of sampling on results is less critical

-It is really critical for spiky signals (as SPDs from fluorescents..)



-The sampling interval influences the perceived color, as we can see from the RGB values in these two samples.

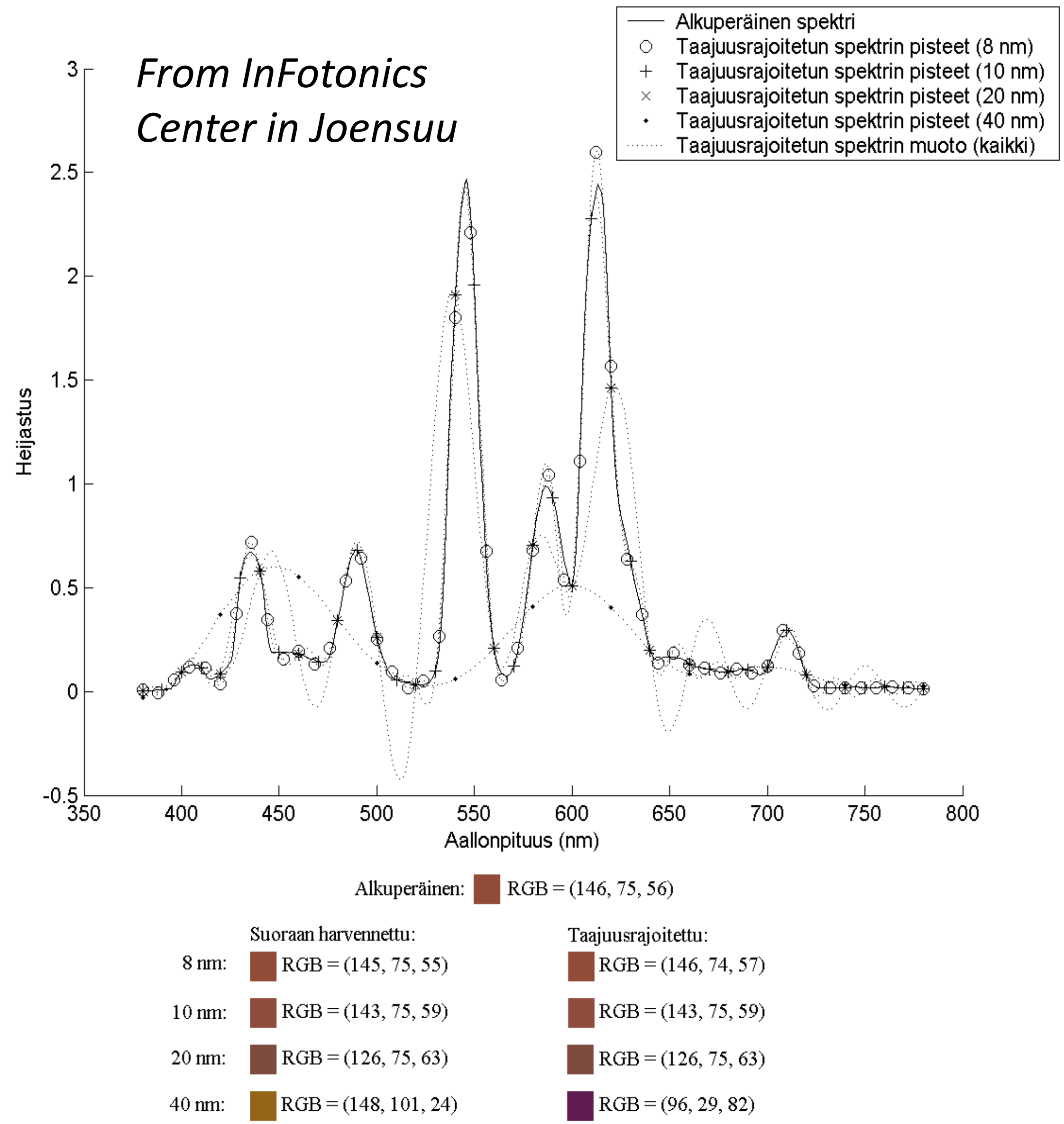
-They correspond to non-flat but smooth reflectances

From InFotonics Center in Joensuu

-Other examples of the sampling influencing RGB values for a “spiky” signal.

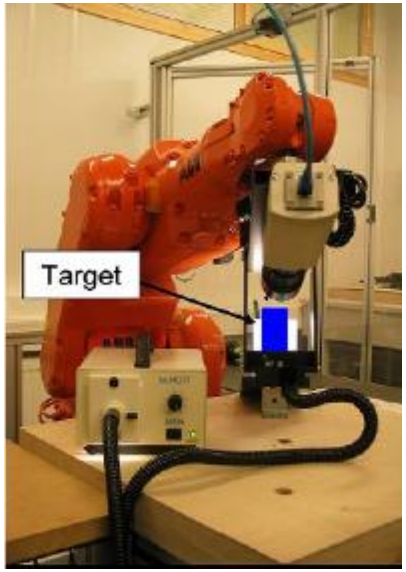
-General advise: always less than 10 nm.

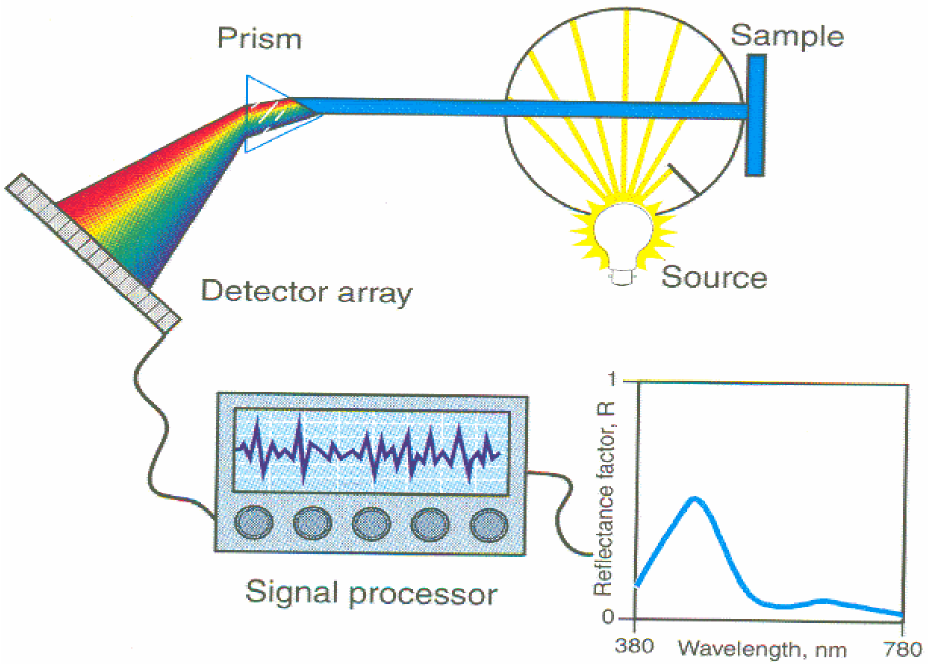
-For bandpass signals: 5 nm or less according to the width of the peak or peaks (and the optical resolution of our instrument)



4.2. Optical resolution and accuracy of the instruments

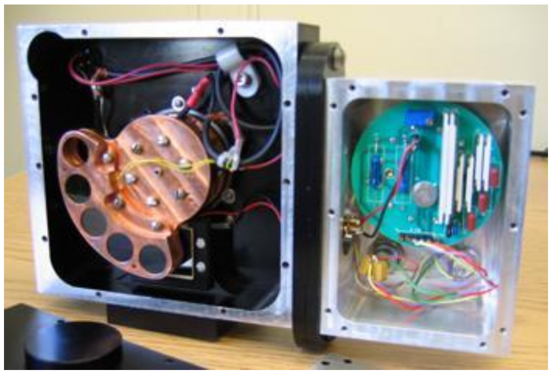
-Optical resolution limited by the slit width, grating and sensor features.

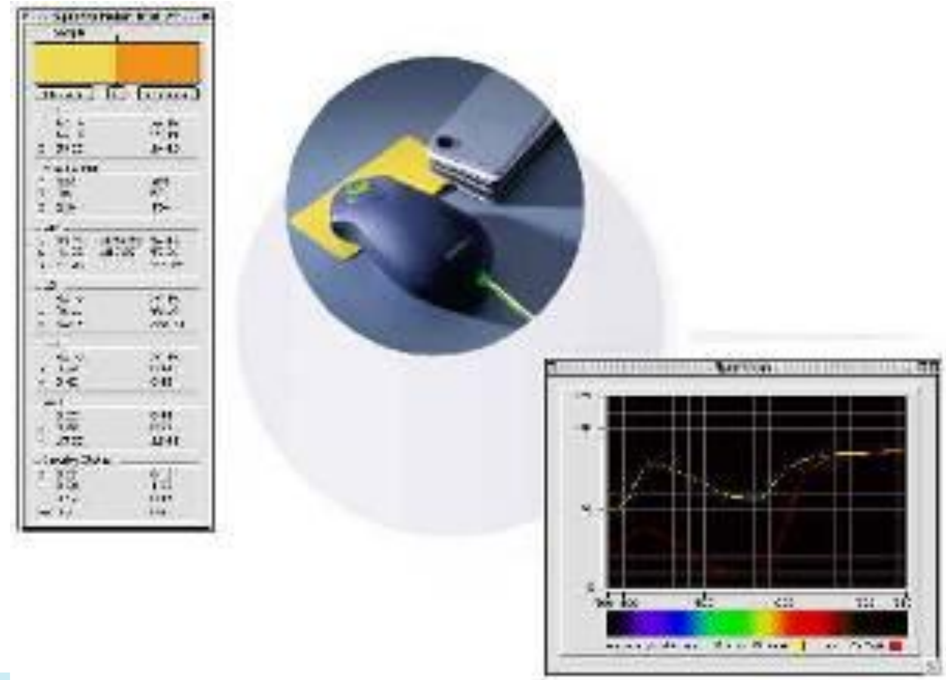


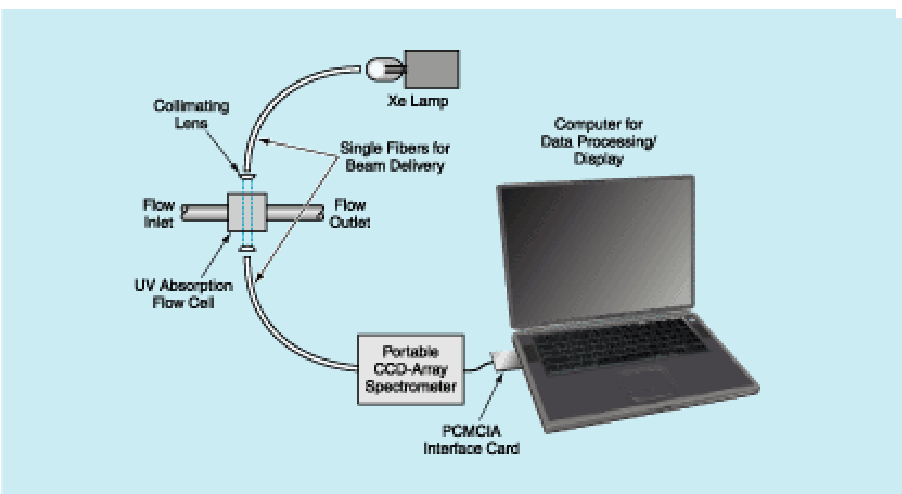


A detector-array spectrophotometer.

-General advise: for luminance measurements: 1-2% relative error.



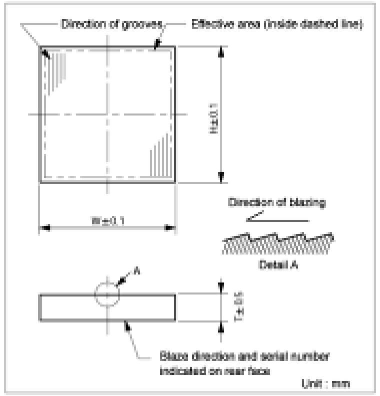


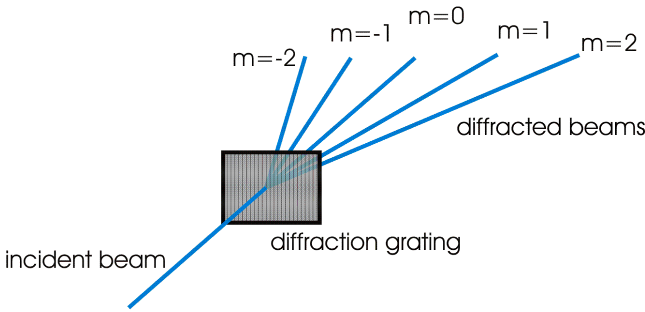


-For chromaticity coordinates: 0.001 for the A illuminant is the maximum limit. Most instruments have less relative error

4.3. Additional sources of error

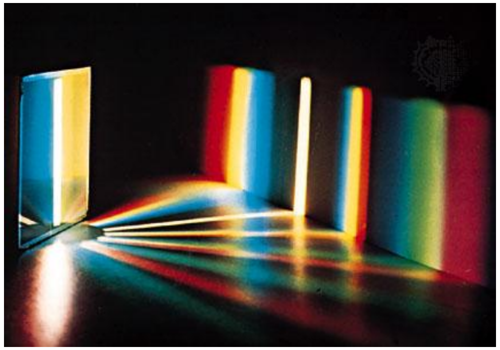
-Stray light






AFM Image of Laminar Grating Grooves (depth emphasized)

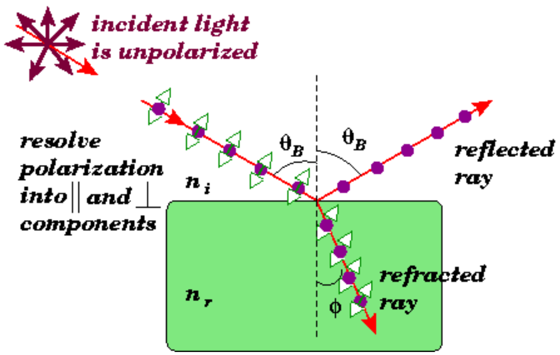
-Second-order effects



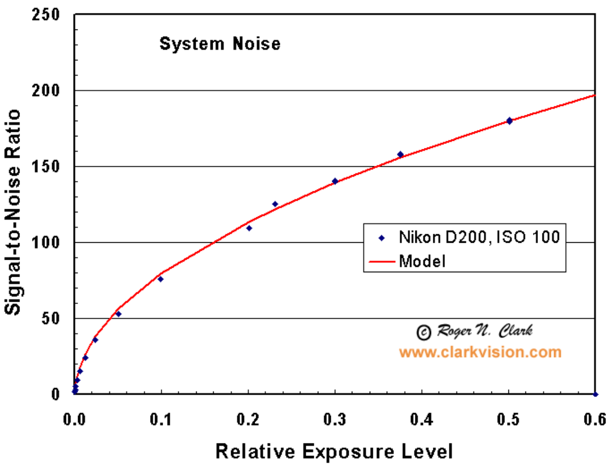
-Polarization sensitivity

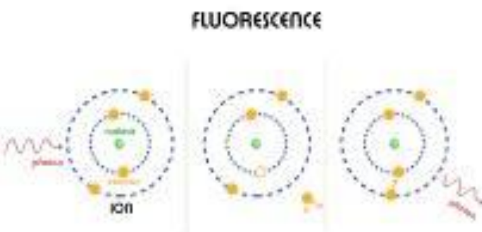
http://pe.taylorjl.net/PE_Blog/?p=231

https://www.perkinelmer.com/CMSResources/Images/44-155817PRD_006991A_04_%20LAMBDA650-1050PolarizerDepolarizerOptions.pdf



-Noise in the detector





-Fluorescence of the sample

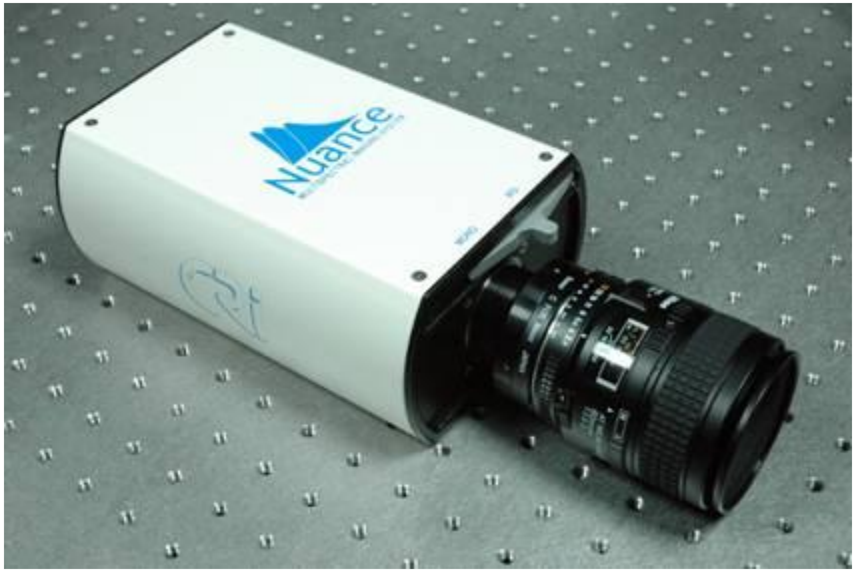
1) Colorimeters

2) Spectroradiometers-spectrophotometers

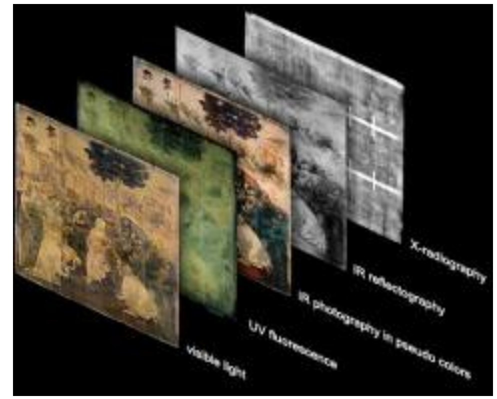
Where are we going in the future?

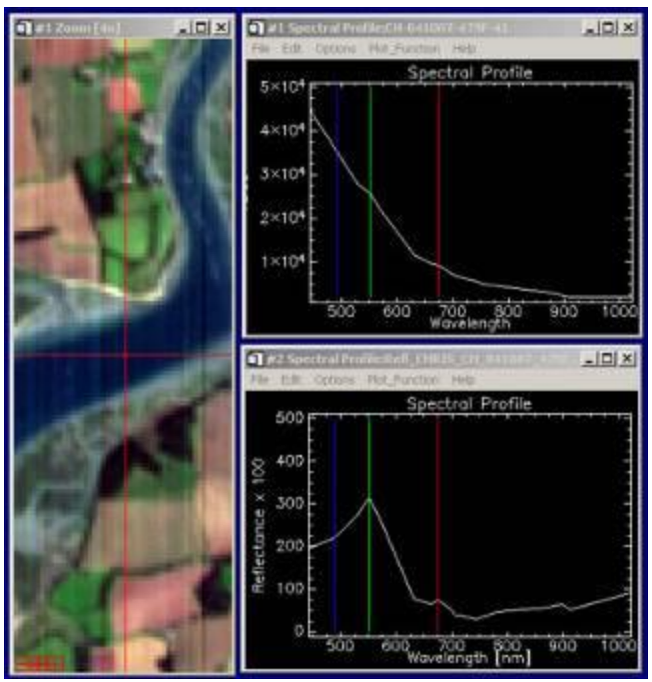
We are becoming……. Multispectral!!!!

-Multispectral systems allow us to obtain spectral signals on a pixel-by-pixel basis!



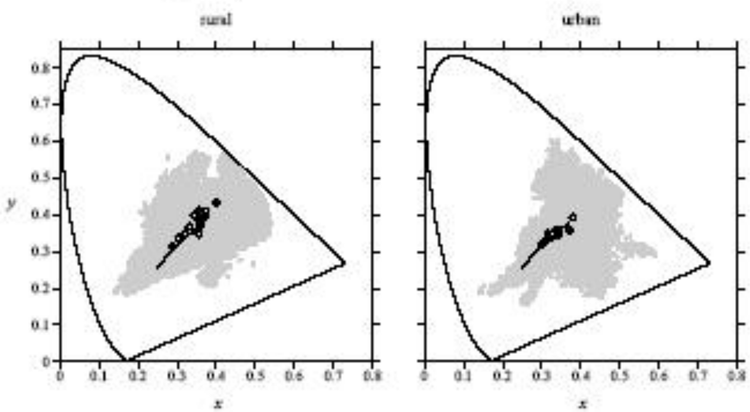
-Much more spatial resolution, but also rather more complex to use than a spectroradiometer…

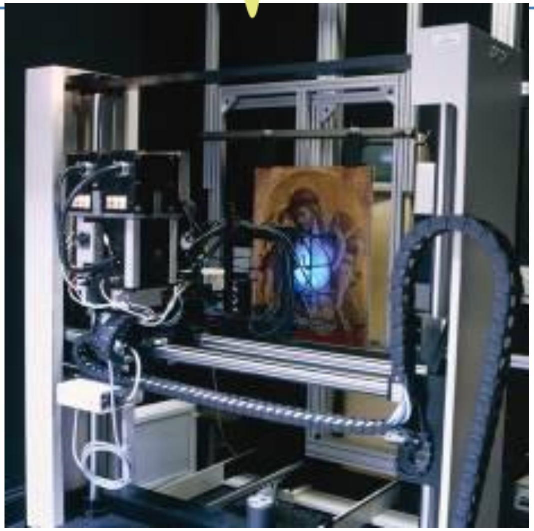


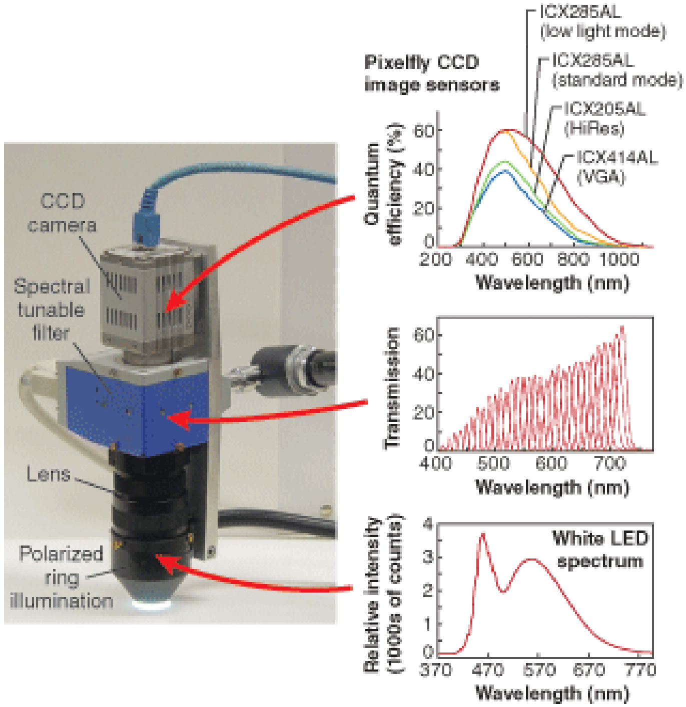


-Also more “customized” according to the application…

Fig. 2 Samples of rural and urban scenes used in this study.



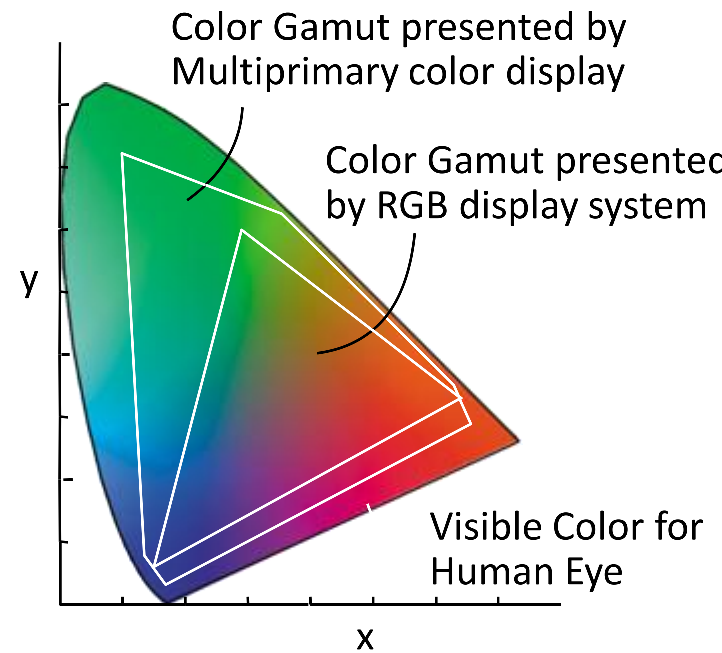


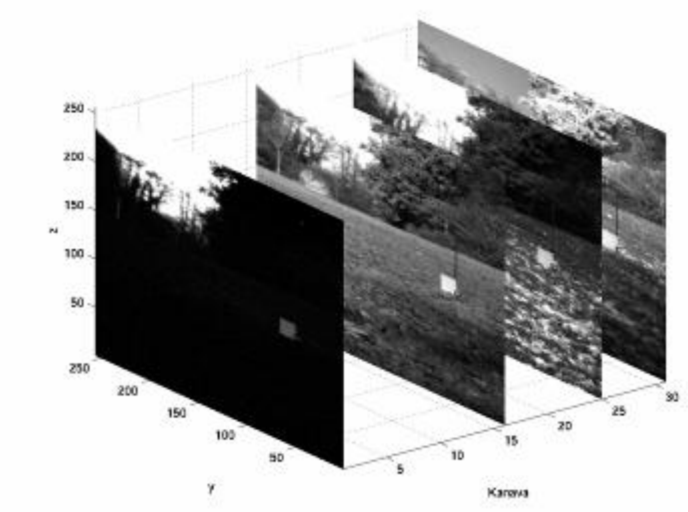


Number of channels / bands	Name
1	Monochrome
3	RGB or trichromatic
From 4 to 9	Multispectral
From 10 to 100	Hyperspectral
More than 100	Ultraspectral

Why multispectral?

- More information than just color information
- Potentialities of spectral color imaging
- Not limited to the human visual range: advantages to include the infrared (IR) and UV (ultraviolet)
- Metamerism is avoided
- Illuminant changes can be simulated
- Much more information: applications from remote sensing, astronomy, medicine, art restoration, cosmetics, printing, computer graphics, biology, agriculture, etc.
- Etc





Bibliography and links

1. Günther Wyszecki, W. S. Stiles., Color Science: Concepts and Methods, Quantitative Data and Formulae, (Wiley Series in Pure and Applied Optics). Ch. 1
2. J. Y. Hardeberg, "Acquisition and reproduction of color images: colorimetric and multispectral approaches," (Dissertation.com, 2001). (Revised second edition of Ph.D. dissertation, Ecole Nationale Supérieure des Télécommunications, 1999)

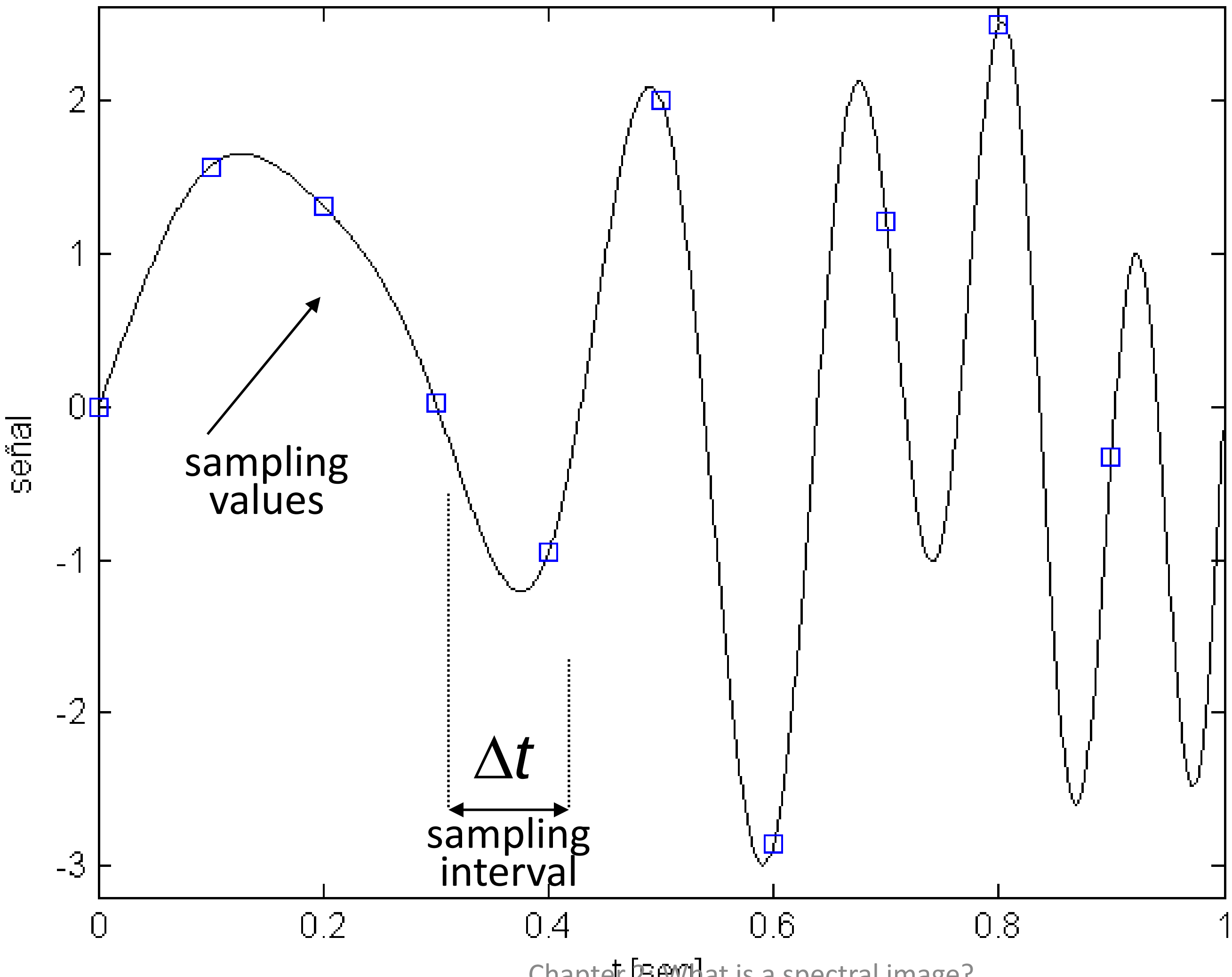
www.multispectral.org
http://cs.joensuu.fi/colorlab_toolbox/
http://en.wikipedia.org/wiki/Colorimeter
http://www.cri-inc.com/products/nuance.asp
http://www.oceanoptics.com/
http://www.avantes.com/
http://www.photoresearch.com/
http://las.perkinelmer.com/
http://www.jascoint.co.jp
http://www.konicaminolta.com/

Open questions after Chapter 2

- Do spectroradiometers or spectrophotometers take multispectral images?
- What is the difference between a spectral image, a multispectral image and a hyperspectral image?
- Imagine we change our cornea or our lens by a prism? Would we “see” spectra?
- How many dimensions a sensor should have to take a multispectral image?
- How many different types of cones we should have to have spectral vision?

How many channels?

Shannon-Whittakker theorem (sampling theorem)



sampling frequency

$$\frac{1}{\Delta t}$$

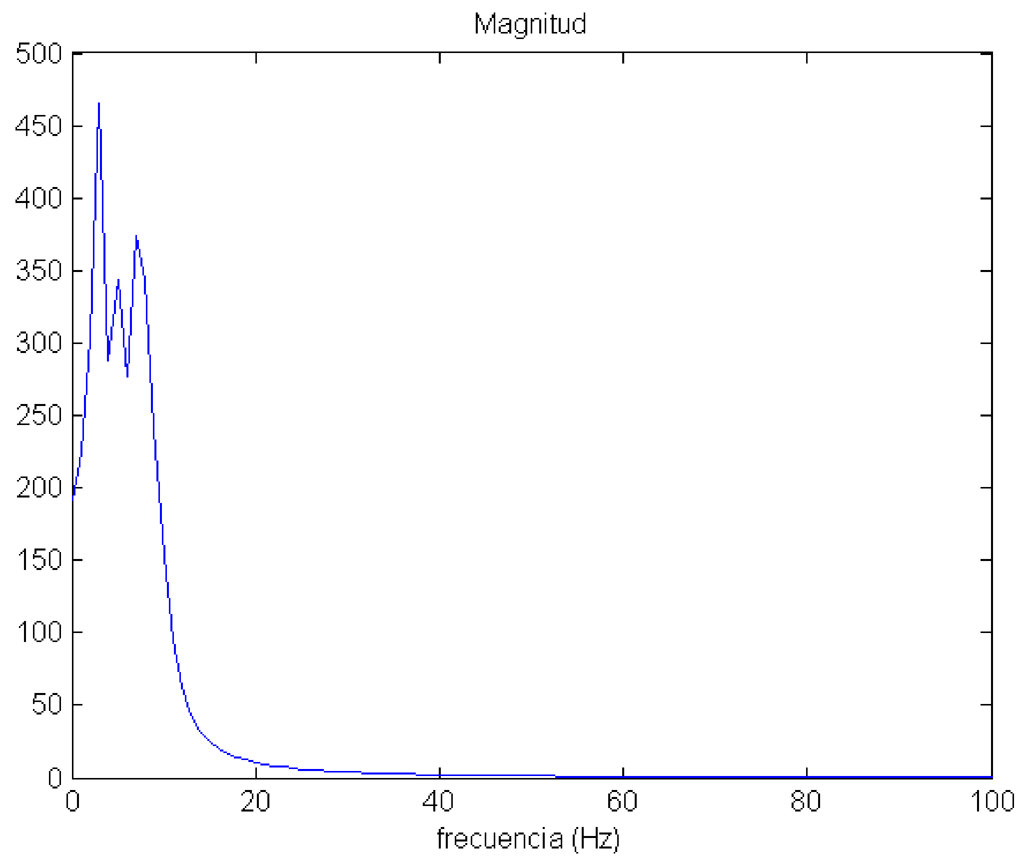
How many channels?
Shannon-Whittakker theorem

g(t) with a Fourier Transform G(f) band-limited (G(f)=0 over a cut frequency f_0)

$$g_m = g(mT) \qquad \frac{1}{T} = 2\, f_0$$

$2f_0$ = Nyquist frequency

$$\boxed{g(t) = \sum_{m=-\infty}^{\infty} g_m \, sinc\left(2 f_0\, t - m\right)}$$



Questions you should know how to answer after Chapter 2

1. What is a colorimeter? How to make one?
2. What is a spectroradiometer? How to make one?
3. What is a spectrophotometer? How to make one?
4. What is a depolarizer?
5. Why some of these instruments take a spectral measurement in just one click and others need some time?
6. Why some of these instruments make noise when doing the measurement?
7. Luther’s condition? Do we have to consider the sensor’s responsivity?
8. Difference between a CCD and a CMOS?
9. What are the correct units of spectral responsivity?
10. Technical specifications of instruments? Which kind of parameters?

Questions you should know how to answer after Chapter 2

11. Why spatial resolution and light sensitivity are in conflict?
12. How many pixels the sensor in a colorimeter should have?
13. Why some colorimeters have 4 filters instead of 3?