



Advanced Camera and Image Sensor Technology

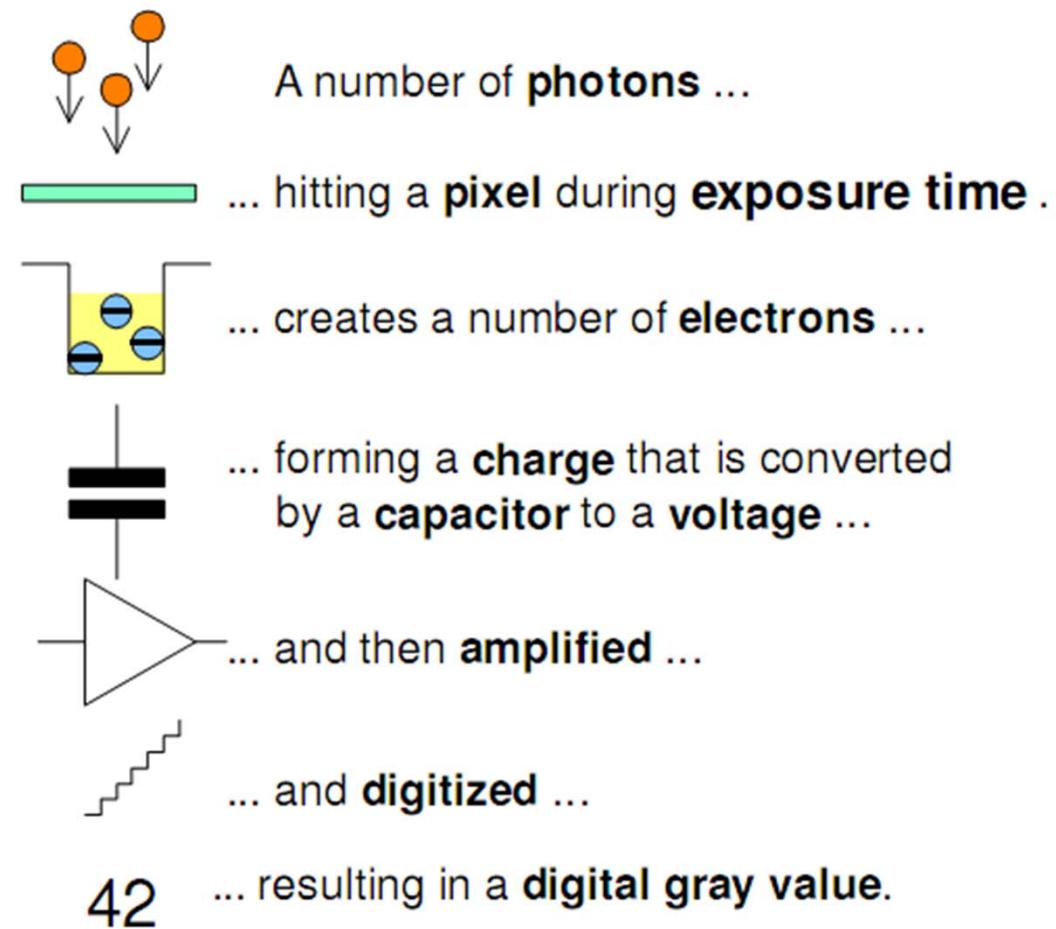
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Content

- Physical model of a camera
- Definition of various parameters for EMVA1288
- EMVA1288 and image quality
- CCD and CMOS sensors, image artifacts
- 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

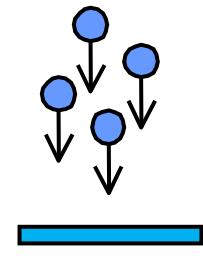


What are the Important Things?

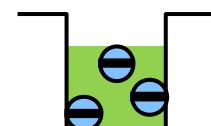
Quantum Efficiency

- When light is emitted from a light source, then 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).

$$QE = \text{number of electrons} / \text{number of photons}$$



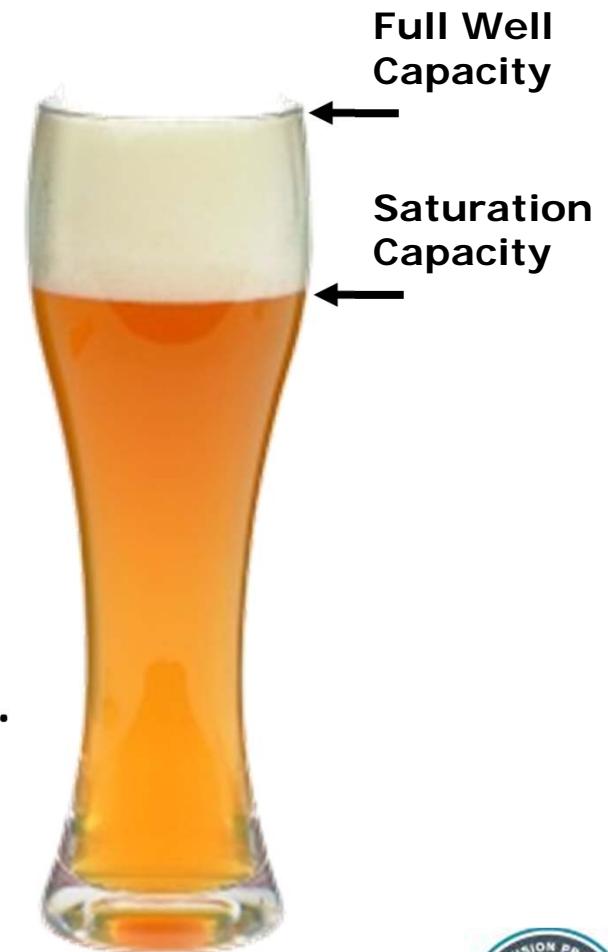
- Typical values are 30 to 60 %.



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 as the maximum capacity is reached.
- A pixel may have a saturation capacity 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 to the same previous value, there is a slight jitter in the amount of electrons created. This “noise” is equivalent to the square root of the number of electrons.

$$\text{noise} = \sqrt{e^-}$$

- So the maximum Signal to Noise Ratio (SNR_{max}) is:

$$SNR_{max} = \frac{e^-_{max}}{\sqrt{e^-_{max}}} = \frac{\text{sat.cap.}}{\sqrt{\text{sat.cap.}}} = \sqrt{\text{sat.cap.}}$$

- $\sqrt{5000e^-} = \text{approx. } 224$
- Refilled beer glasses do not have the same content.



What are the Important Things?

Dark noise

- There is always some residual noise, even when 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.
- Heat is a contributor.



What are the Important Things?

Detection Limit

- If the signal is the same as the dark noise, we call this detection limit.
- CCD sensors usually have a detection limit of 8 to 25 electrons. This corresponds to 15 - 70 photons.
- CMOS sensors will start at 10 to 110 electrons, or 24 -100's of photons.



Detection
Limit
↔
Dark Noise



What are the Important Things?

Dynamic Range

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

So, a pixel's dynamic range is:

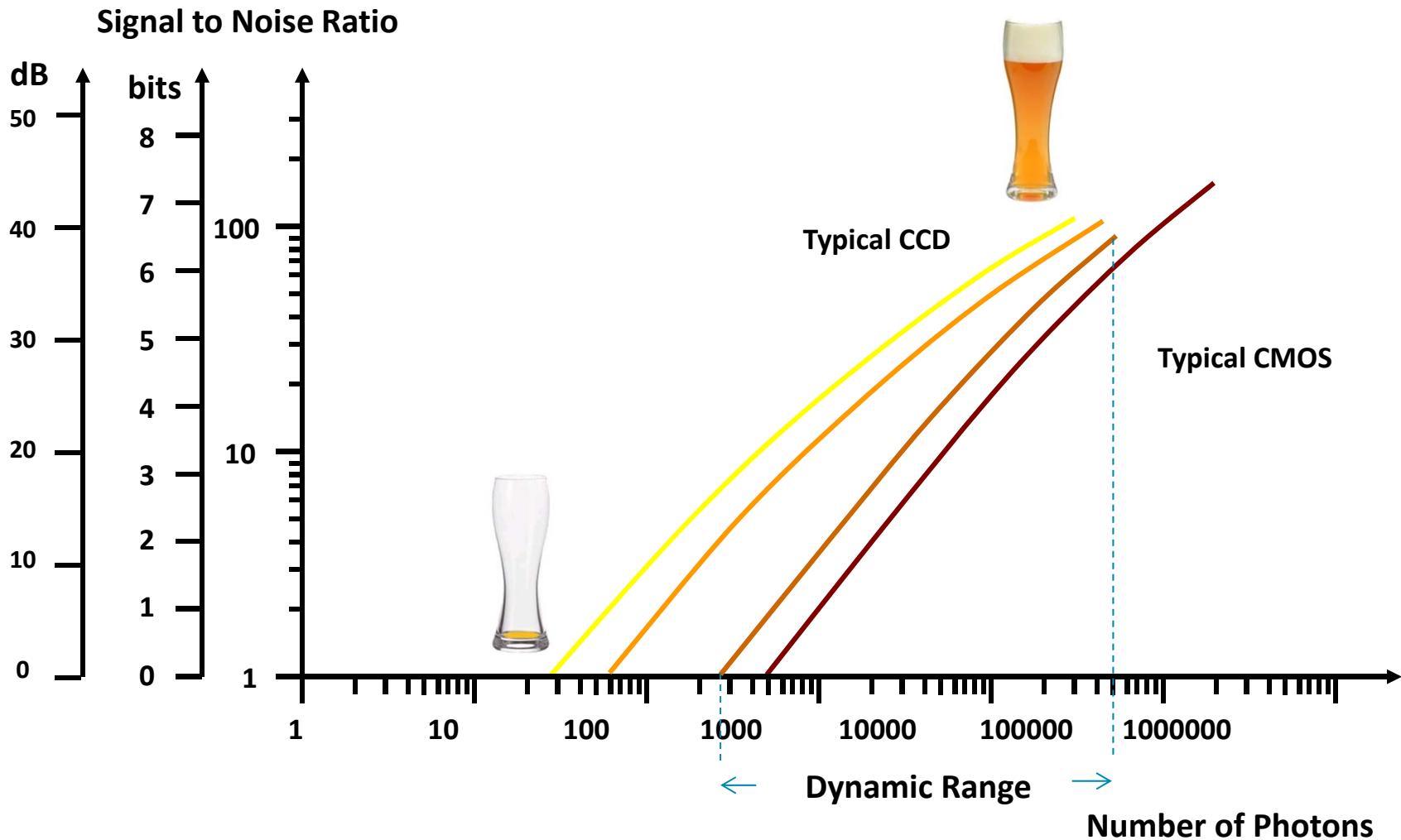
$$DYN = \frac{sat.cap.}{dark\ noise} = \frac{50000e^-}{25e^-} = 200$$



- A glass of beer will always have dynamics!



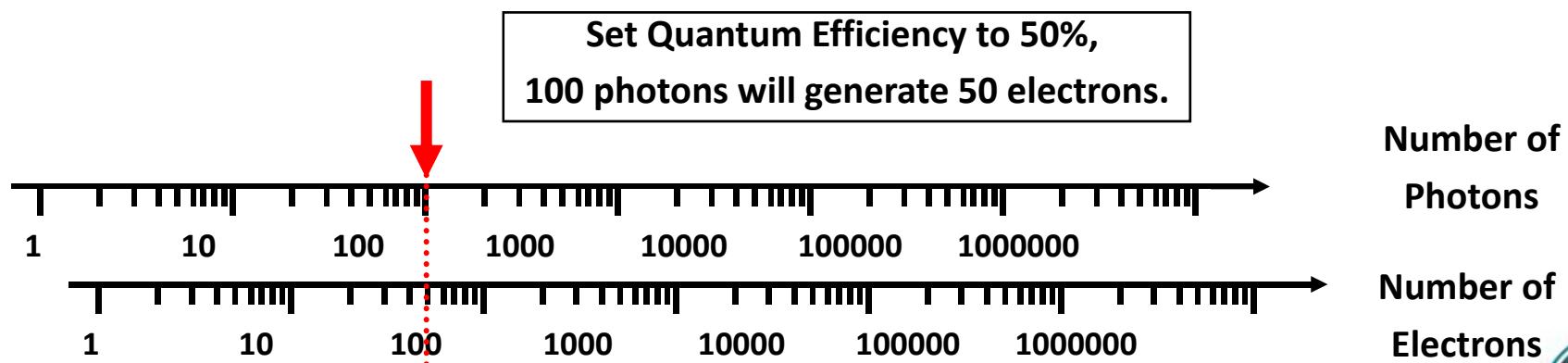
The Diagram



How to Understand the Diagram?

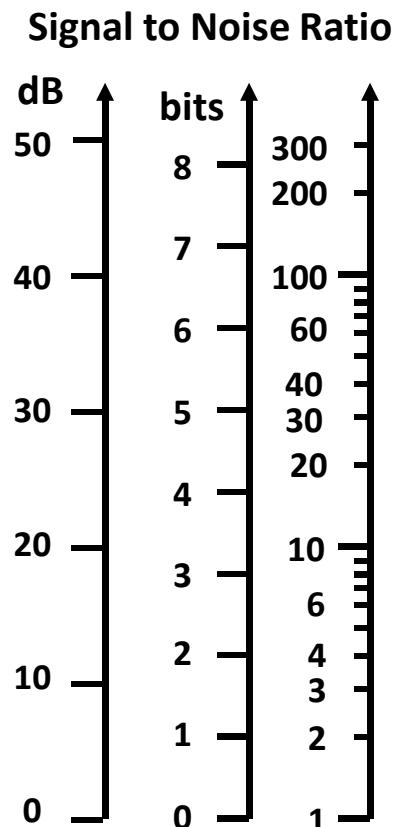
The x-Axis

- We use a logarithmic scale to display the large range of values we are concerned with.
- A linear scale will not represent this properly.
example: Imagine a scale that can display both kilometers and millimeters at the same time with the same precision.



How to Understand the Diagram?

The y-Axis



Actual SNR is also displayed on a logarithmic scale.

A linear scale always adds the same unit.

A logarithmic scale always multiplies by the same unit.

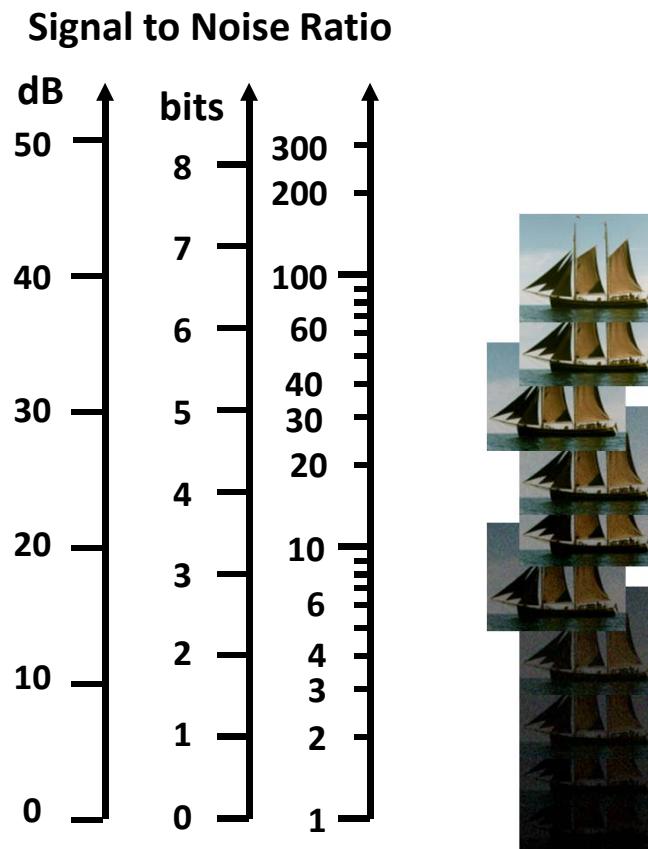
Bits (2^n) and decibel (dB) are logarithmic scales.

Multiplying SNR by 2 =
increasing by 1 bit = 1 bit = 6.02 dB
increasing by 6 dB.



How to Understand the Diagram?

Image Quality



- An excellent image is $\text{SNR} = 40$ or better.
- A good image quality is $\text{SNR} = 10$.



Examples: Sony ICX285

Saturation capacity: 18000 electrons

Dark noise: 9 electrons

QE @ 545 nm: 56 % (electrons per photons)

Saturation reached with:

$$\frac{18000}{0.56} \approx 32140 \text{ photons}$$

Detection limit: $\sqrt{9} / 0.56 \approx 16 \text{ photons}$

Max SNR:

$$\sqrt{18000} \approx 134 \approx 7.1 \text{ bits} \approx 43 \text{ dB} (134 \approx 128 = 2^7)$$

Dynamic range:

saturation cap./dark noise =

$$18000 / 9 = 2000 \approx 11 \text{ bits} \approx 66 \text{ dB} (2000 \approx 2^{11})$$



Examples: Sony ICX274

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

Saturation with
Detection limit $\frac{8000}{0.50} \approx 16000$ photons
 $\frac{8}{0.50} \approx 16$ photons

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

Dynamic range:
saturation cap./dark noise =
 $16000/16 = 1000 \approx 10$ bits ≈ 60 dB (1000 \approx 1024 = 2^{10})

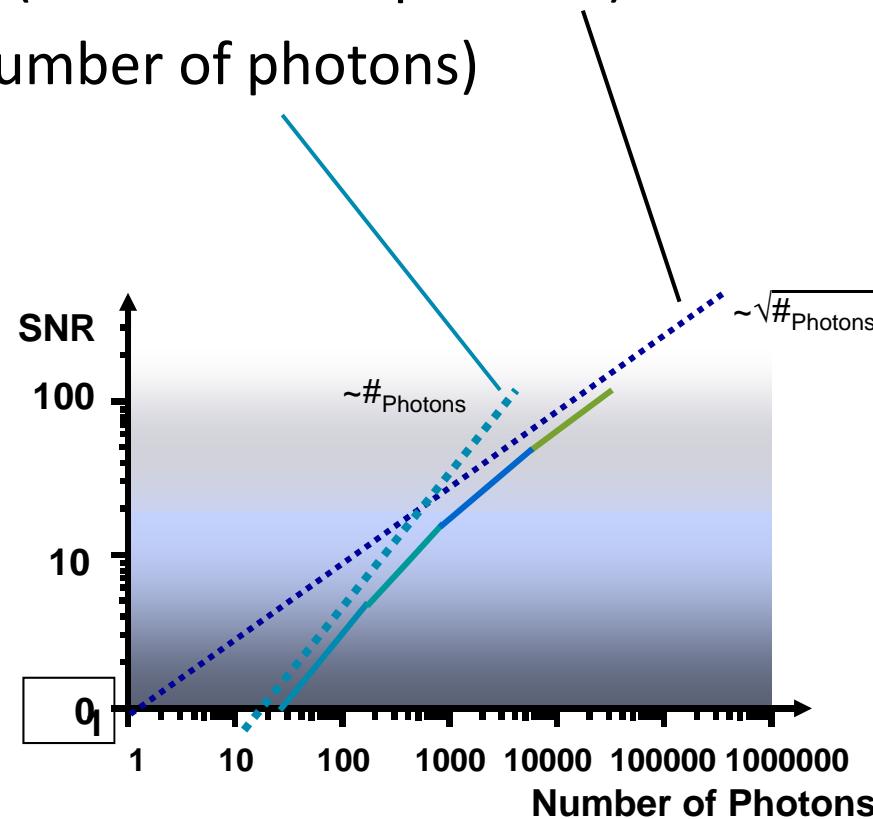


Limitations in the Diagram

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

Total noise consists of:

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



Today's CMOS Sensors

- Today's CMOS sensors are able to achieve the same low read noise as CCD sensors (about 7 to 10 electrons).
- In sensors with a rolling shutter, it can be even less, due to less transistors being used.



Progressive Scan vs. Interlaced Scan

Why is progressive scan important?

- Progressive scan gives you a full image for all lines (or pixels).
- Interlaced scan uses the odd & even lines separately.
- This can result in a “fringe effect” like you see in a TV's news ticker.
- Progressive Scan:



- Interlaced Scan:



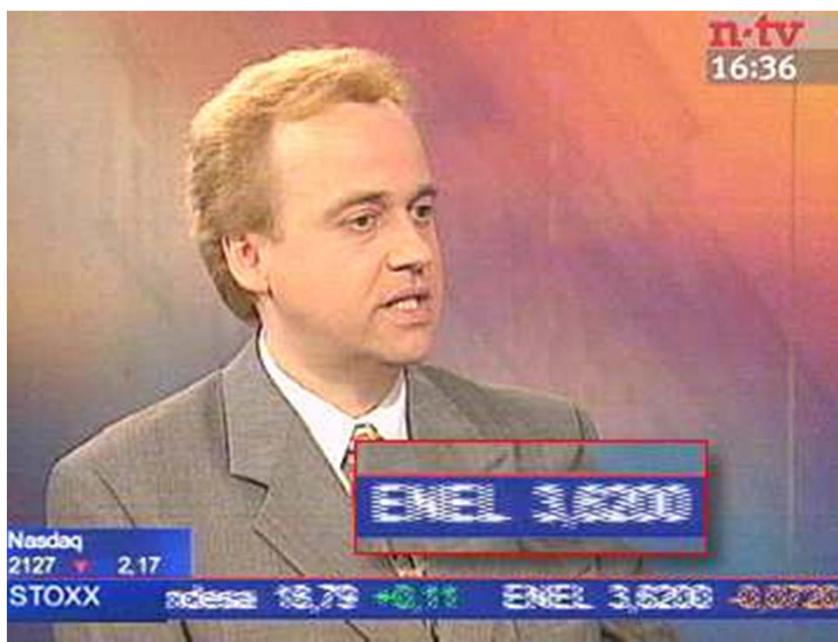
Standard Resolution, Progressive Scan



Standard Resolution, Interlaced



Interlaced Artifacts

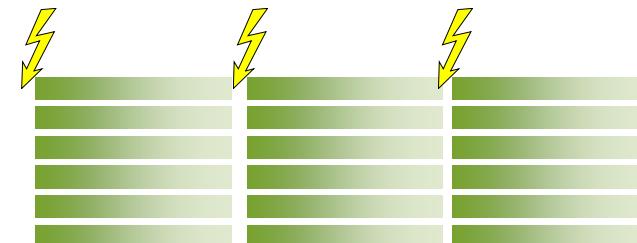
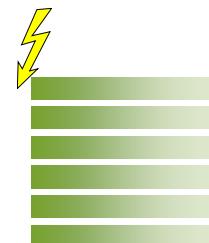


Global Shutter vs. Rolling Shutter

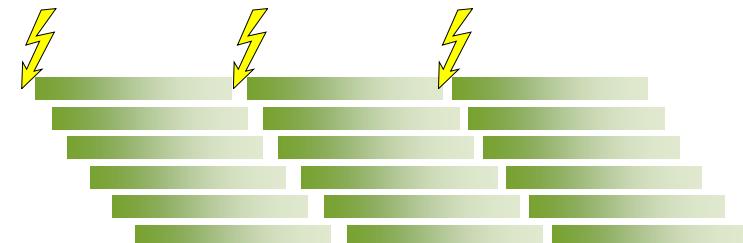
Why is global shutter important?

- Global shutter has the start and stop of exposure time for all pixels at the same time.
- A rolling shutter starts and stops exposure one line after the other (sequentially). This is like a flatbed scanner.

- Global Shutter:



- Rolling Shutter:

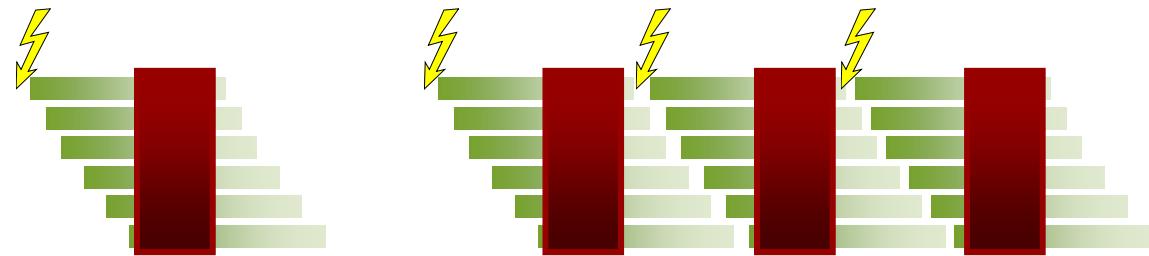


Flash Window and Hybrid Mode

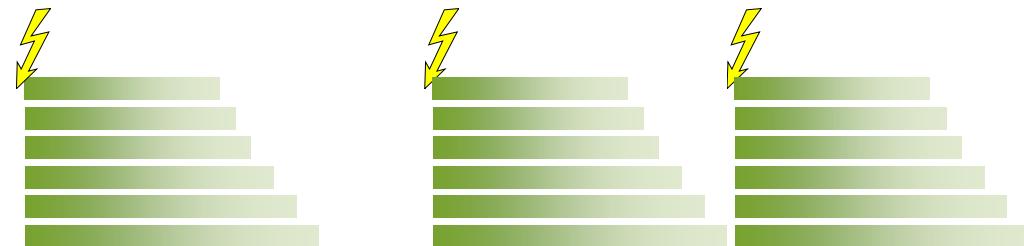
Rolling shutter cameras can offer a flash window.

When the last line starts exposure, the flash window opens until the first line stops exposure. Using a strobe light during this time can freeze the image, effectively becoming a global shutter.

- Flash Window:



- Some "hybrid" sensors exist that start exposure like a global shutter, and end exposure like a rolling shutter. Downside is uneven exposure times.



Standard Resolution, Global Shutter



Standard Resolution, Rolling Shutter



Global Shutter Artifacts



Source: Wikipedia



Resolution

What is the best or required resolution?

- Most people think, the higher the resolution, the better.
- This is not true for machine vision, because all data have to be calculated and displayed.
- Often the higher sensor resolution results in a smaller pixel size.
- Smaller pixels are often below optical resolution and have a lower saturation capacity. A lower saturation capacity results in a worse signal-to-noise ratio and a lower dynamic range.

SNR =

$$\sqrt{\text{saturation capacity}}$$



Dynamic range =



Standard Resolution

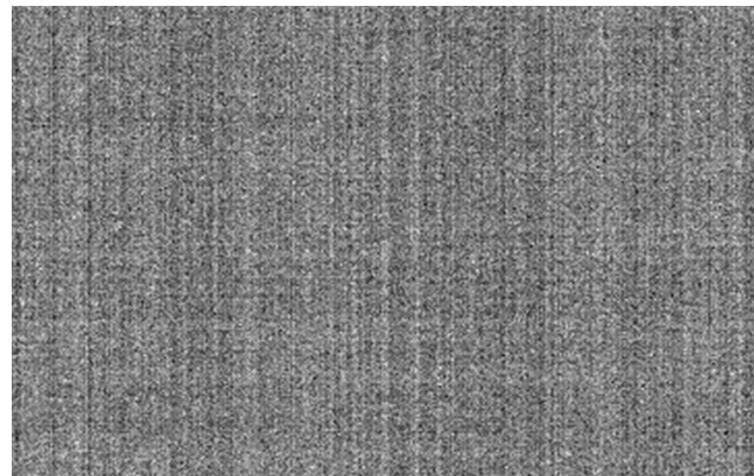


High Resolution



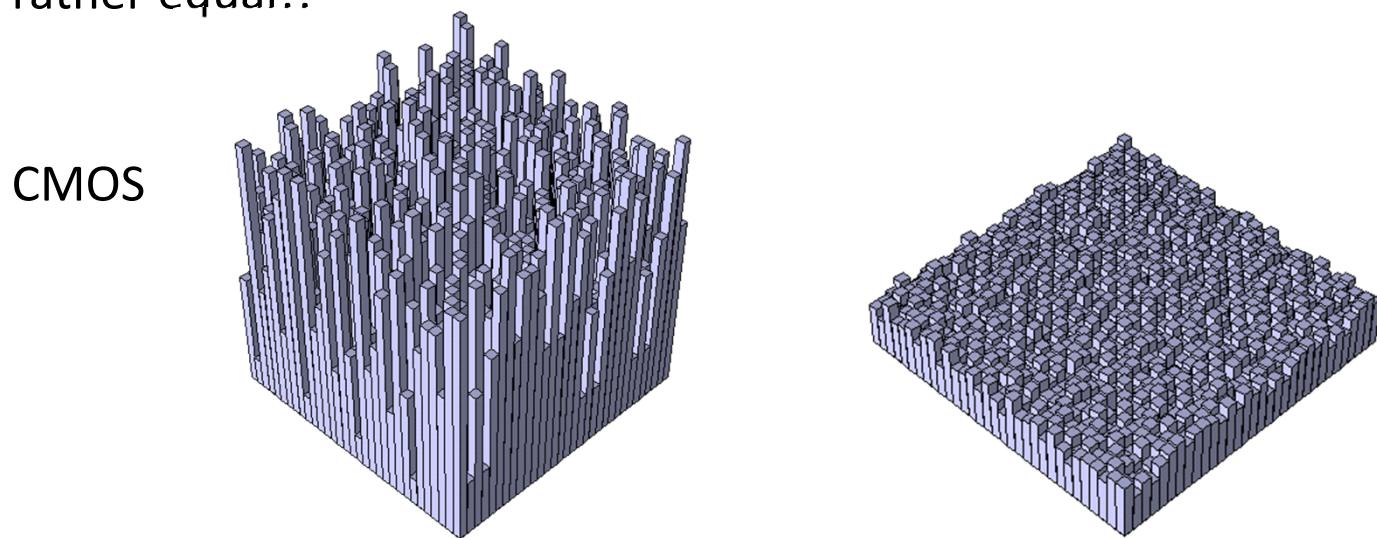
Column Noise

- Usually a CMOS sensor has one ADC (analog to digital converter) per column, a CCD has only one (per tap), meaning typically 1 to 4 ADCs for a CCD.
- In the case of a 4 Mpixel CMOS camera, there are 2048 ADCs.
- All of them will be slightly different.
- A correction done in the dark and without power to the sensor can calibrate all ADCs.



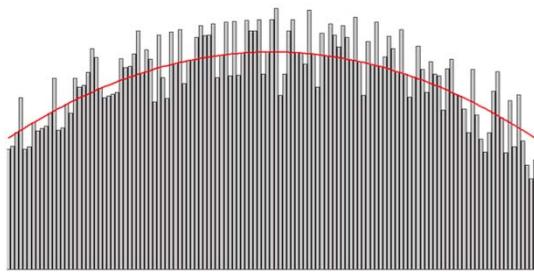
FPN or DSNU

- Fixed pattern noise (FPN) or Dark Signal Non-Uniformity (DSNU) occurs, when all voltages are applied to the sensor, but no light is collected.
- This can be corrected by adding a certain offset per pixel.
- CMOS's FPN is up to 10x worse than a CCD's, but latest designs are rather equal!!

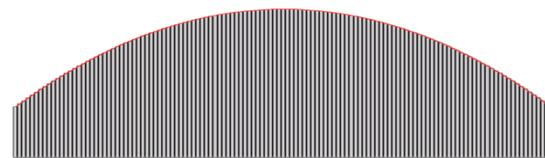


PRNU

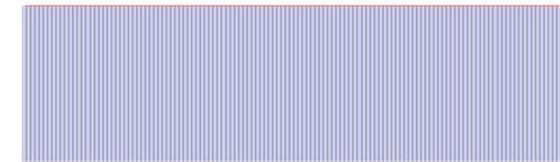
- Photo Response Non-Uniformity (PRNU) describes the different gain per pixel.
- With an illuminated sensor, the different (conversion-) gains can be corrected to create an homogeneous image under bright light conditions.
- CMOS and CCD behave the same.



Raw data



Through a low pass

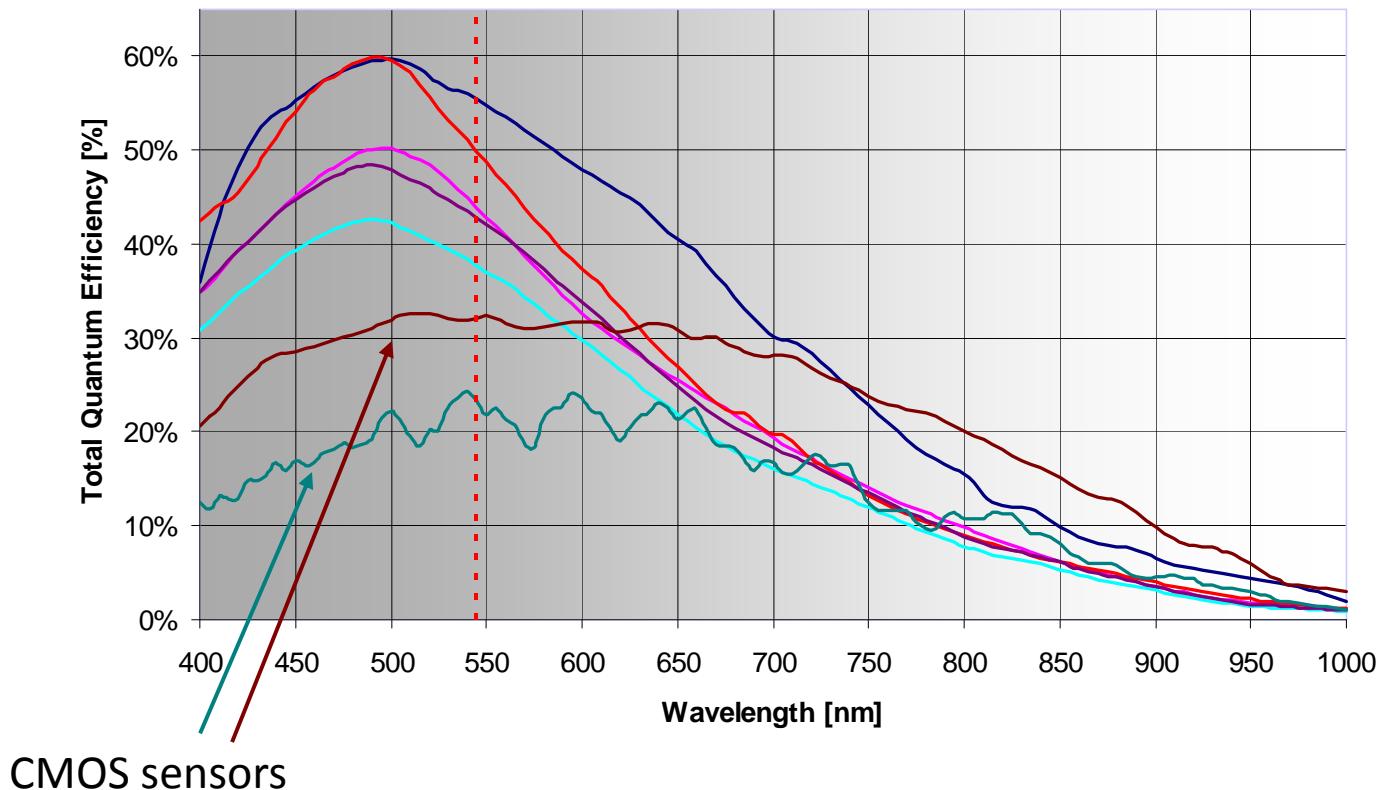


shading corrected



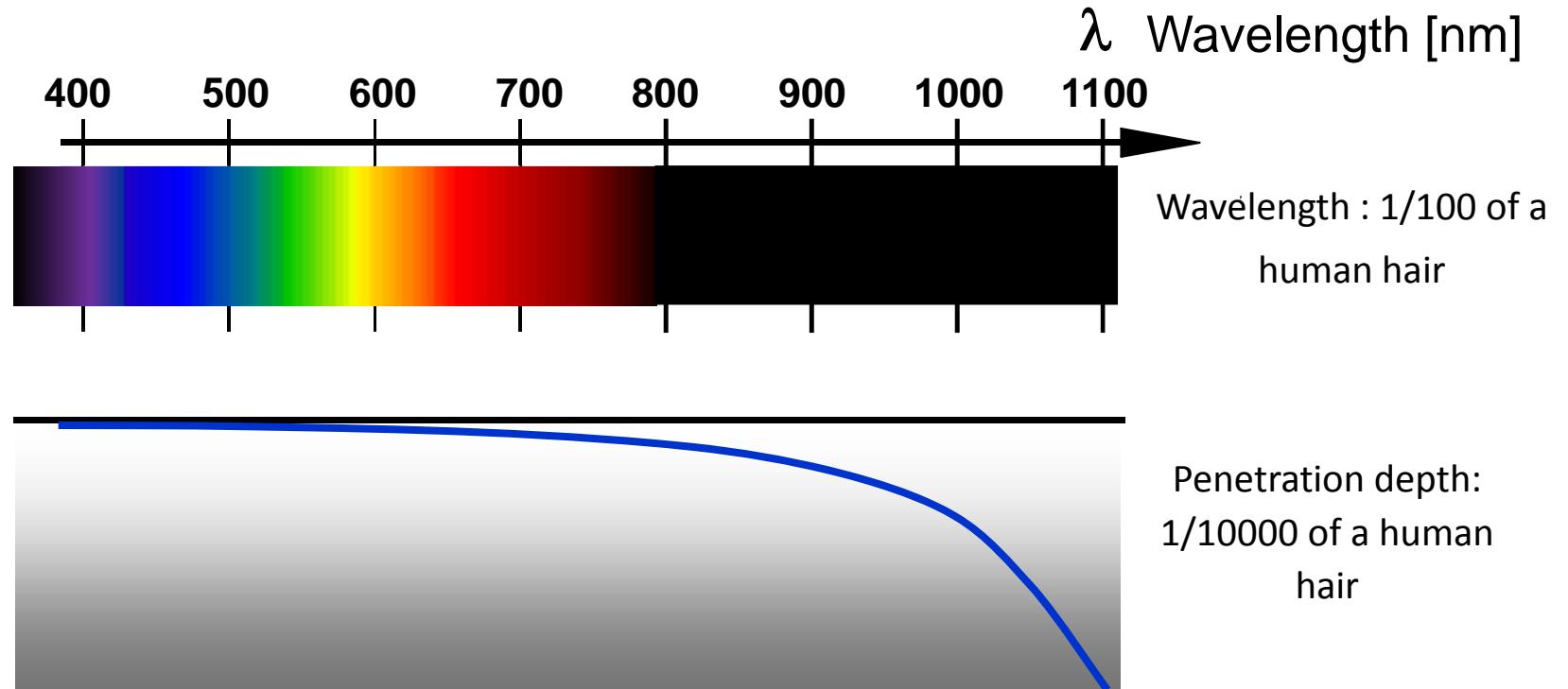
Spectral Response

The spectral response depends on wavelength and sensor type.
CMOS sensors often have 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 analogous to a digital still camera.
 - 1 shot and the 2D 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 analogous to 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!



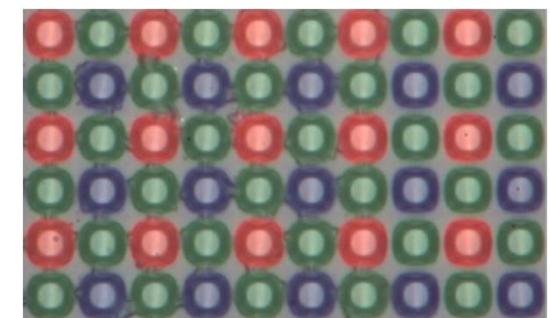
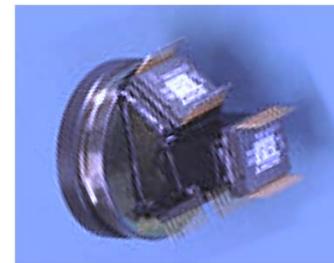
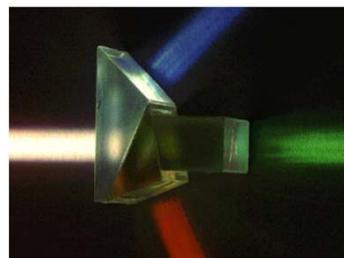
The Need of Spatial Trigger

- Camera speed independent of object speed can distort.
(e.g. acceleration after a traffic light).
- Only a spatial trigger gives the right information.
- It synchronizes the camera with the object (e.g., an encoder).



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.

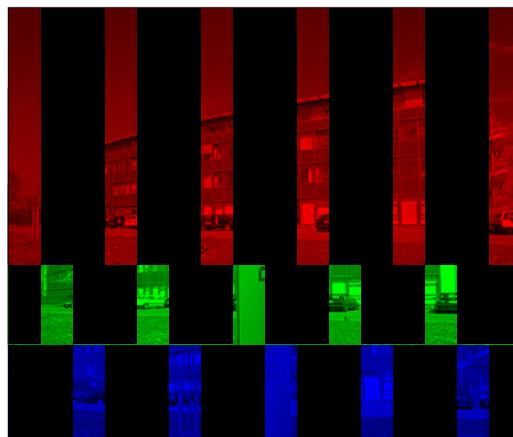


- In most cameras a Bayer pattern is used.

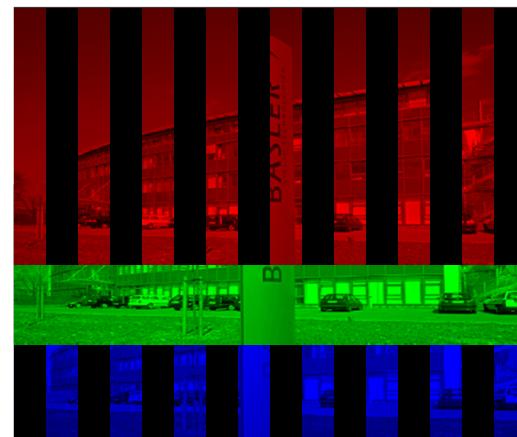
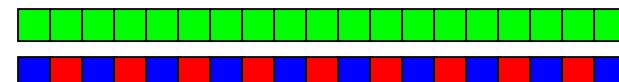


Color: Line Scan I

Single Line

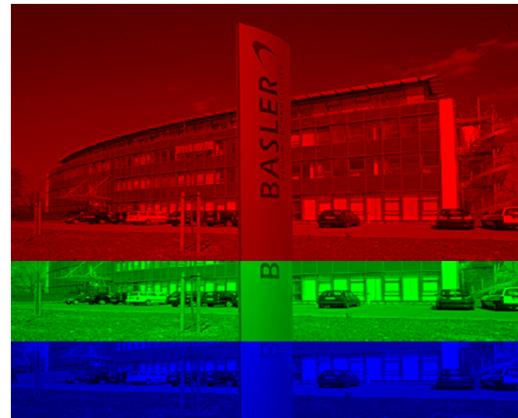
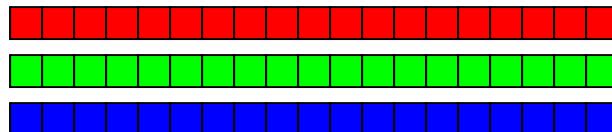


Dual Line

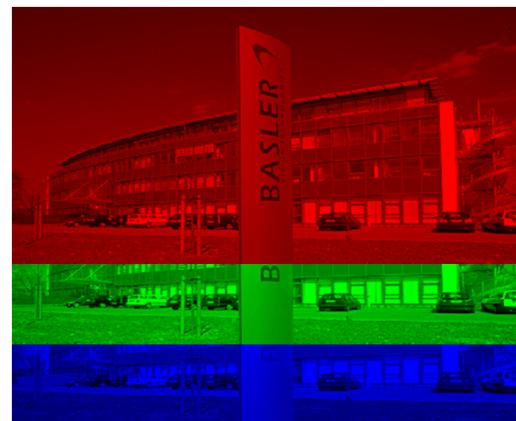


Color: Line Scan II

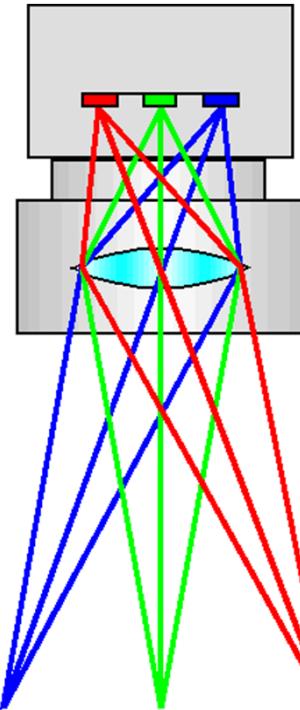
Triple Line



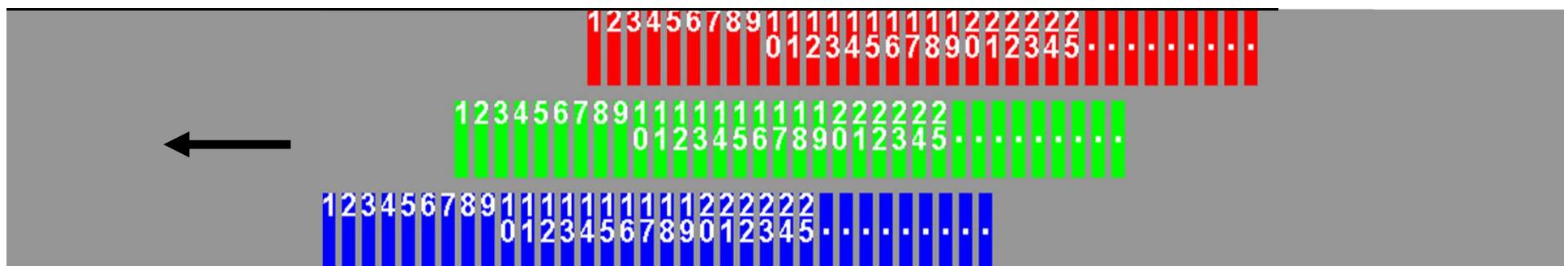
3 CCD Line



How to Match RGB to One Image I



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

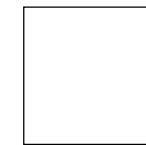


How to Match RGB to One Image II

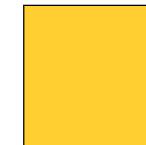
- Take 1, 8, and 15, but there is a color shade within one group RGB.



Lines 1, 8, 15:



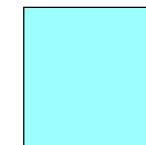
Lines 2, 9, 16:



Lines 3, 10, 17:



Lines 4, 11, 18:



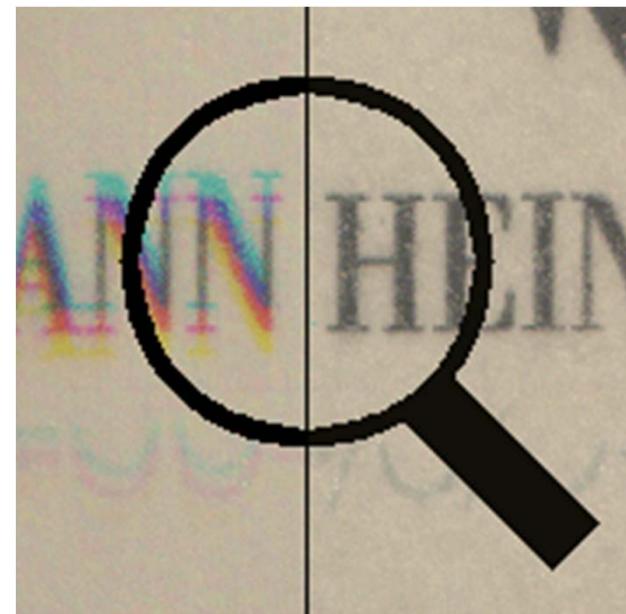
What is Possible with the Camera?

- Raw Image



Raw

Corrected

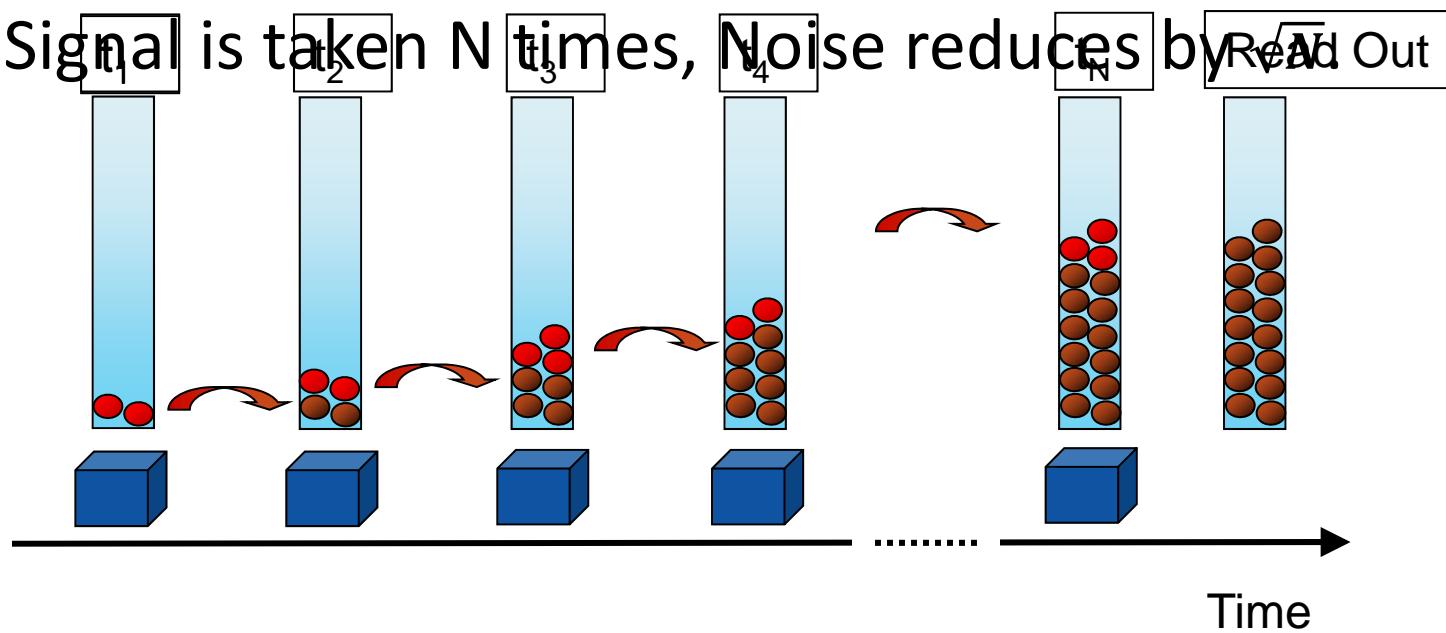


- Corrected Image



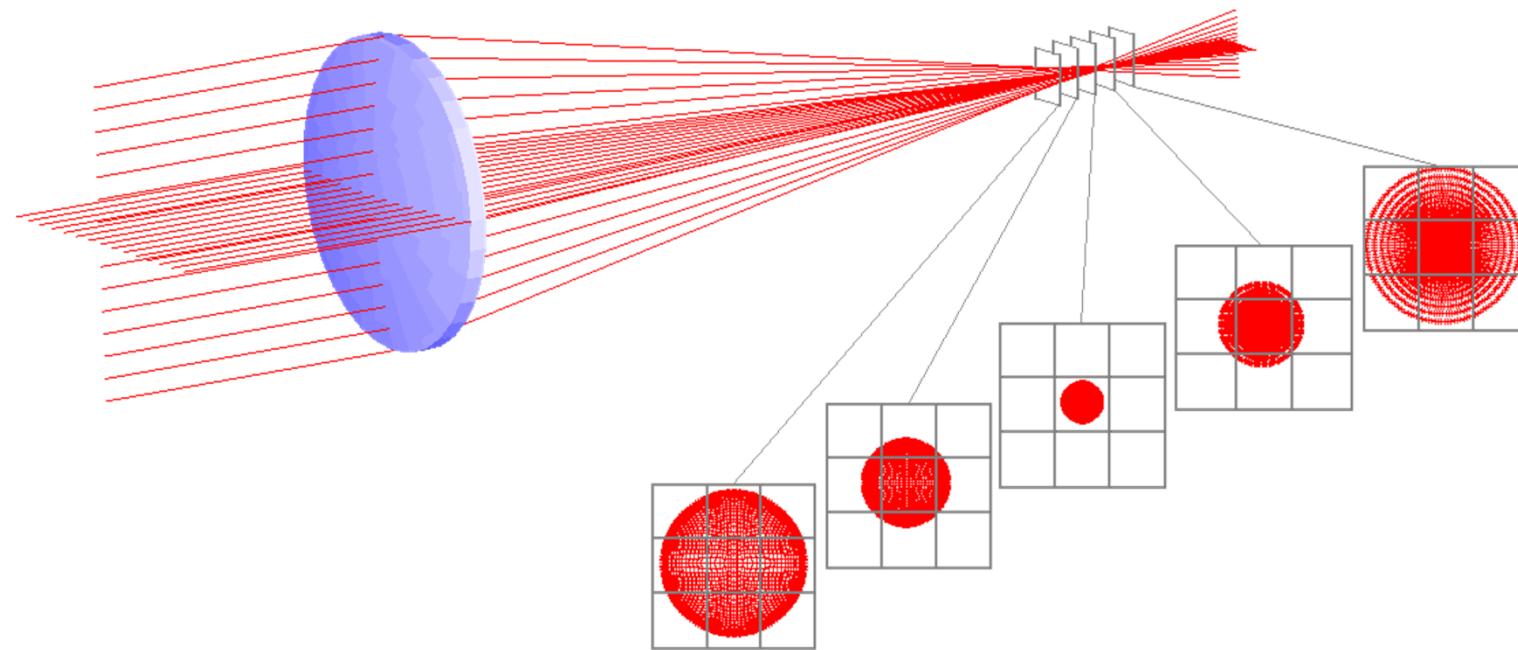
TDI Line Scan Sensor

- TDI stands for Time Delay and Integration.
- The object is exposed several times across many lines, charges are accumulated and shifted simultaneously with the trigger.
- Signal is taken N times, Noise reduces by Read Out



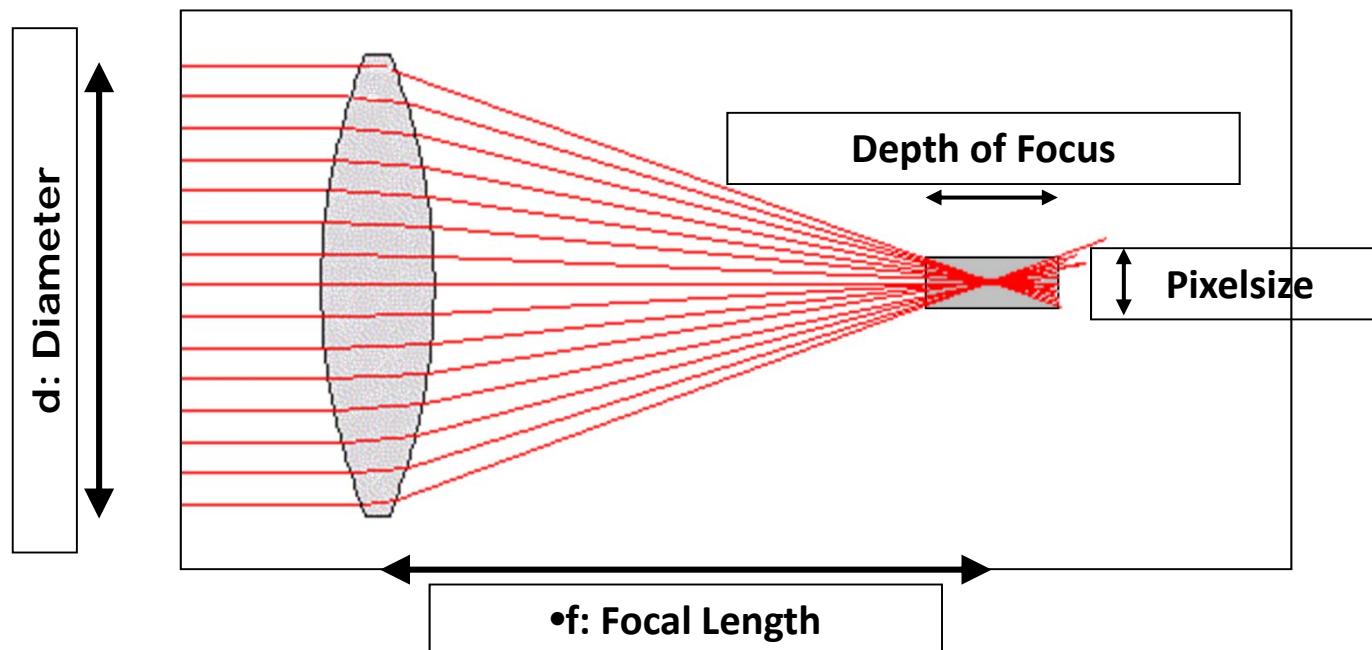
Depth of Focus (DOF)

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



Depth of Focus (DOF)

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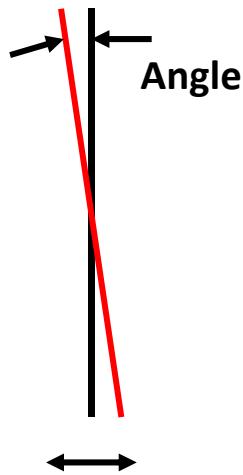


$$\text{DOF} = 2 * \text{Pixel size} * f / d = 2 * \text{Pixel size} * F/\#$$

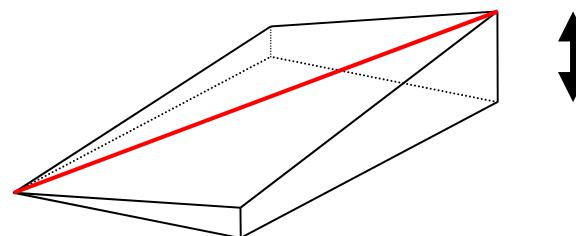


Tilt of the Sensor

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



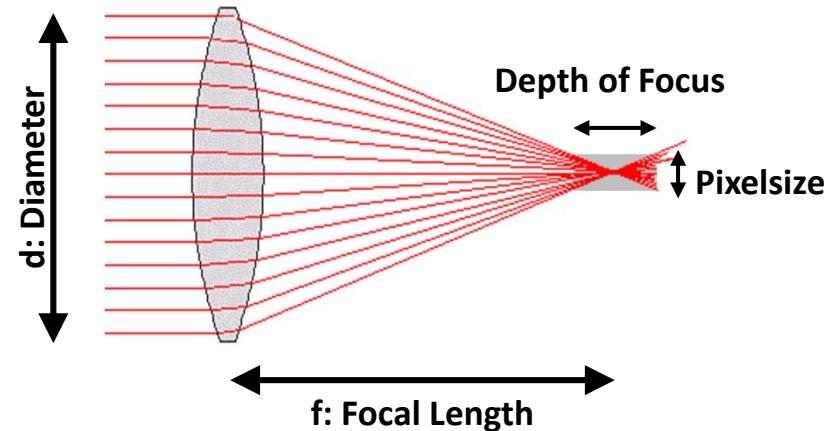
Examples of Geometrical DOF

Real numbers:

Pixel size = 5 μm

F/# = 4

Depth of Focus: $\pm 20 \mu\text{m}$ (40 μm)



Real numbers:

Pixel size = 4 μm

F/# = 2

Depth of Focus: $\pm 8 \mu\text{m}$ (16 μm)



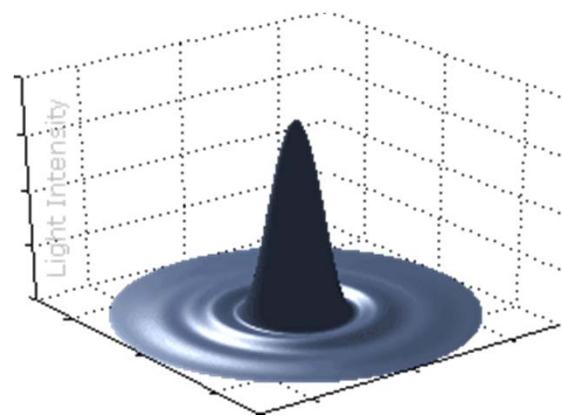
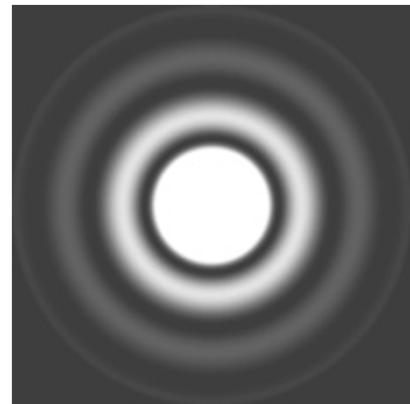
Diffraction

Due to the physical structure of light as an electromagnetic wave, the rays are blurred by diffraction.

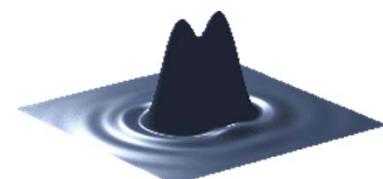
Diffraction depends on the F-number and wavelength λ .

$$\phi_{\text{Airy}} = 2.44 * \lambda * F/\#$$

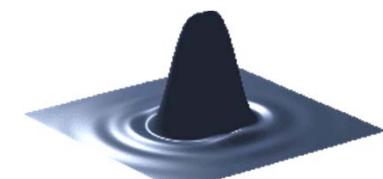
As a rule of thumb, the diameter of the Airy disc is $F/\#$ in microns, like $F/\#$ is 4, the diameter of the Airy disc is approx. 4 μm .



resolved



Barely resolved



No longer
resolved

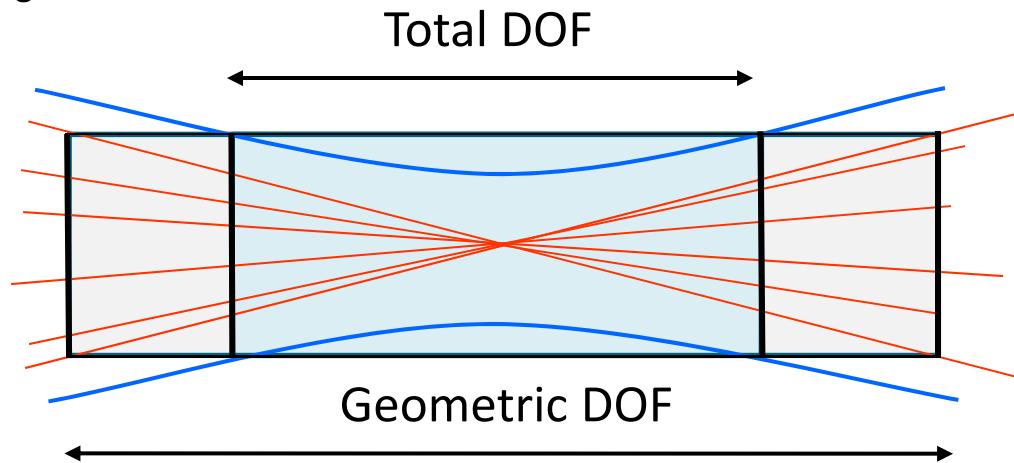


Real Spot-size and DOF

The real spot-size and DOF is the geometrics folded with the diffraction.

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

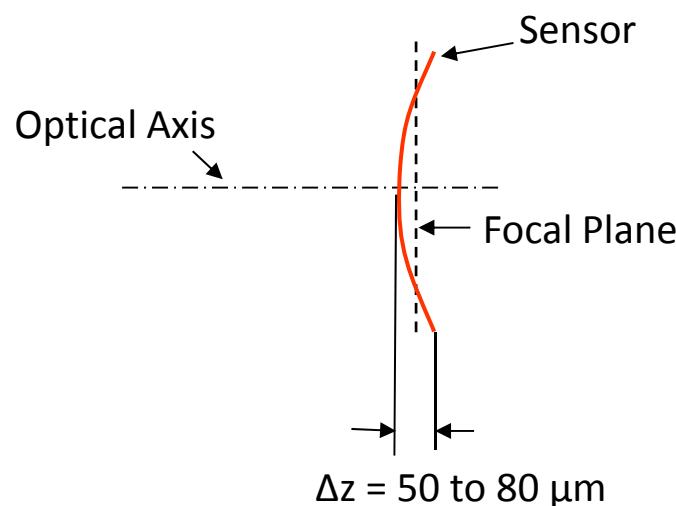
$$\phi_{\text{total}} = \sqrt{\phi_{\text{geom}}^2 + \phi_{\text{diff}}^2}$$



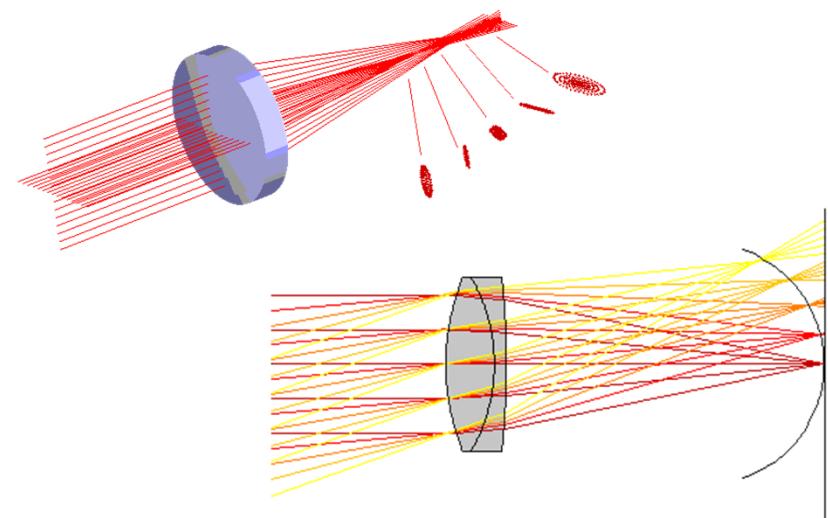
Errors of Higher Order

In case of an 8k line scan sensor with $10 \mu\text{m}$ pitch we might have a further issue:

The sensor might be bent by $\Delta z = 50$ to $80 \mu\text{m}$ (acceptable)

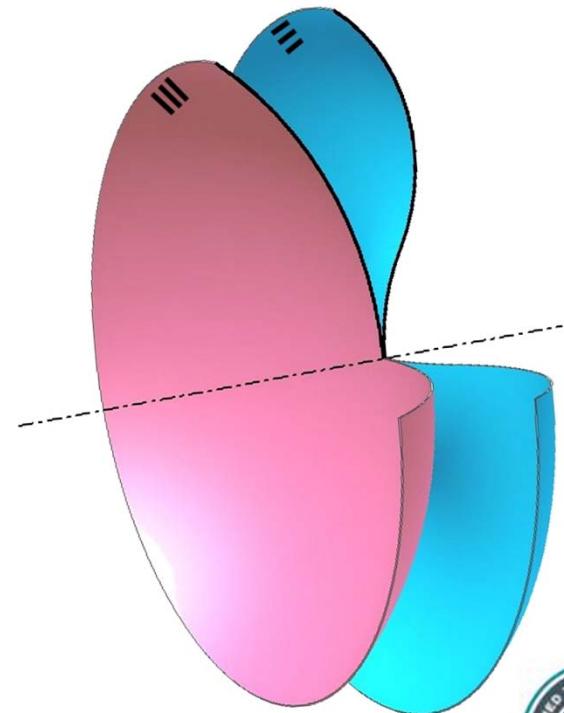
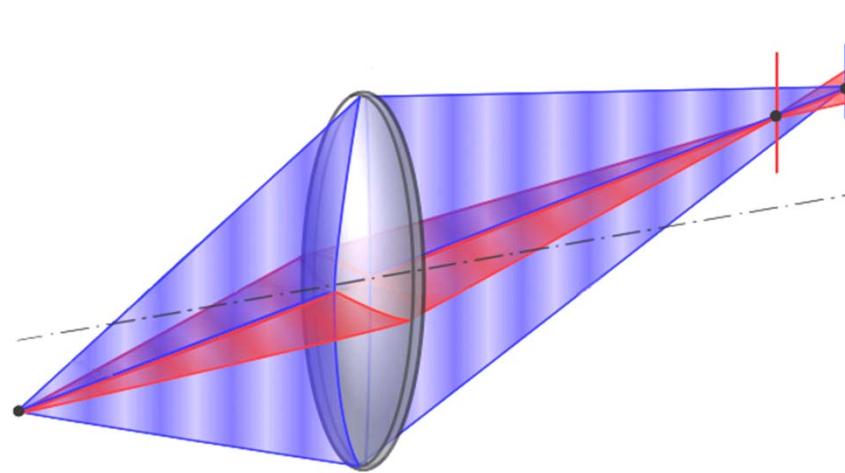


The lens (e.g. 5.6/90mm) will cause a field curvature of $\Delta z = 50$ to $100 \mu\text{m}$, whereas the astigmatism might occur and the meridional and sagittal focal plane might run the opposite direction.



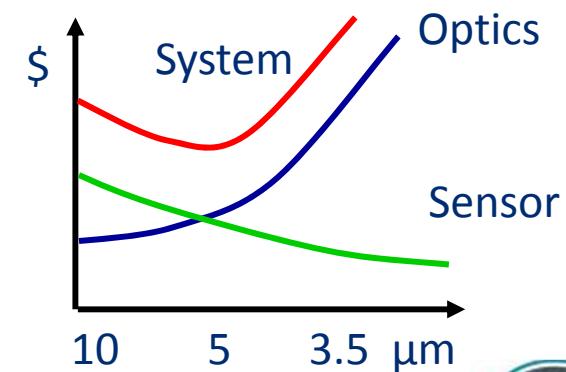
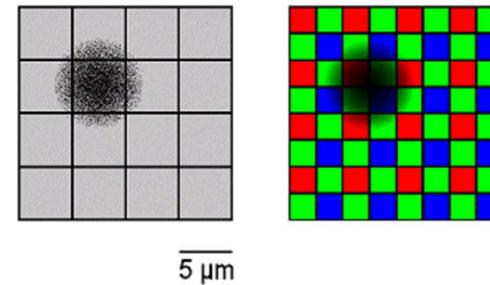
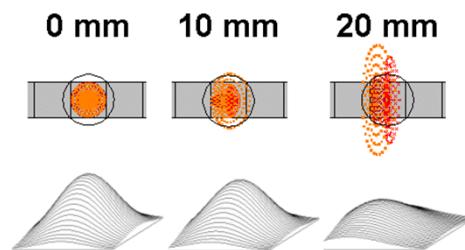
Field Curvature and Astigmatism

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).



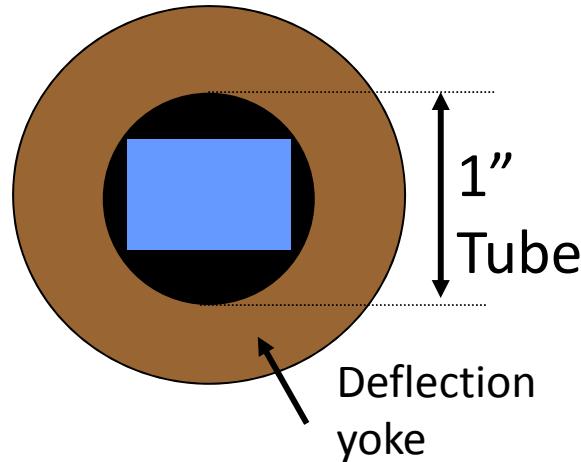
Pixel Size

- Pixels are mainly between 10 to 3.5 μm .
- Trend is toward smaller pixels, because they allow higher resolution with less silicon \rightarrow More sensors from a single wafer \rightarrow lower cost.
- "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.



CCD and CMOS Sensors

Image Format

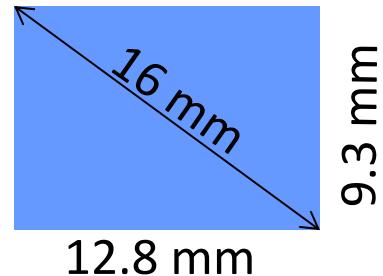


1" format

Sony: Type 1

Diagonal: 16 mm

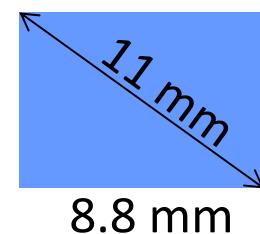
Image
size



2/3" format

Type 2/3

11 mm

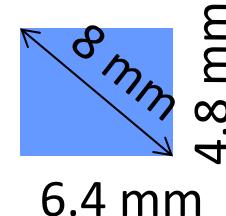


1/2" format

Type 1/2

8 mm

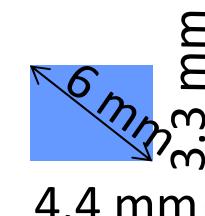
6.6 mm



1/3" format

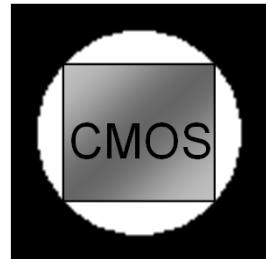
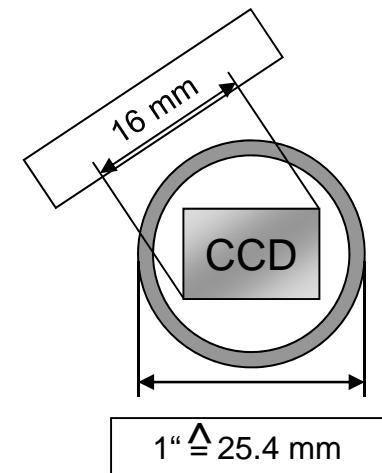
Type 1/3

6 mm



Optical Sizes

- In case of C-mount lenses are usually restricted to 2/3" optical format imagers. Longer focal length or higher f-stop lenses may work up to 1" format
- The CMOSIS sensor 2MP is 2048 x 1088 pixels with a 12.75 mm in diagonal and fits 2/3" optical format. The 4MP sensor is 2048 x 2048 pixels, with a diagonal of 15.93 mm requiring a 1" format lens.
- The 4 MP sensor must use proper lenses! Otherwise there is a shading or vignetting seen in the image.



16 mm sensor with 1" format



16 mm sensor with 2/3" format will cause vignetting



Recommended Mechanical Interfaces (Mounts)

Class	Min. Image Size [mm]	Max. Image Size [mm]	Optical Size [type]	Mechanical Interface (1st Choice)
I	0	4	$\approx \frac{1}{4}$	C-, CS-, NF-, S-Mount
II	4	16	≈ 1	C-, CS-, NF-, S-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 check with JIIA LER-004-2010 for more details.



Questions?



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