UiO : Department of Informatics
University of Oslo

IN5350 – CMOS Image Sensor Design

Lecture 8 – Characterization

Project schedule

	Task/milestone	Start	Finish
✓	Chose topic/scope	1-Sep	8-Sep
✓	Create project plan (tasks, milestones, schedule)	8-Sep	15-Sep
✓	**MS1 – project plan approved by Johannes**	15-Sep	22-Sep
✓	Study literature on the topic	22-Sep	29-Sep
	Design/simulation	**29-Sep**	**13-Oct**
	Write up prelim report (inc references, design, results)	13-Oct	20-Oct
	MS2 – submit preliminary report to Johannes	20-Oct	20-Oct
	Design/simulation	20-Oct	27-Oct
	Write up final report (incl references, design, results)	27-Oct	3-Nov
	MS3 – submit final report to Johannes & presentation	3-Nov	3-Nov
	MS4 – grading (pass/fail) by Johannes & Tohid	10-Nov	10-Nov
	Exam	18-Nov 2020	

Contents

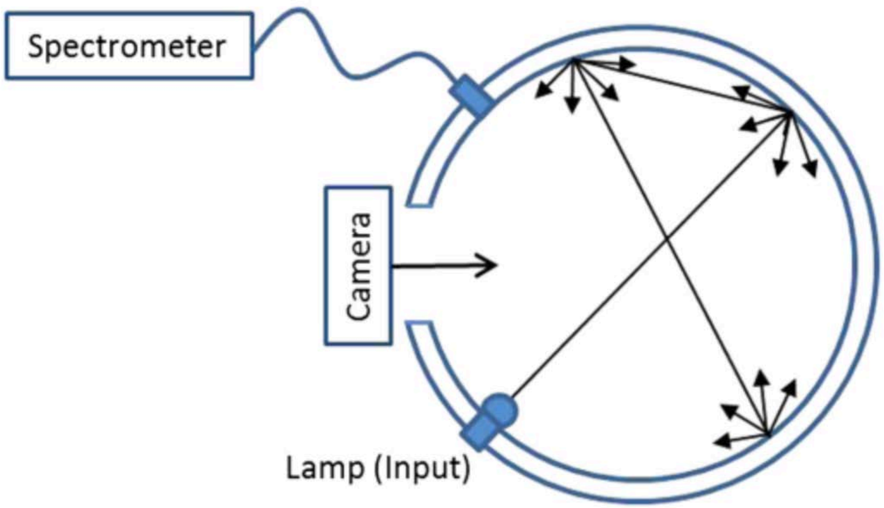
- Measurement tools
- QE – Quantum efficiency
- CG – Conversion gain
- RN - Readnoise
- DC – Dark current
- DSNU – Dark signal non-uniformity
- PRNU – Photoresponse non-uniformity
- VFPN – Vertical fixed pattern noise
- HFPN – Horizontal fixed pattern noise

Recommended reading

- EMVA 1288 Standard for image sensor characterization
  - https://www.emva.org/wp-content/uploads/EMVA1288-3.1a.pdf
- SPIE book by Jim Janesick: Photon Transfer
  - Available at UiO
- PhD thesis on CIS characterization
  - file:///Users/eier/Downloads/Utsav_jain_thesis_report.pdf
- SPIE paper on Raspberry Pi based camera characterization
  - https://www.spiedigitallibrary.org/journalArticle/Download?fullDOI=10.1117%2F1.JEI.26.1.013014

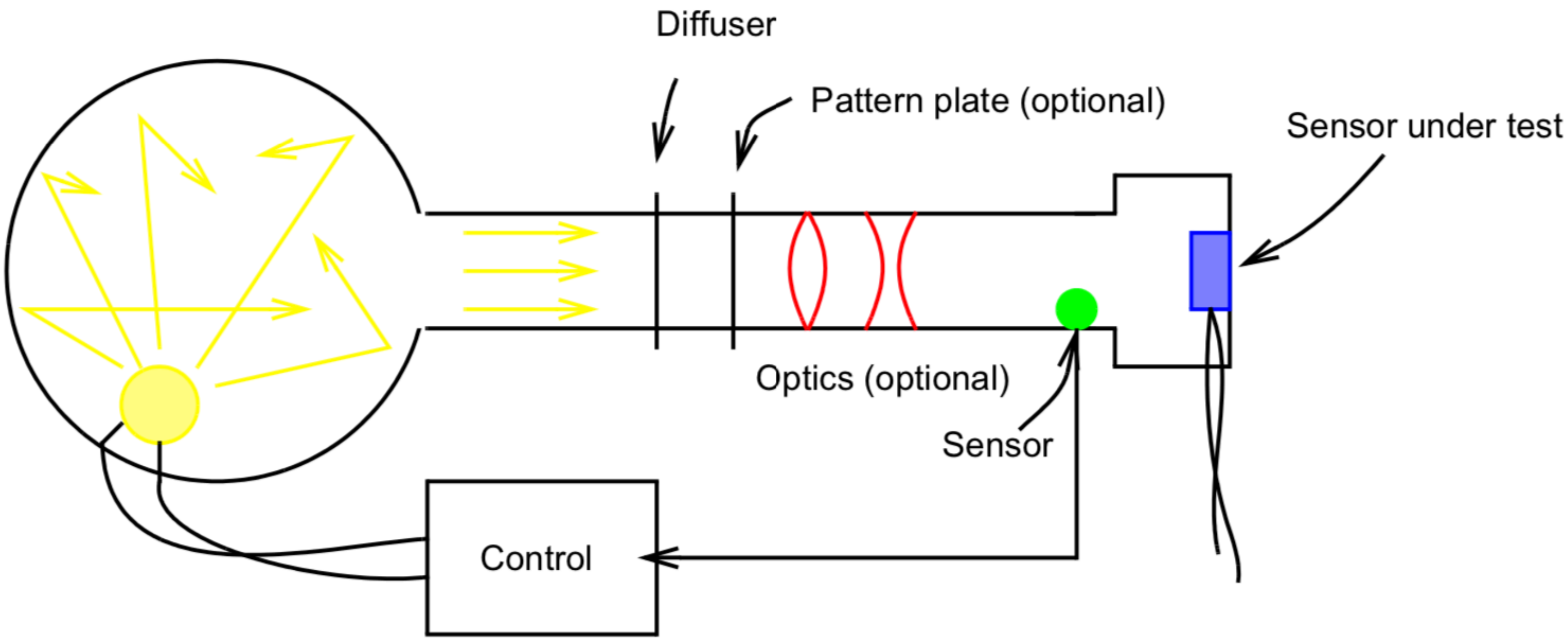
Integrating sphere

- Illuminating a sensor uniformly on all pixels
  - Can be combined with a filter to select specific wavelength(s)



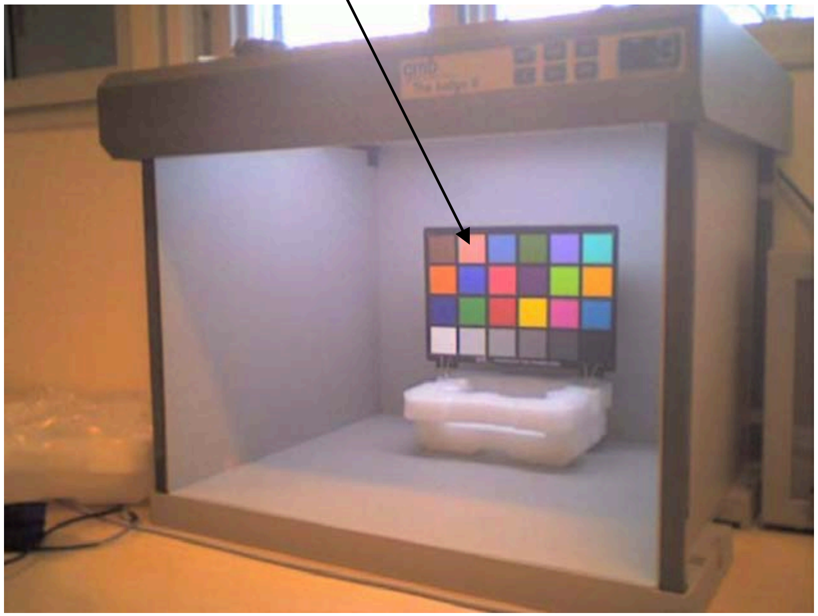
Optoliner

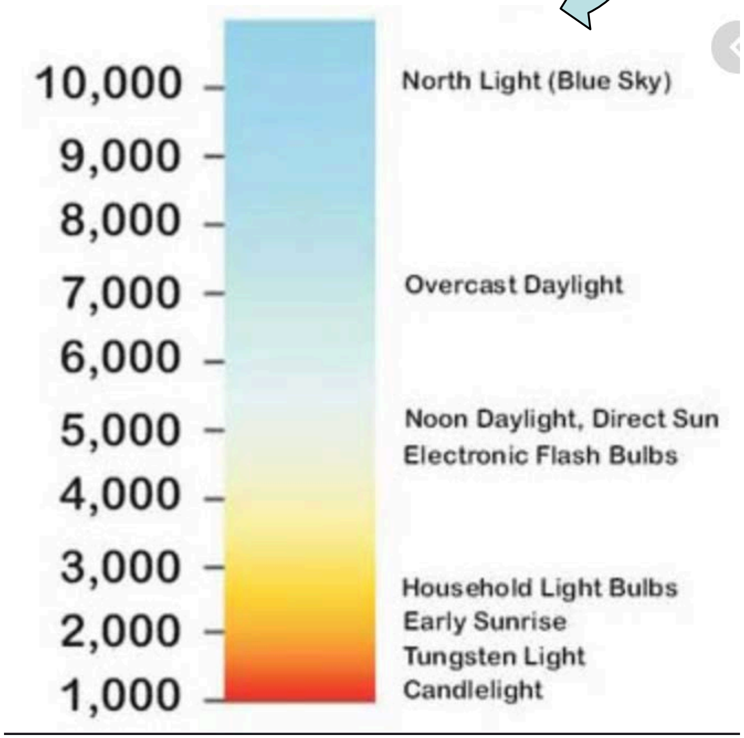
- Integrating sphere + filters + optics
- Illumination w/test pattern



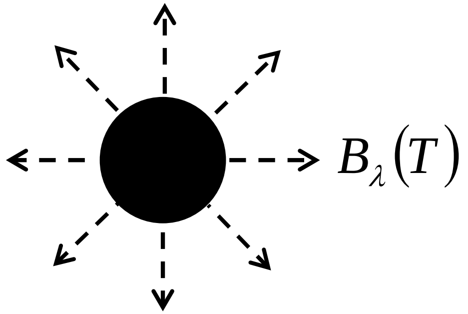
Light box with Macbeth colour checker chart

- Illumination w/colour temperature settings
- Ref: RGB coordinates of Macbeth colours





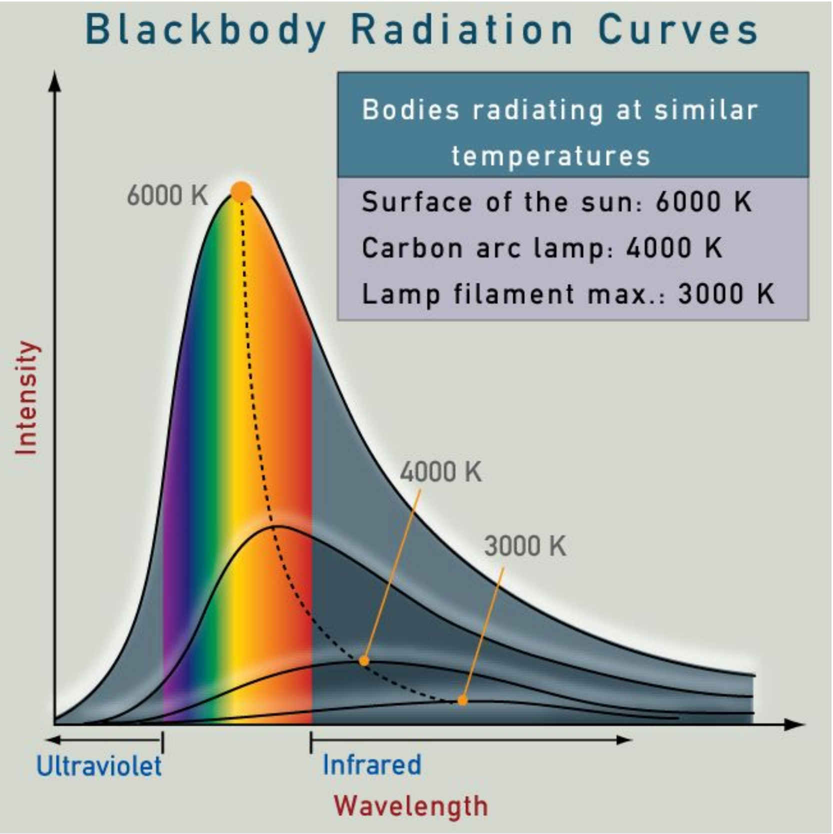
Light spectrum from a blackbody is determined by its body temperature



Planck's radiation law:

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \cdot \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

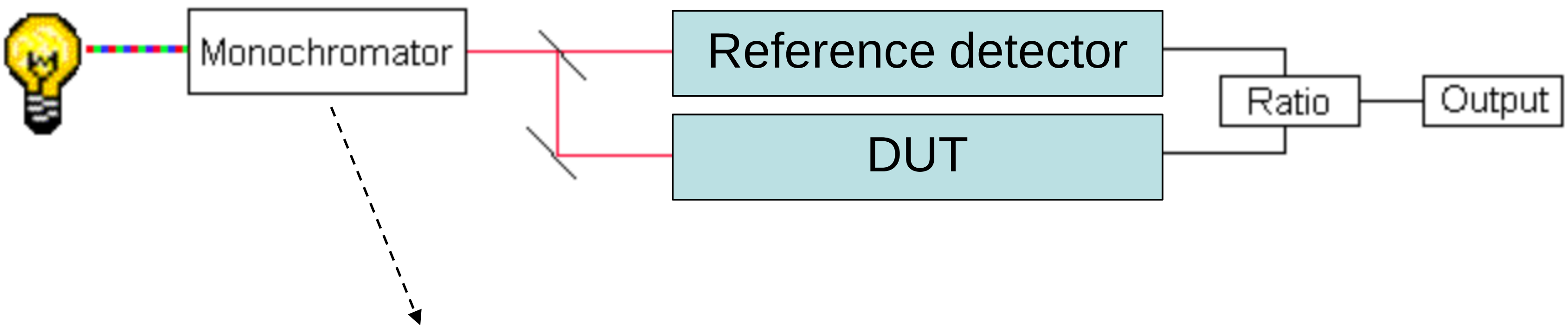
$B_\lambda(T)$=spectral energy (J/(s sr m³))
h=Planck's constant (6,6 x 10^{-34} Js)
λ=wavelength (m)
c=speed of light (3×10^8 m/s)
k=Boltzmann's constant ($1{,}38 \times 10^{-23}$ J/K)



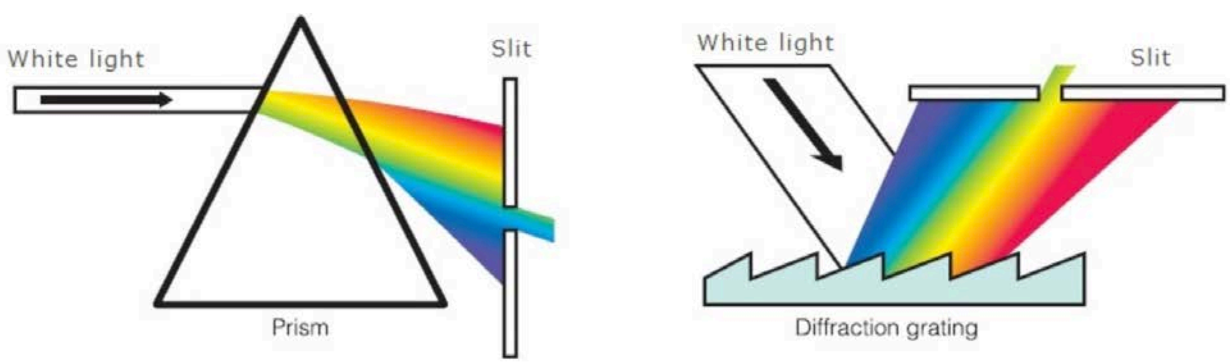
More details: J Nakamura, Appendix-1.

Monochromator

- Purpose: Narrowband wavelength selection
- Used for: Spectral response measurement (QE)

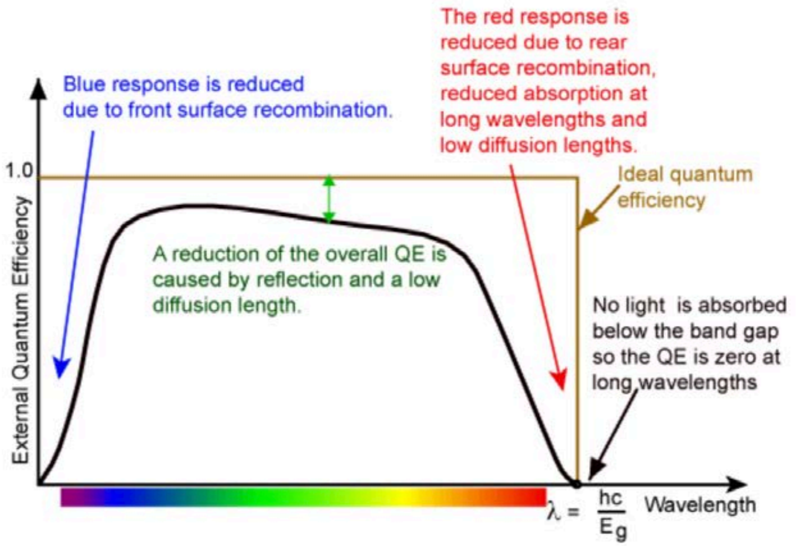


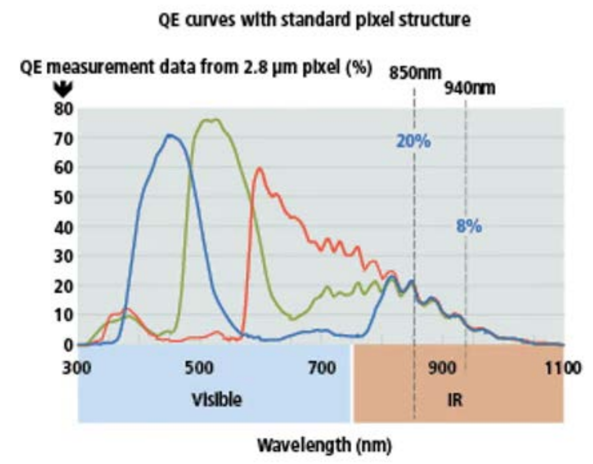
Monochromator principles: (i) prism, (ii) grating



Quantum efficiency

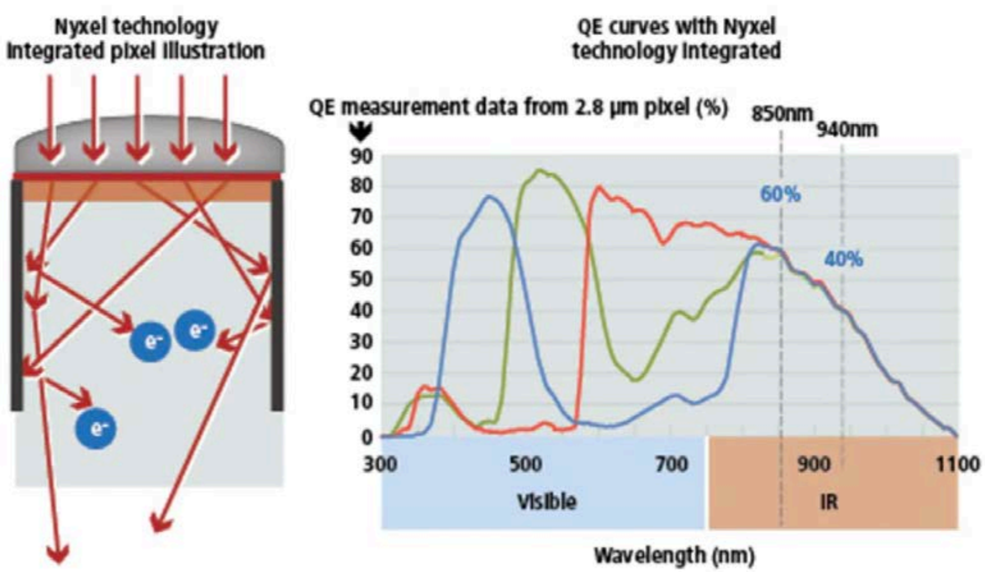
- Definition: Probability of a pixel detecting a photon of a given wavelength (spectral sensitivity)
- Method: With a monochromator, step through each wavelength and measure average output pixel value, calculate back to #electrons captured, then divide by #photons incident on the pixel to get QE value





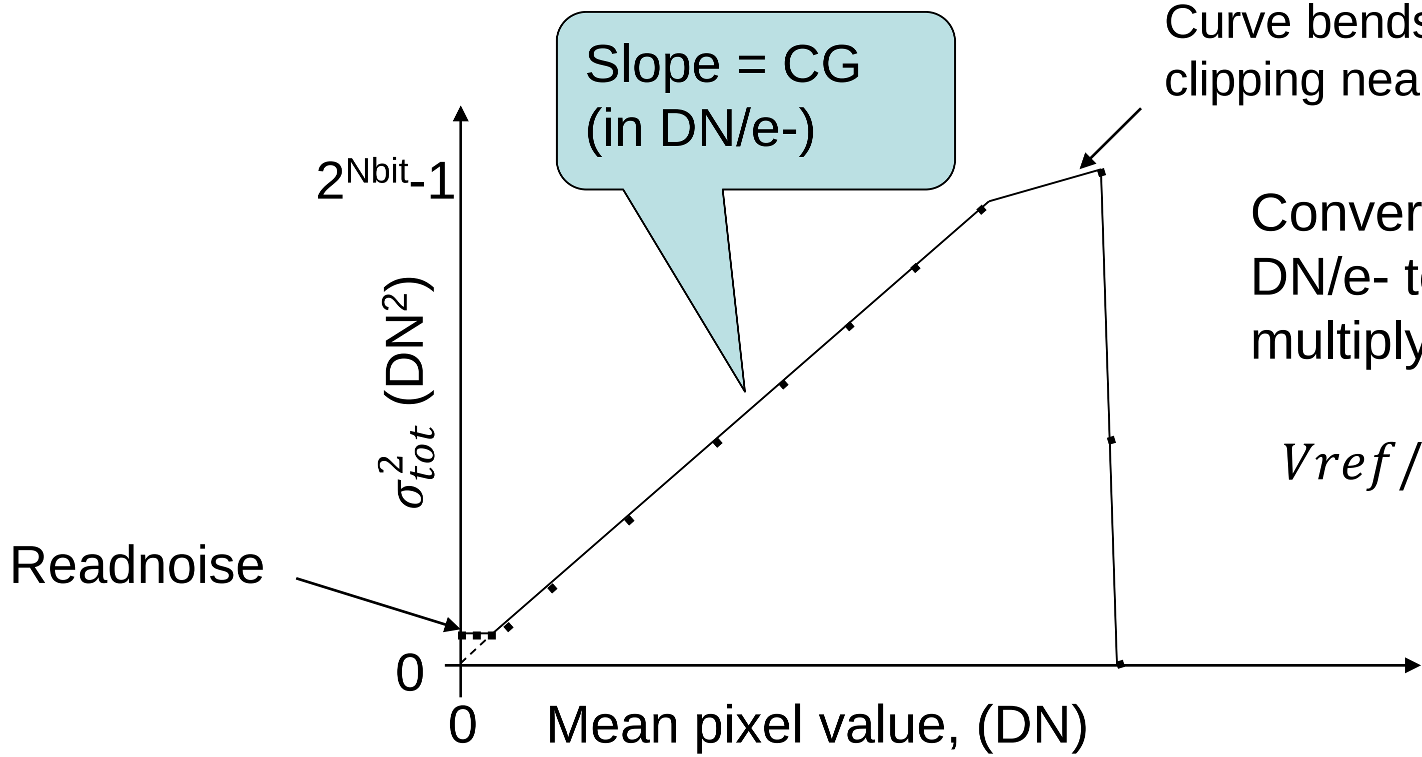
QE remarks

- QE influenced by angle of incidence
  - Wide angle => more crosstalk to neighbour pixels
  - Using small array in the centre minimizes crosstalk
- Interference oscillations from optical stack
- Latest innovation to boost QE in NIR
- Ref: [Scientific Reports, Vol. 7, Article No. 3832, June'17]



Photon Transfer Curve (PTC)

- PTC: plot of variance vs mean (in DNs, Volts, or electrons)



Convert from DN/e- to uV/e- by multiplying with:

$$Vref/2^{Nbit} \cdot 1/Asf$$

Photon Transfer Curve

Let $$S_{out} = \alpha \cdot N_{elec} + \beta \qquad (1)$$

, where
S_{out}= output pixel value (DN)
α = conversion factor (DN/e-)
N_{elec}= number of electrons captured (e-)
β = black level offset (DN)

From (1), the noise output variance (σ_{out}^2) can be expressed by

$$\sigma_{out}^2 = \sigma_{elec}^2 + \sigma_{RN}^2 = \alpha^2 N_{elec} + \sigma_{RN}^2 \qquad (2)$$

, where
σ_{elec}^2 = electron shot noise (DN^2)
σ_{RN}^2 = readnoise floor at zero illumination (DN^2)

Photon Transfer Curve (cont.)

From (1) we have $S_{out} - \beta = \alpha \cdot N_{elec}$ (3)

Replacing into (2) gives

$$\sigma_{out}^2 = \alpha(S_{out} - \beta) + \sigma_{RN}^2 \qquad (4)$$

Deriving (4) with respect to S_{out} gives

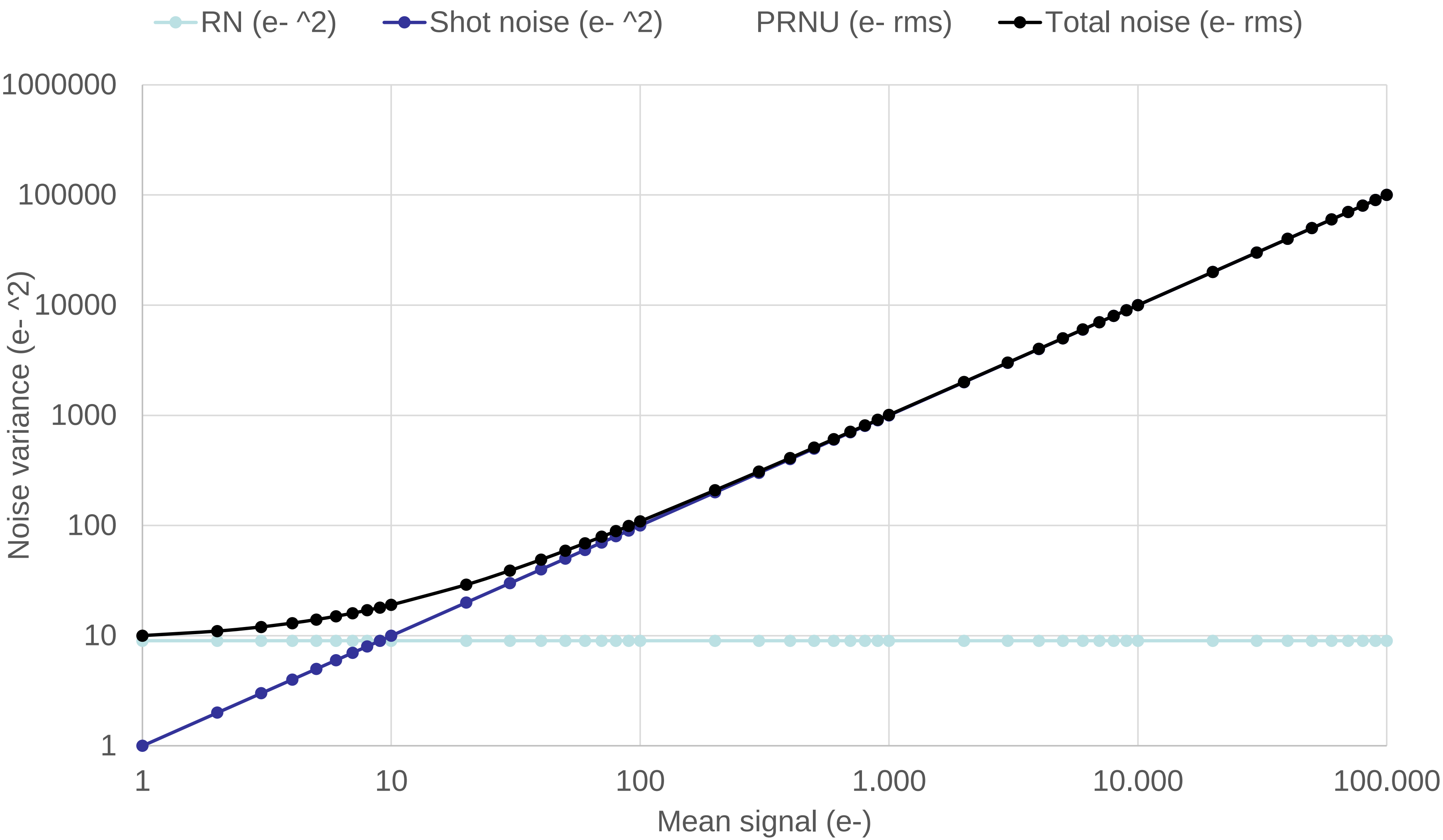
$$\frac{d\sigma_{out}^2}{dS_{out}} = \alpha \qquad \text{(DN/e-)} \qquad (5)$$

Conclusion: Conversion gain (in DN/e-) is slope of output variance versus mean curve. Can be referred back to FD node by dividing by ADC gain and SF gain.

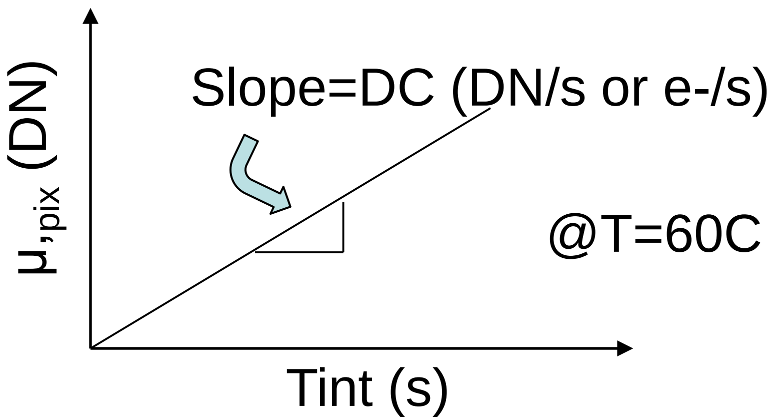
PTC remarks

- Vary light level by changing integration time
  - High precision from crystal oscillator
  - Tint=0 gives readnoise value (RN)
- To measure mean value (x-axis), prudent to capture dark frame (black level) for each setting
- To measure variance (y-axis), convenient to use difference between two subsequent captures
  - Removes black level and fixed pattern noise
  - Remember to divide by 2 since noise variance is additive
  - Pixel values start to clip near saturation (measurement error)
- For extra precision calculate variance for each pixel independently, i.e. by capturing 100-1000 pictures for each light level setting
  - Avoids the influence of PRNU at high signal levels

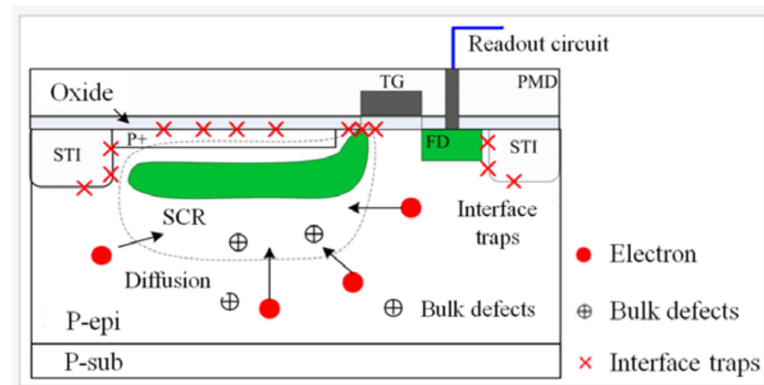
PTC example


RN (e- ^2)
Shot noise (e- ^2)
PRNU (e- rms)
Total noise (e- rms)
Noise variance (e- ^2)
1000000
100000
10000
1000
100
10
1
1
10
100
1.000
10.000
100.000
Mean signal (e-)

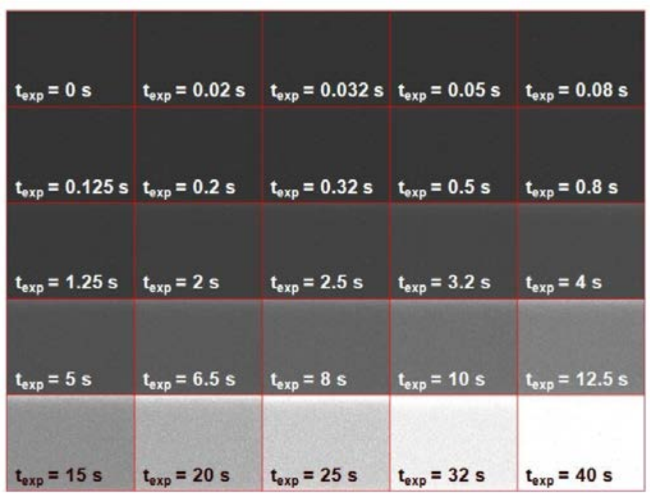
Dark current (DC) measurement

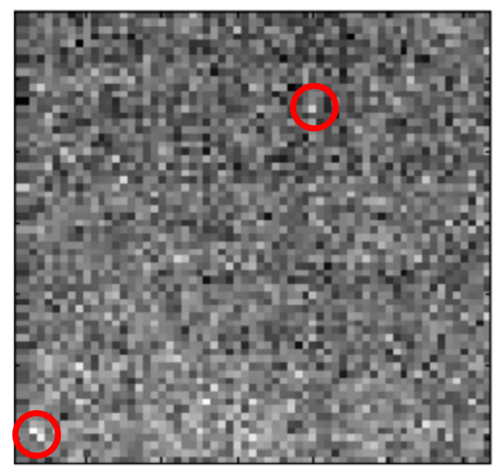


Sources of DC



DC captures at constant temp.





Example of bright pixels

Source: Harvest Imaging blog

Dark current measurement remarks

- Ensure sensor has reached a stable temperature since DC is highly temperature dependent (DC doubles every 6-8℃)
- Avoid light exposure (sometimes challenging)
- Beware of DC shading. Could be due to non-uniform doping or contaminant levels and/or heat glow from circuits nearby (e.g. high power voltage driver)
- Plot DC vs Tint. Slope gives DC in e-/sec.
  - DC can be calculated as average per frame OR individually for each pixel and then averaged
  - In the latter case, you can calculate the RMS variation of the DC. This is called the DSNU (dark signal non uniformity).
  - DSNU sometimes artificially large due to ’outliers’ in the DC distribution (ie bright pixels or black pixels). Could be filtered out.

Photoresponse non-uniformity (PRNU)

- As the name suggests, PRNU is a measure of the variation in responsivity from pixel to pixel
- It’s definition varies in the literature, but the most common is as follows

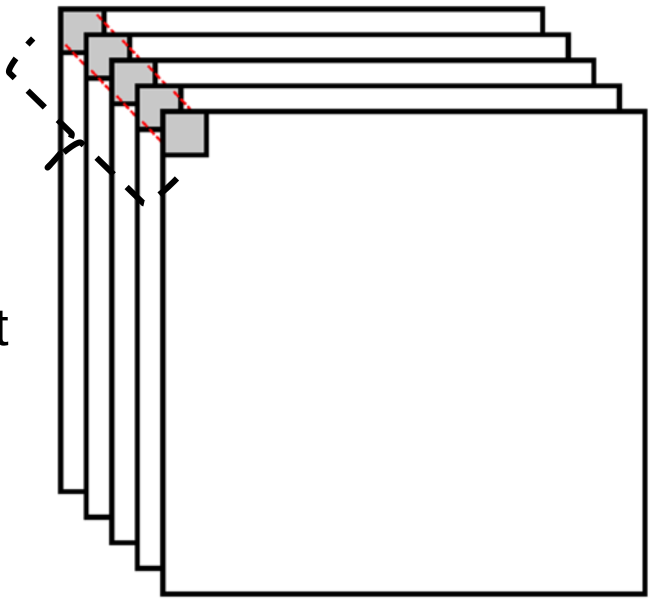
$$PRNU = \frac{\sqrt{\sigma_{50\%}^2 - DSNU^2}}{(\mu_{50\%} - \mu_{dark})} \qquad \text{(\% rms)}$$

- Where $\sigma_{50\%}$ is the rms variation of pixel mean values across the frame at 50% saturation (i.e. all the temporal noise is removed by averaging multiple frames, e.g. 100-1000 frames)

PRNU remarks

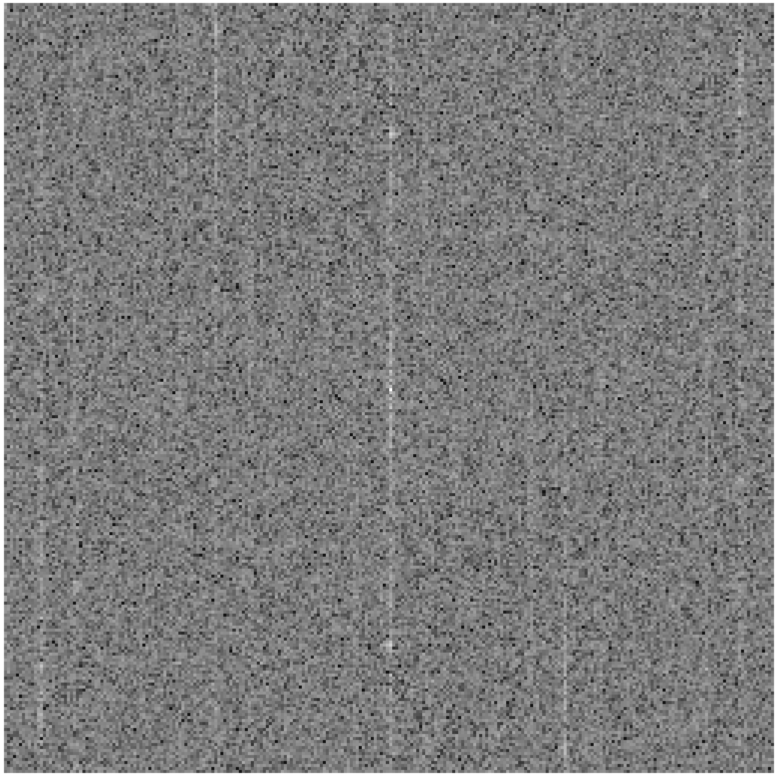
- Convenient to re-use data from PTC measurements (assuming 100-1000 frames were captured for each integration time)

Remove temporal noise by calculating mean (μ) for each pixel position. Use it to calculate PRNU which is spatial and fixed noise.



Stack of captures each with identical setting (values vary due to temporal noise, only)

Vertical Fixed Pattern Noise (VFPN)



- VFPN induced by col-to-col variations in Vth and parasitic couplings causing signal DC offset variations
- Measured by (i) capturing dark frame, (ii) averaging all rows to form one single row without temporal noise, (iii) calculate rms value of row
- VFPN value should be 10x smaller than RN to be invisible in image

Hnoise (rownoise)

- Temporal noise on all pixels along one row induced by spikes on array signals or on VDD or GND during CDS readout (same noise spike on all pixels along one row)
- Hnoise measured similarly to VFPN, ie average all columns to remove temporal noise, then calculate rms value