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# Advanced Camera and Image Sensor Technology

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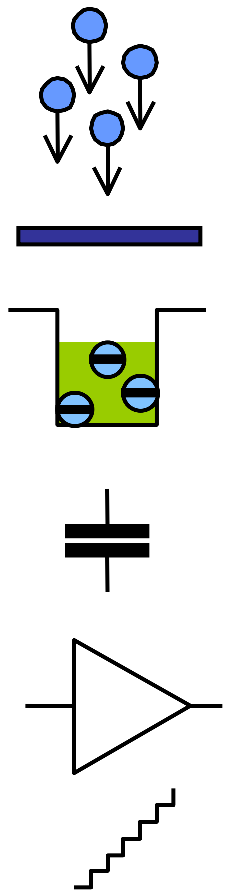
# Content

- Physical model of a camera
- Definition of various parameters for EMVA1288
- EMVA1288 and image quality
- Noise in cameras
- Spectral response and penetration depth
- Area scan and line scan
- Spatial trigger
- Monochrome and color
- Single-, dual-, tri-linear sensors, TDI
- Mechanical and optical pixel size limitations
- Camera mounting standards

# Physical Model of a Camera

A number of **photons** ...

... hitting a **pixel** during exposure time ...

... creating a number of **electrons** ...

... forming a **charge** which is converted by a **capacitor** to a **voltage** ...

... being **amplified** ...

... and **digitized** ...

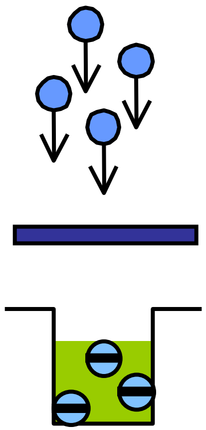
**IOOIOIII** ... resulting in the **digital gray value**.

# What Are The Important Things?
# Quantum Efficiency

- When light is emitted from a light source and passes through the optics and hits the Silicon, electrons will be generated.

- The probability of how many electrons will be generated per 100 photons is called Quantum Efficiency (QE).

QE = number of electrons / number of photons



- Typical values are 30 to 60 %.

# What Are The Important Things?
# Full Well and Saturation Capacity

- Each pixel has a maximum capacity to collect electrons.
- But we will limit that to a lower maximum, because non-linear effects occur.

- A pixel has a saturation capactity of 50000 electrons.
- A glass of wheat beer contains approx. 50000 drops of beer.
- A glass of wine or champagne might have 10000 drops.

# What Are The Important Things?
# Signal to Noise Ratio

- When refilling the pixel there is a slight jitter, although you try to get the same amount of electrons in. The „noise“ is equivalent to the square root of the number of electrons.

- Noise = sqrt (number of electrons)

  Max. Signal to Noise Ratio (SNR)
  =(max number of elec.)/(sqrt(max number of elec.))
  =Saturation Capacity/(sqrt(Saturation Capacity))
  =sqrt(Saturation Capacity)

- Sqrt(50000) = approx. 224

- Refilled beer glasses do not have the same content.

# What Are The Important Things?
# Dark Noise

- There is some remaining noise, although no light hits the sensor.
- Depending on the sensor, this is between 8 to 110 electrons.
- Compare this to the remaining drops of beer in an “empty“ glass.

# What Are The Important Things?
# Detection Limit

- If the signal is the same as the dark noise, we call this detection limit.
- CCD sensors have a detection limit of 8 to 25 electrons. This is according to 15 to 70 photons.
- CMOS sensors will start at 14 to 110 electrons, corresponds to 33 to a few hundreds.

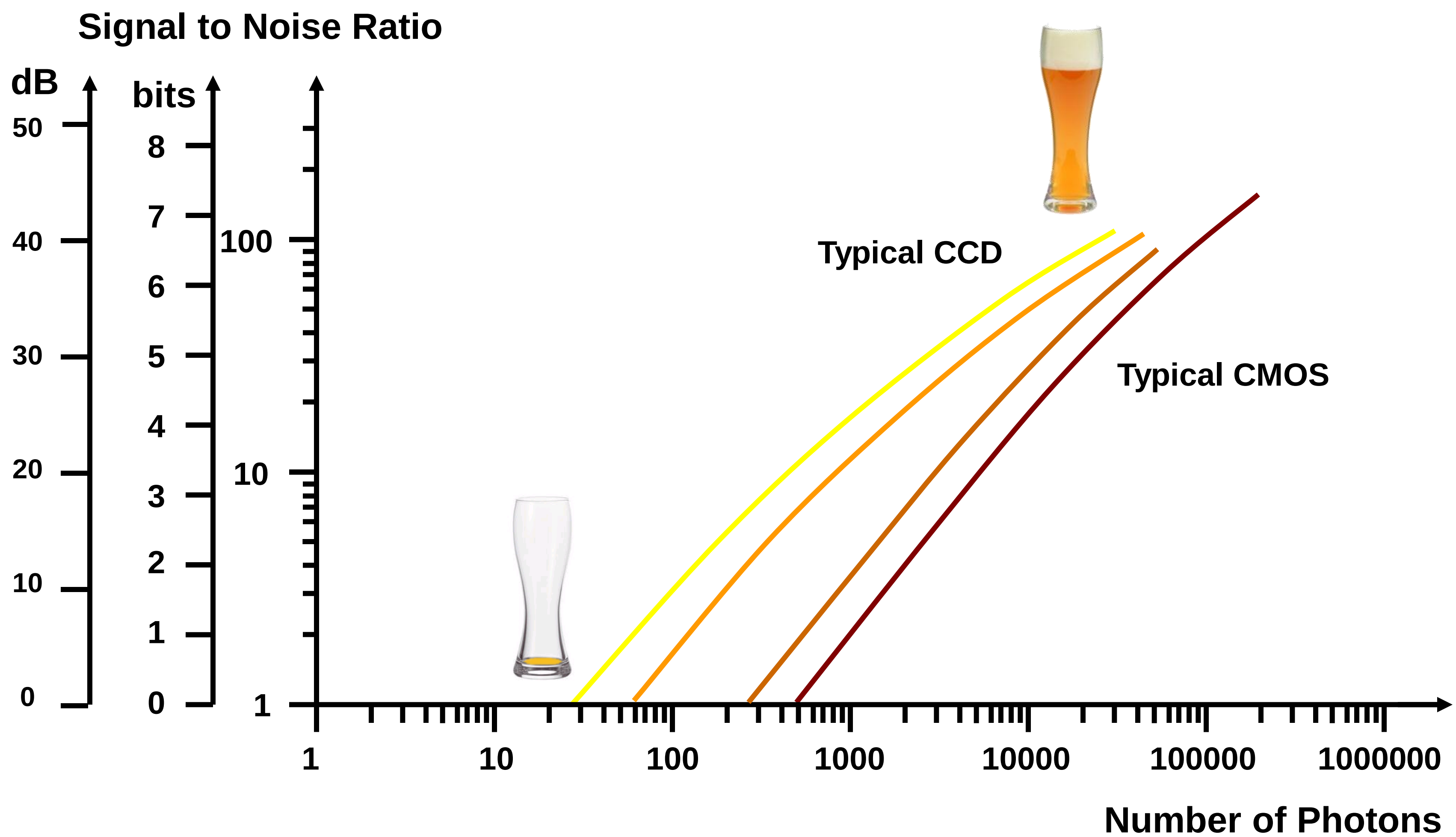
# What Are The Important Things?
# Dynamic Range

- Dynamic range is the ratio between a full and an empty glass of beer.

  Dynamic range
  = Full / Empty
  = Saturation Cap. / Dark Noise
  = 50000 / 25
  = 200

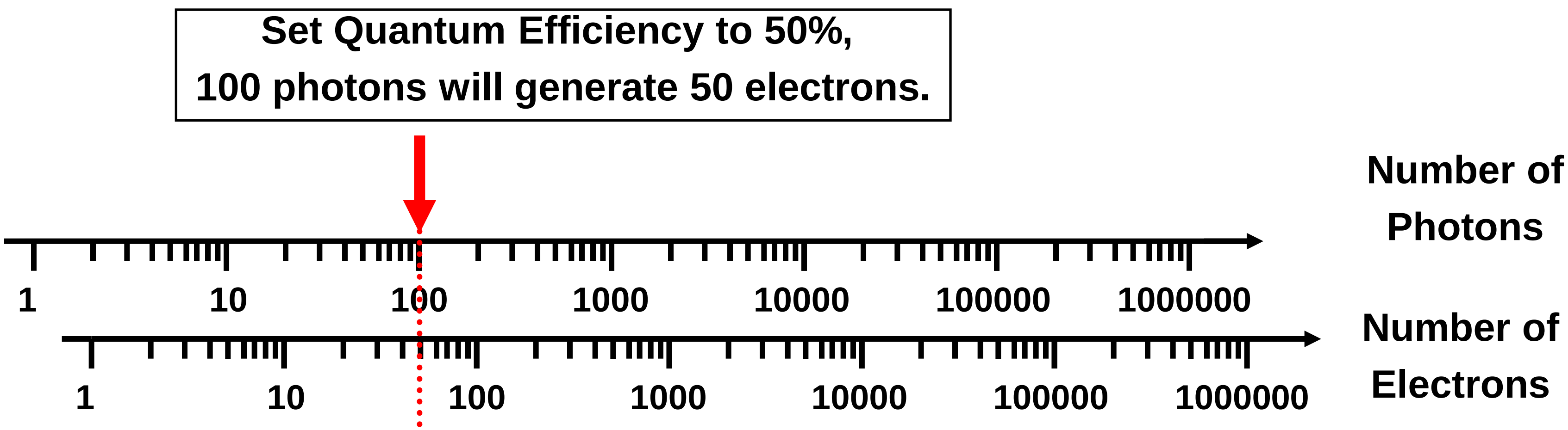
- A glass of beer will always have dynamics!

# The Diagram


Signal to Noise Ratio
dB
50
40
30
20
10
0
bits
8
7
6
5
4
3
2
1
0
100
10
1
Typical CCD
Typical CMOS
1
10
100
1000
10000
100000
1000000
Number of Photons

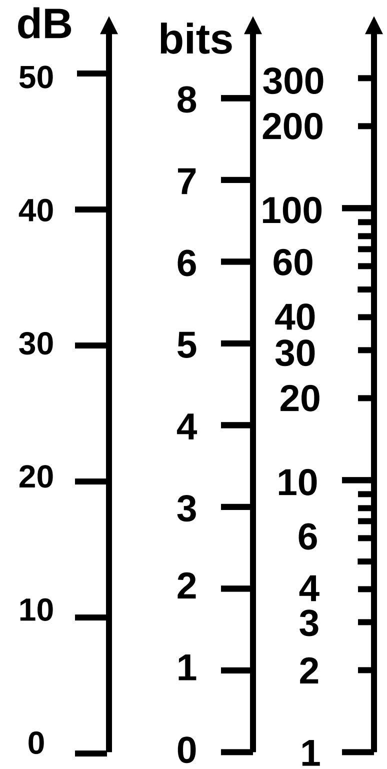
# How To Understand The Diagram?
# The x-Axis

- We are using a logarithmic scale to cover from small to large numbers.
- On a linear scale you will not see the small numbers (a total scale of 1 meter has to show the detection limit in the range of less than a millimeter).



# How To Understand The Diagram?
# The y-Axis

**Signal to Noise Ratio**




We are using a logarithmic scale to cover from small to large numbers.

A linear scale always adds the same unit.

A logarithmic scale always multiplies with the same unit.

Bits ($2^n$) and decibel (dB) are logarithmic scales.

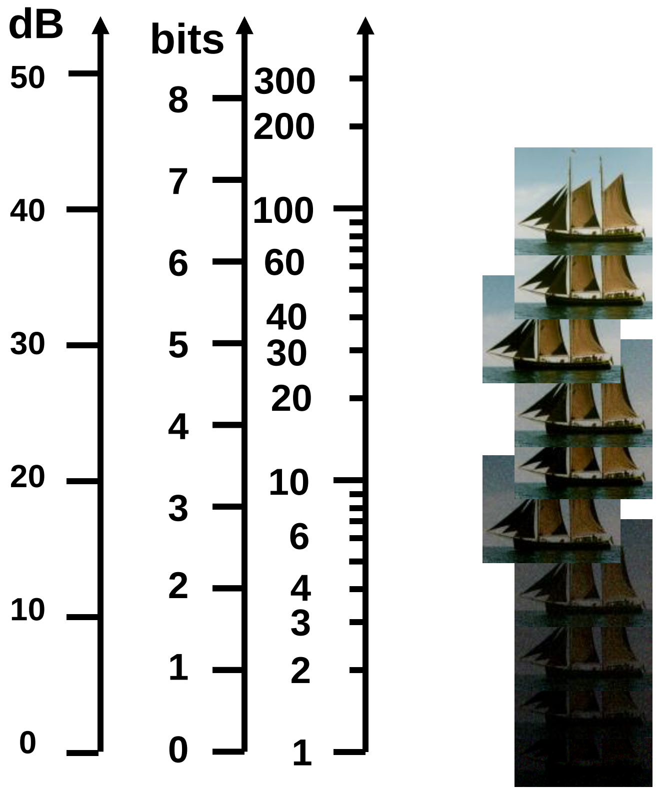
Multiplying by 2 is 1 bit or 6 dB.

$$1 \text{ dB} = 20 * \log x$$

**1 bit = 6.02 dB**

# How To Understand The Diagram?
# Image Quality

**Signal to Noise Ratio**




- An excellent image is SNR = 40 or better.
- A good image quality is SNR = 10.

# Examples: Sony ICX285

Saturation capacity: 18000 electrons
Dark noise: 9 electrons
QE @ 545 nm: 56 % (electrons per photons)

Saturation with 18000 / 0.56 ≈ 32140 photons
Detection limit 9 / 0.56 ≈ 16 photons

Max SNR: sqrt(18000) ≈ 134 (this is close to $128 = 2^7$)
7.1 bits or 43 dB

Dynamic range: saturation cap./dark noise =
18000 / 9 = 2000
(this is close to $2048 = 2^{11}$)
11 bits or 66 dB

# Examples: Sony ICX274

Saturation capacity: 8000 electrons
Dark noise: 8 electrons
QE @ 545 nm: 50 % (electrons per photons)

Saturation with 8000 / 0.50 ≈ 16000 photons
Detection limit 8 / 0.50 ≈ 16 photons

Max SNR: sqrt(8000) ≈ 89 (this is between 64 = $2^6$ and 128 = $2^7$ )
6.5 bits or 39 dB

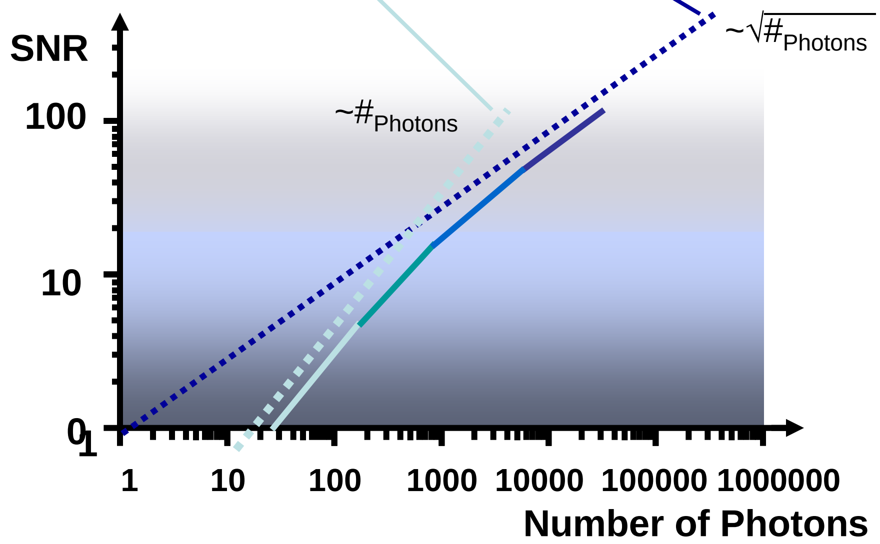
Dynamic range: saturation cap./dark noise =
16000 / 16 = 1000
(this is close to 1024 = $2^{10}$ )
10 bits or 60 dB

# Limitations in the Diagram

Image quality depends on the signal to noise ratio (SNR).

Total noise consists of:

- Temporal Noise (~ $\sqrt{\text{number of photons}}$)
- Dark Noise (~ number of photons)



# Noise in Cameras I

There are three main noise sources on a sensor:

- ADC noise
  - When using two (like on a CCD) or multiple (like on a CMOS sensor) the ADCs might behave a little different from one device to the next.
  - It can be corrected / aligned if there is no light to the sensor and no voltage to the pixels.

- Fixed Pattern Noise (FPN) or Dark Signal Non Uniformity (DSNU):
  - Every single pixel has a different threshold when starting to convert photons to electrons. Especially on CMOS sensors the FPN is an issue.
  - It can be corrected / aligned with all voltages on, but no light to the sensor. The worst pixel is the threshold.

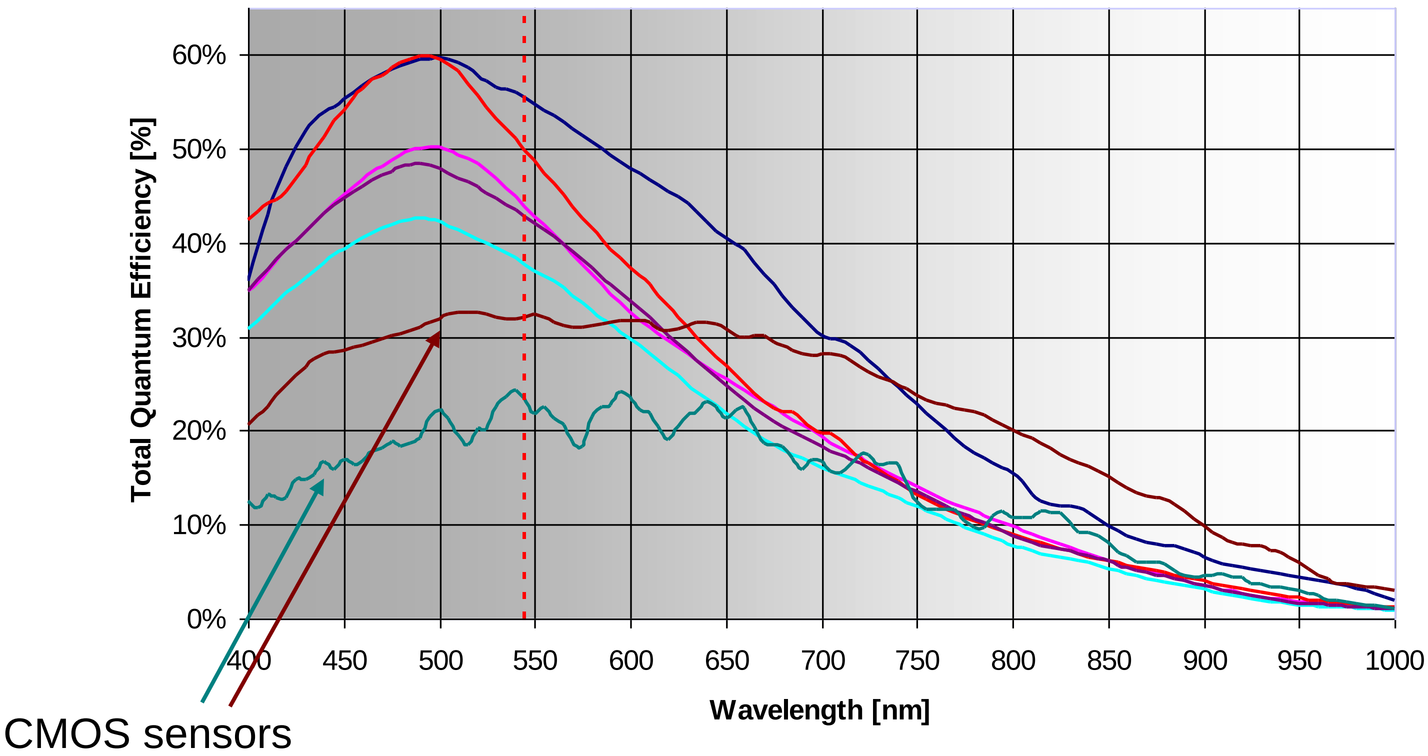
# Noise in Cameras II

- Photo Response Non-Uniformity (PRNU)
  - Every single pixel has a slightly different conversion factor. This depends on geometric factors, material differences, etc.
  - It can be corrected / aligned if there is a uniform illumination to the sensor. Variations to the smoothed average are aligned with a individual pixel gain correction.

- Defect Pixels
  - Defect pixels, like dead pixels or hot pixels can be identified by similar measurements. A marked defect pixel can be interpolated by neighbor pixels.

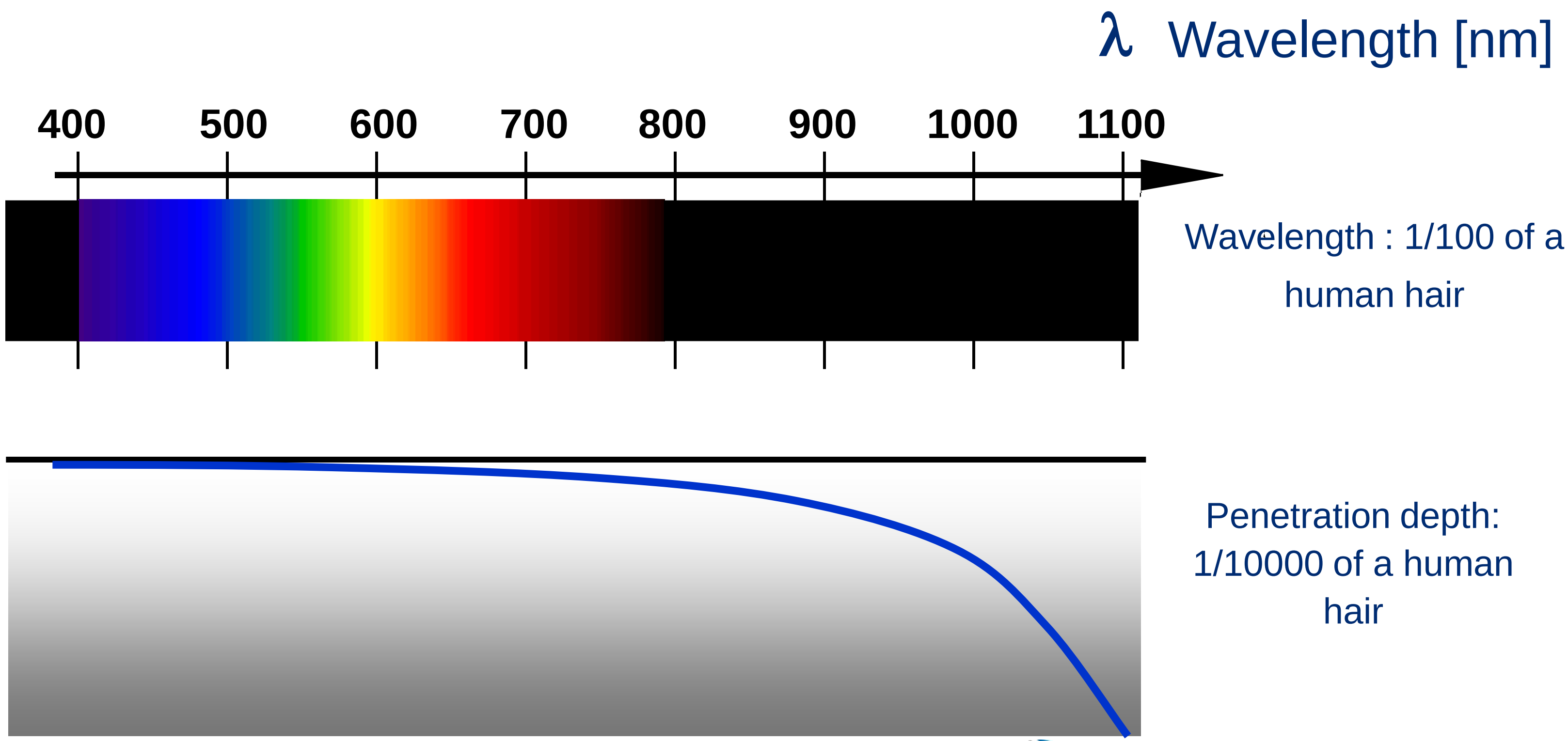
# Spectral Response

The spectral response depends on wavelength and sensor type.
CMOS sensors have often a wavy curve due to interferometric issues.



# Penetration Depth

Cameras cover a spectral range of the visible (VIS) and near infrared (NIR), wavelengths from 400 to 1100 nm.



# Area Scan and Line Scan

- Scan types can be separated by area scan and line scan.

- Area scan is known from a digital still camera.
  - 1 shot and the image is taken.
  - As an example: resolution 1300 x 1000 pixels. After an exposure time of 10 ms, everything is captured. All pixels have an exposure time of 10 ms.

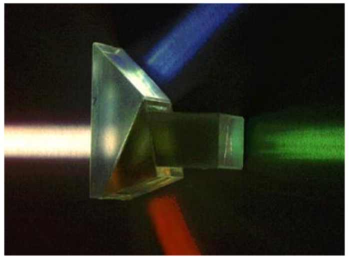
- Line scan is known from a Xerox machine.
  - One line after the other is taken to get the total image.
  - As an example: resolution 1000 pixels, 1300 lines. With a total exposure time of 10 ms the image is taken, BUT: every single line (or each pixel) has only an exposure time of **7.7 µs**!
  - This is a very short exposure time → You need much more light!

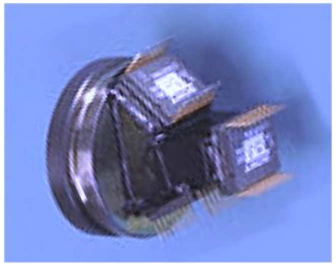
# The Need of Spatial Trigger

- A trigger by time squeezes the object for different speeds (e.g. acceleration after a traffic light).
- Only a spatial trigger gives the right information.
- It does not depend on the speed of the object.

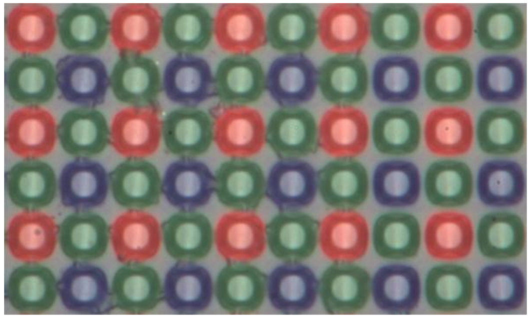
# Color: Area Scan

- Color on area scan can be taken either with a
  - 3 CCD setup: a beamsplitter separates the colors to three different CCDs.
  - Advantage: Every pixel has the full color information.
  - Disadvantages: Expensive, special lenses, alignment, color shades.



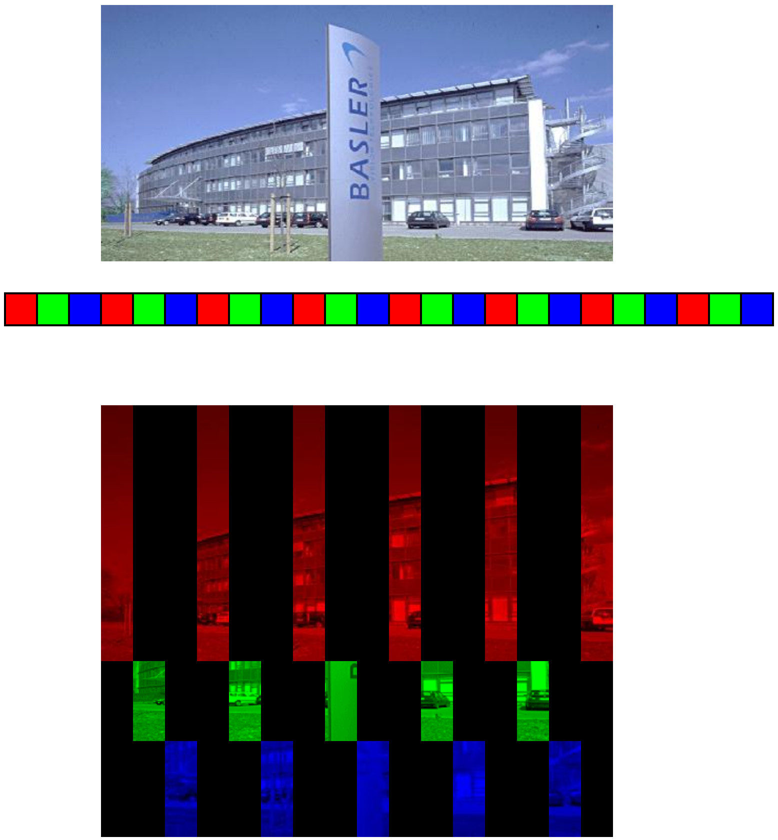


  - In most cameras a Bayer pattern is used.

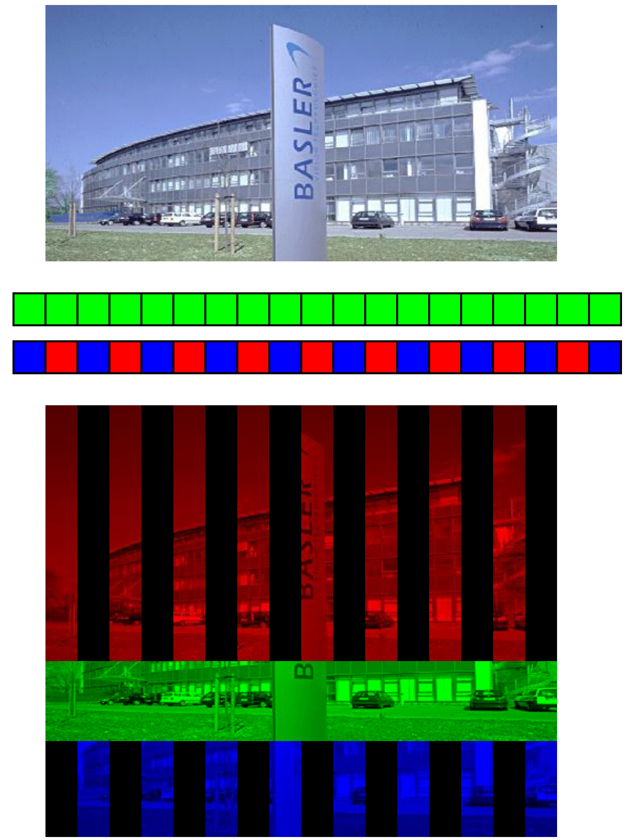


# Color: Line Scan I

Single Line

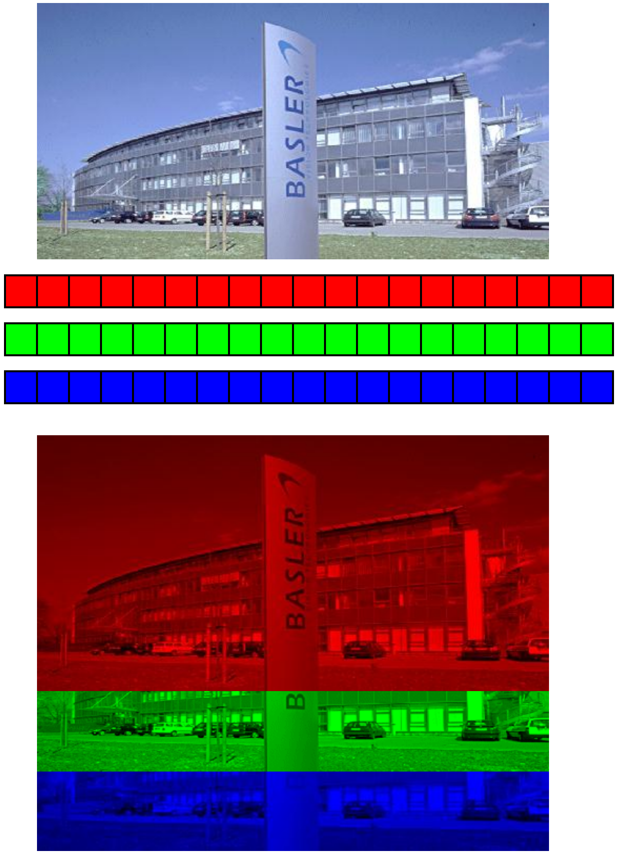



Dual Line

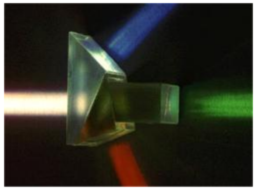


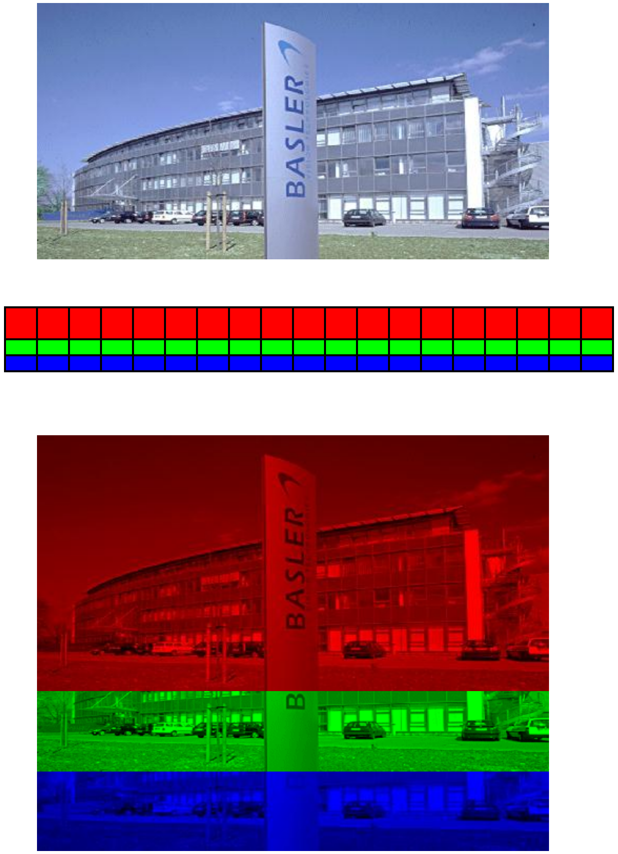
# Color: Line Scan II

Triple Line

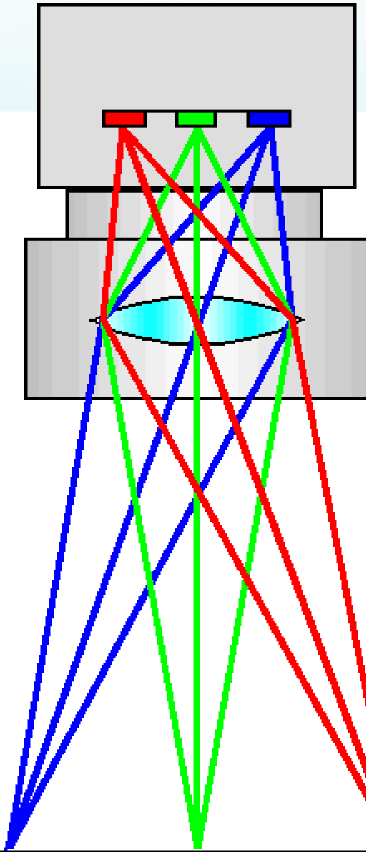



3 CCD Line

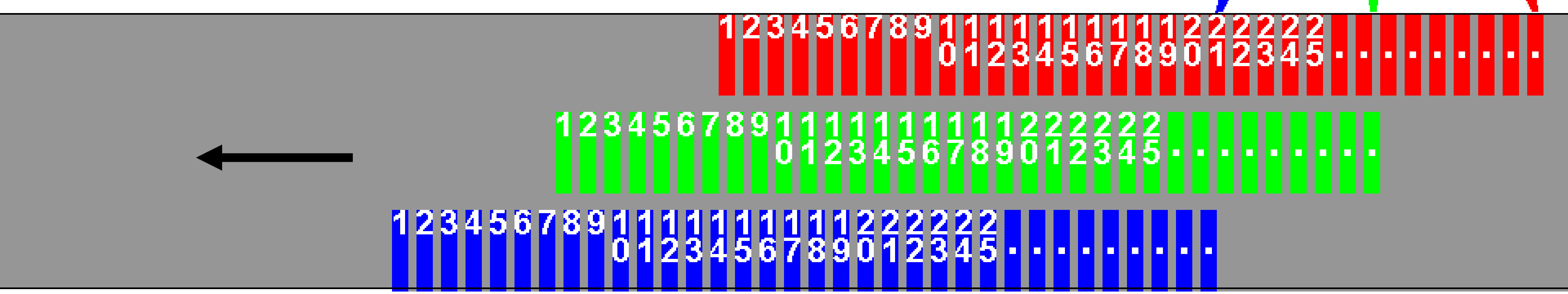




# How to Match RGB to One Image I

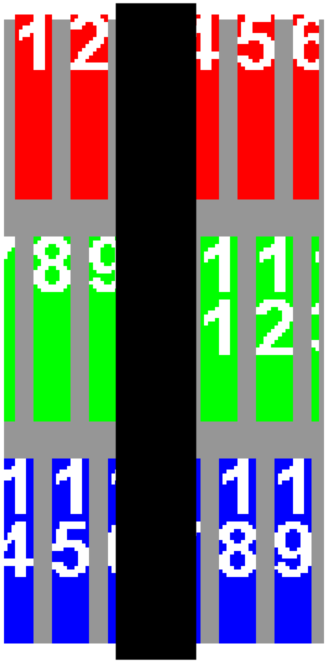


- The object on the conveyer belt is moved beneath the camera.



# How to Match RGB to One Image II

- Take 1, 8, and 15, but there is a color shade within one group RGB.



**Lines 1, 8, 15:**

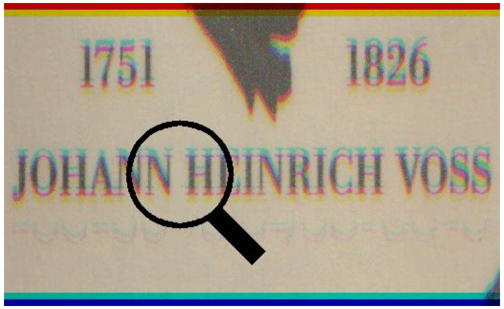
**Lines 2, 9, 16:**

**Lines 3, 10, 17:**

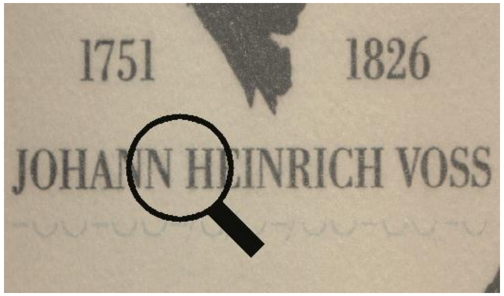
**Lines 4, 11, 18:**

# What is Possible with the Camera?

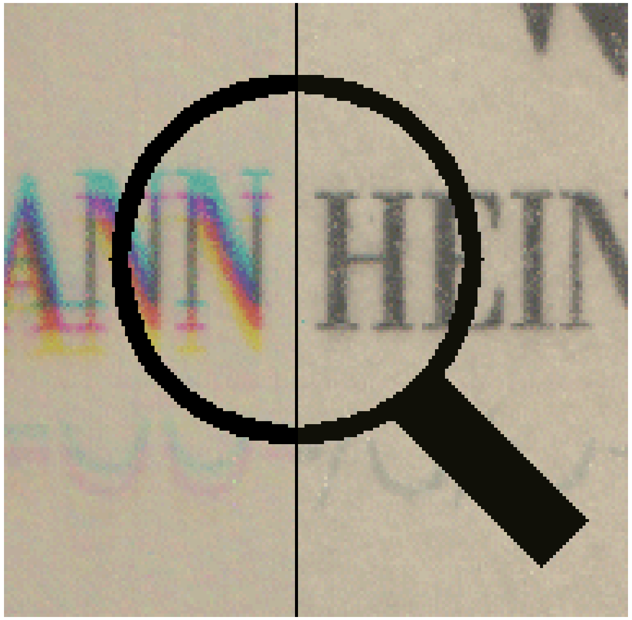
- Raw Image




- Corrected Image

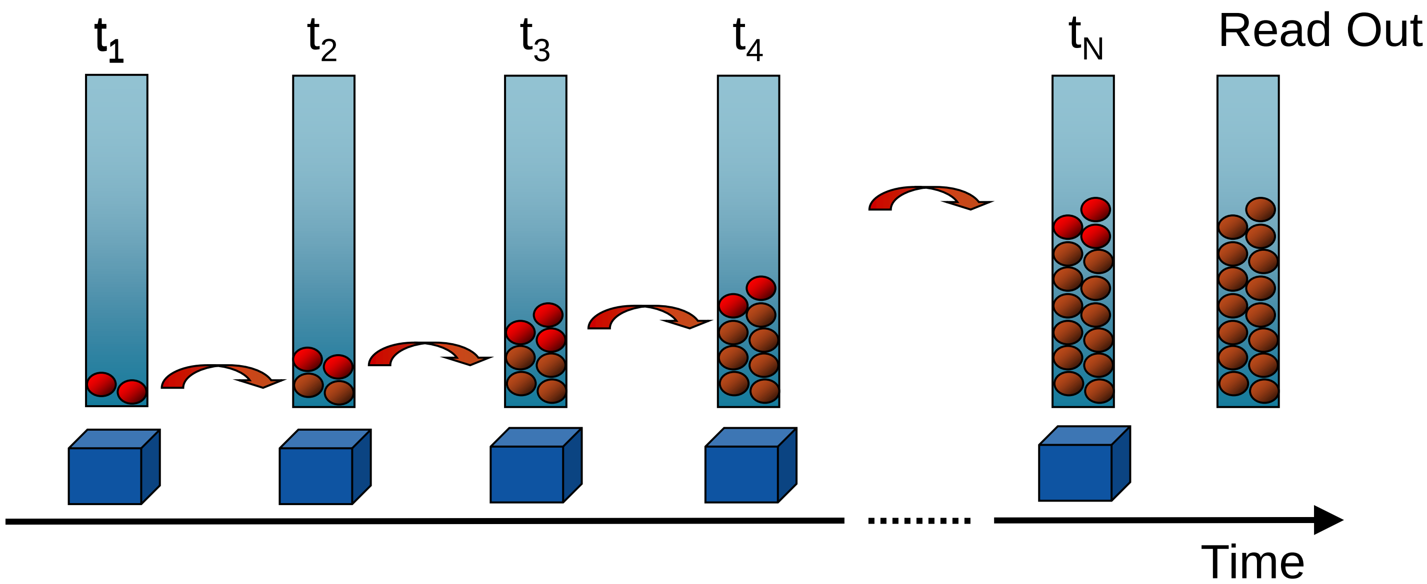



Raw Corrected



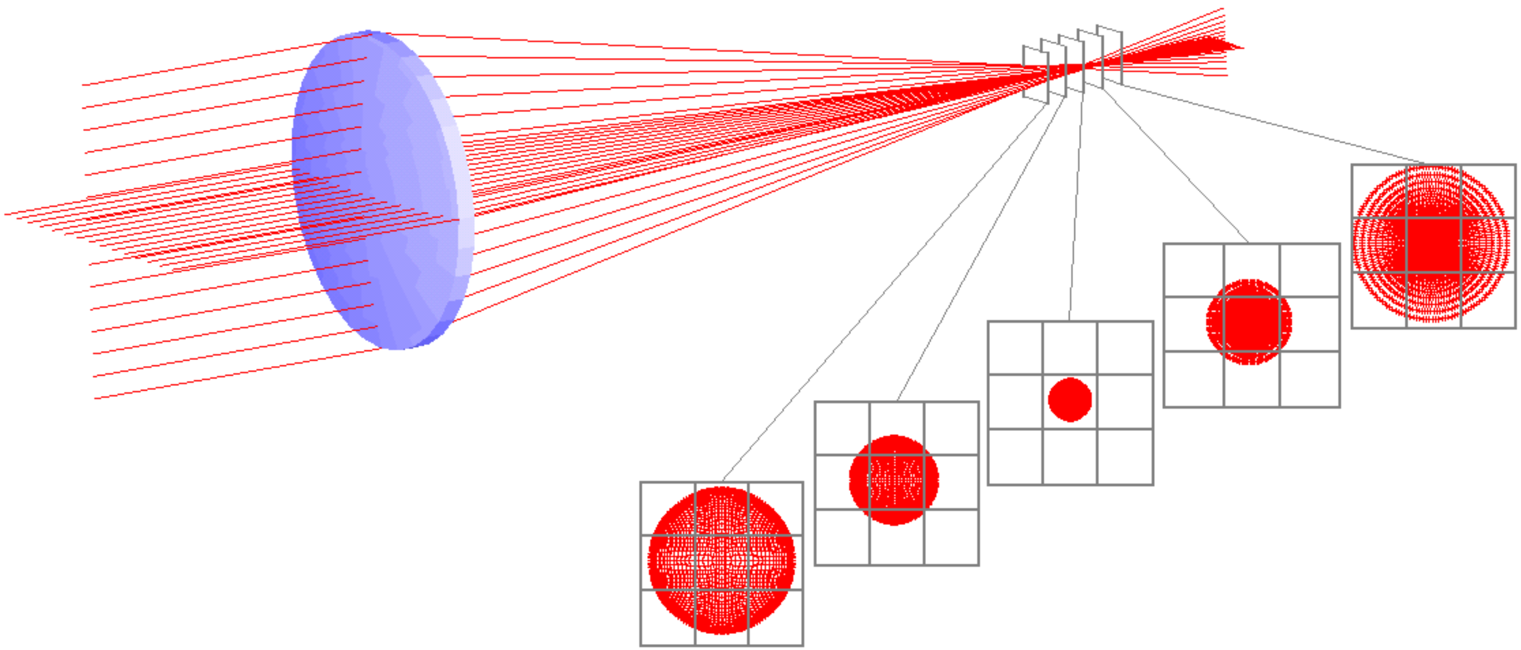
# TDI Line Scan Sensor

- TDI stands for Time Delay and Integration.
- The object is exposed several times, charges are accumulated and shifted simultaneously with the trigger.
- Signal is taken N times, Noise reduces by $\sqrt{N}$.



# Depth of Focus (DOF)

The depth of focus (DOF) depends on the pixel size, the diameter of the iris and the focal length of the lens.



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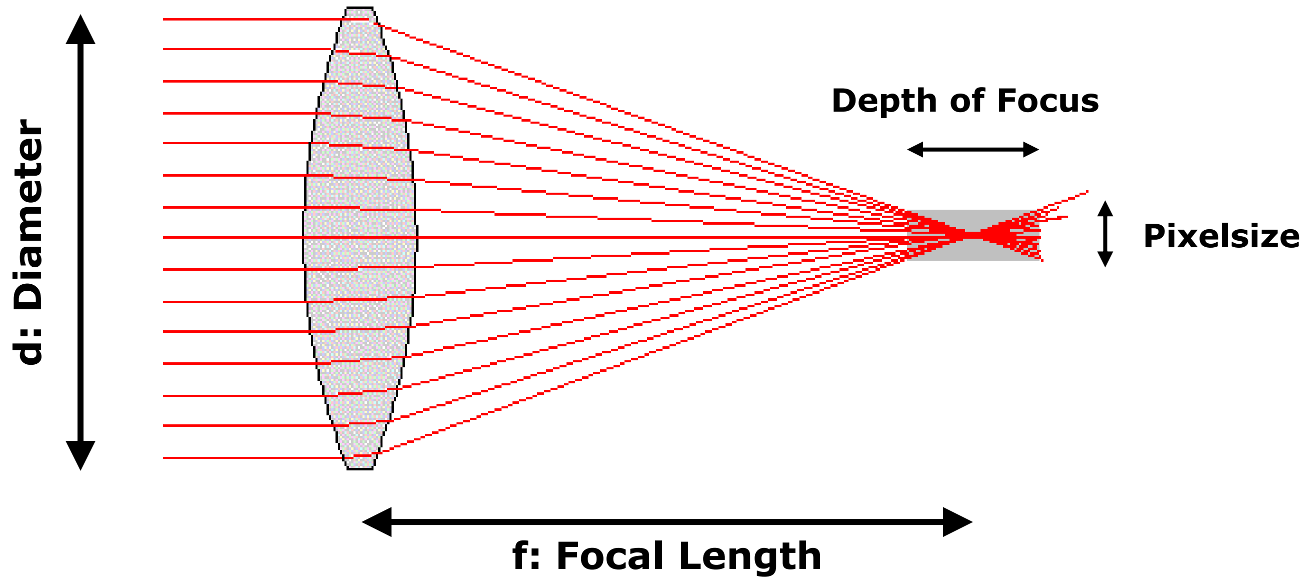
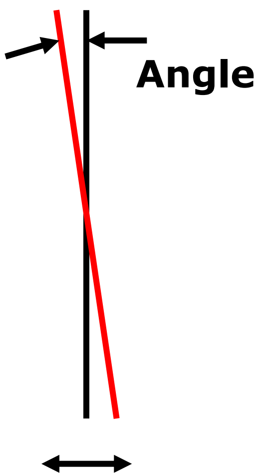


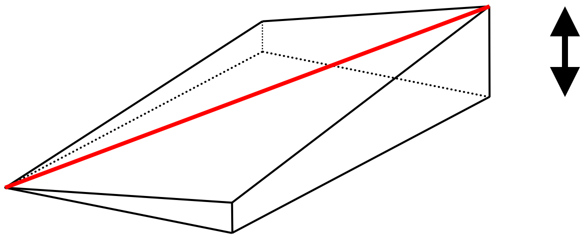

DOF = 2 * Pixelsize * f / d = 2 * Pixelsize * F/#

# Tilt of the Sensor

The sensor has to be aligned perpendicular to the optical axis.




**Given max Depth of Focus**



**The whole sensor has to be taken into account**

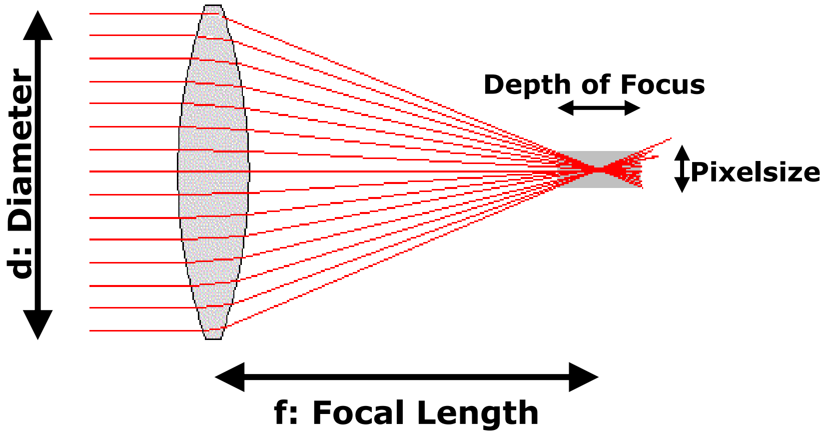
# Examples of Geometrical DOF

Real numbers:

Pixelsize = 5 µm

F/# = 4

Depth of Focus: ±20 µm (40µm)




Real numbers:

Pixelsize = 4 µm

F/# = 2

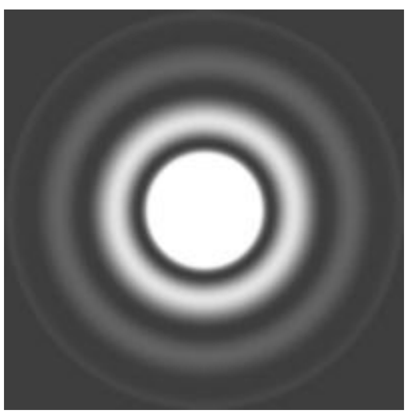
Depth of Focus: ±8 µm (16 µm)

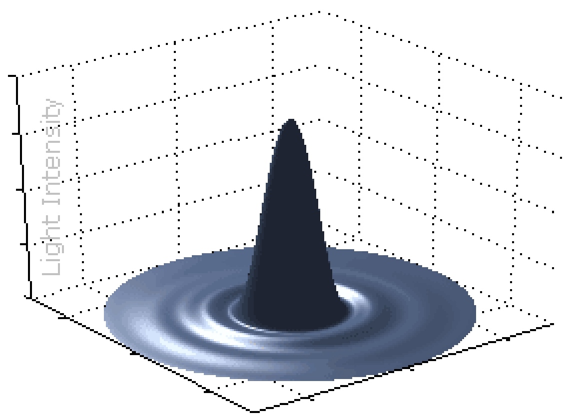
# Diffraction

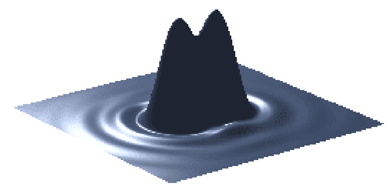
Due to the physical structure of light as an electro-magnetical wave, the rays are blurred by diffraction. Diffraction depends on the F-number and wavelength λ.

$$Ø_{Airy} = 2.44 * \lambda * F/\#$$

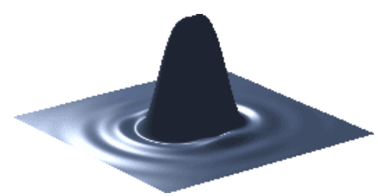
As a rule of thumb the diameter of the Airy disc is F/# in microns, like F/# is 4, the diameter of the Airy disc is approx. 4 µm.





Barely resolved



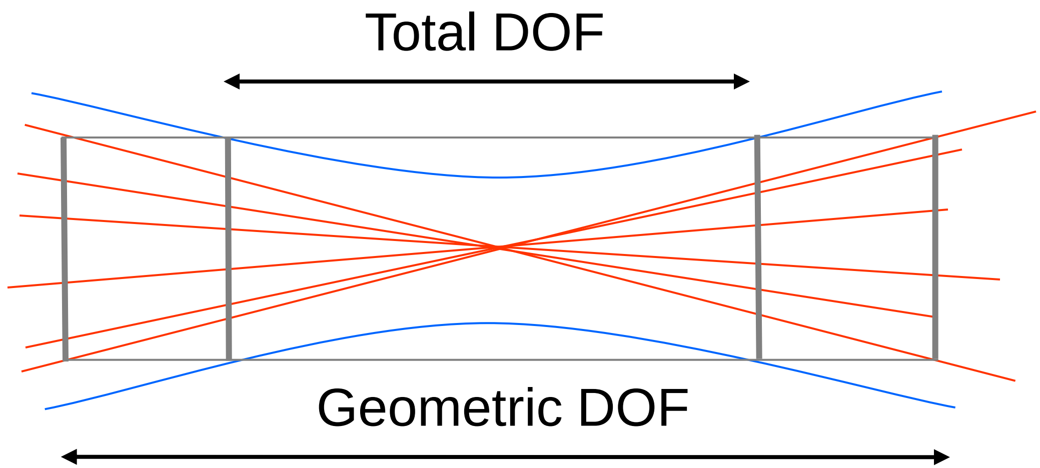
No longer resolved

# Real Spotsize and DOF

The real spotsize and DOF is the geometrics folded with the diffraction.

To make life a little easier we will treat the diameter as independent errors (deviations):

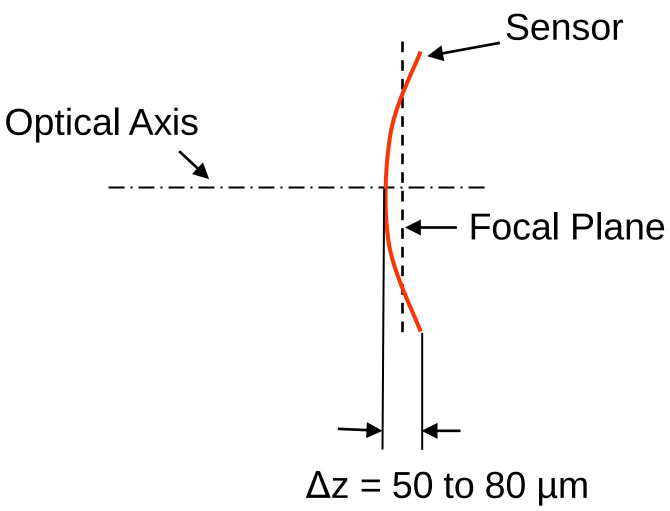
$$\varnothing_{total} = \sqrt{\varnothing_{geom}^2 + \varnothing_{diff}^2}$$



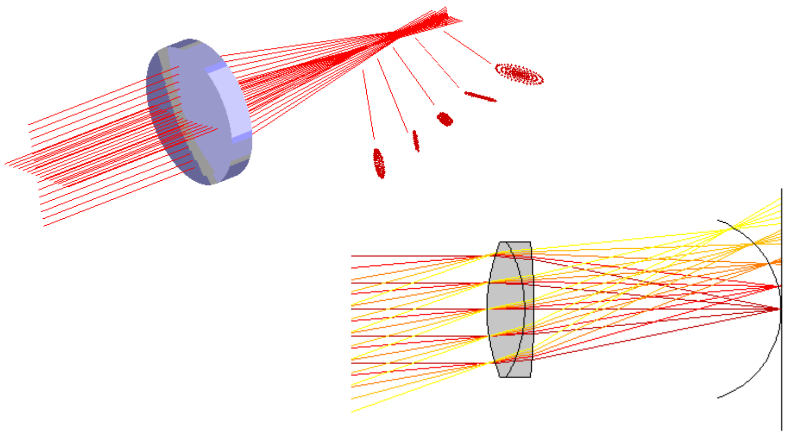
# Errors Of Higher Order

In case of an 8k line scan sensor with 10 µm pitch we might have further issue:

The sensor might be bent by
Δz = 50 to 80 µm (still normal)

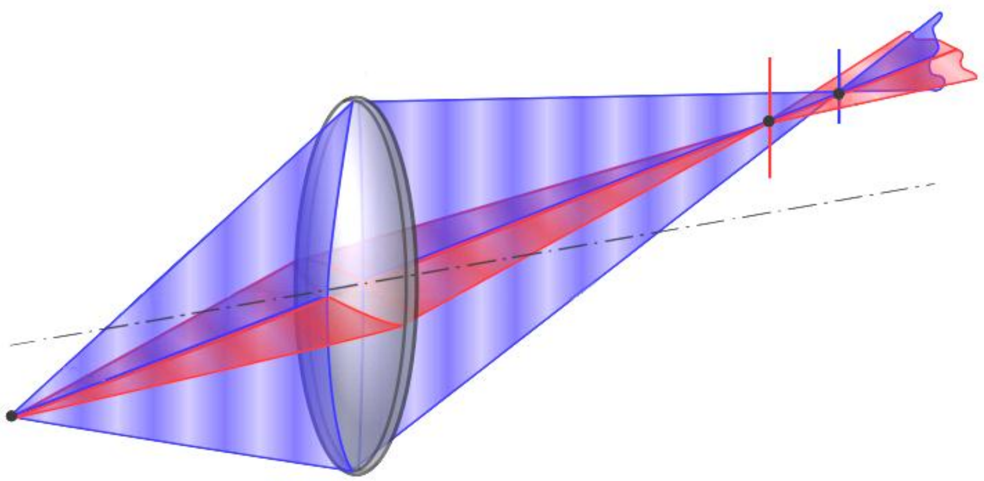


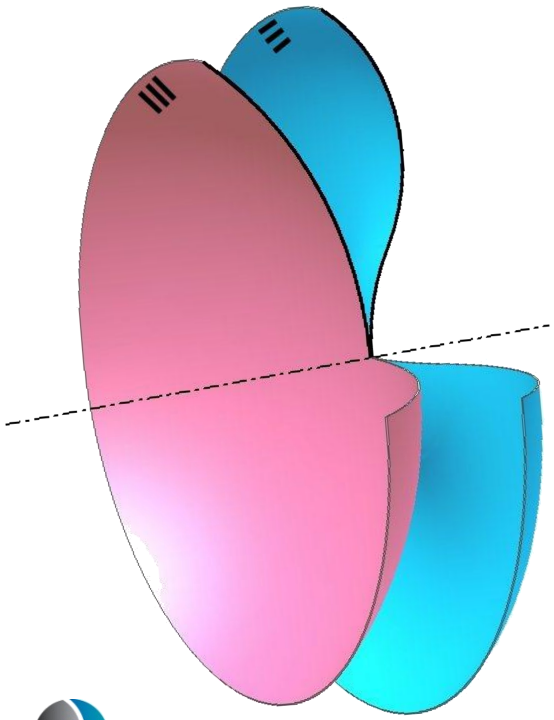

The lens (e.g. 5.6/90mm) will cause a field curvature of Δz = 50 to 100 µm, whereas the astigmatism might occur and the meridional and sagittal focal plane might run the opposite direction.



# Field Curvature And Astigmatism

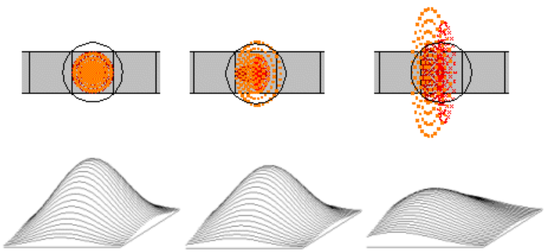
In case of an 8k line scan sensor with 10 µm pitch we might have a difference of about 100 µm between both focal planes (meridional and sagittal).

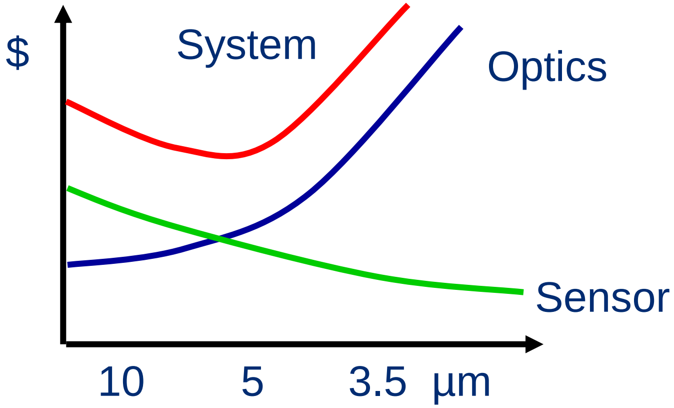




# Pixel Size

- Pixels are mainly between 10 to 3.5 µm.
- People are going to smaller pixels, because higher resolution with less silicon. More sensors from a single wafer.
- “Reasonable“ limit: 5 µm for monochrome, 2.5 µm for color.
- Full-Well capacity (saturation capacity, resp.) is lower for smaller pixels. Therefore the max SNR is not as good as on a larger pixel.





# Recommended Mechanical Interfaces (Mounts)

| Class | Min. Image Size [mm] | Max. Image Size [mm] | Optical Size [type] | Mechanical Interface (1st Choice) |
|---|---|---|---|---|
| I | 0 | 4 | ≈ ¼ | C-, CS-, NF-, S-Mount |
| II | 4 | 16 | ≈ 1 | C-, CS-, NF-Mount |
| III | 16 | 31.5 | ≈ 2 | F-Mount, 48 mm Ring, M42 x 1, M48 x 0.75 |
| IV | 31.5 | 50 | ≈ 3 | M58 x 0.75 (and F-Mount if possible) |
| V | 50 | 63 | ≈ 4 | M72 x 0.75 |
| VI | 63 | 80 | ≈ 5 | M95 x 1 |
| VII | 80 | 100 | ≈ 6 | M105 x 1 |

Please see: JIIA LER-004-2010 (Draft 0.20)

# Contact Information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