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Building the Eyes of a Vision System: From Photons to Bits

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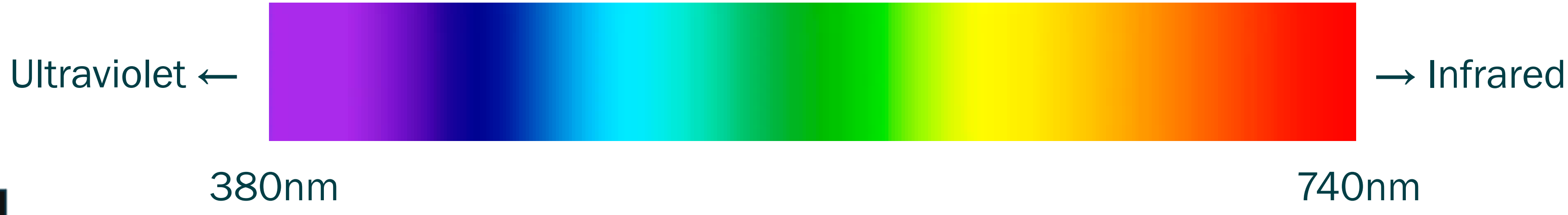
GoPro

Light Basics

What is Light?

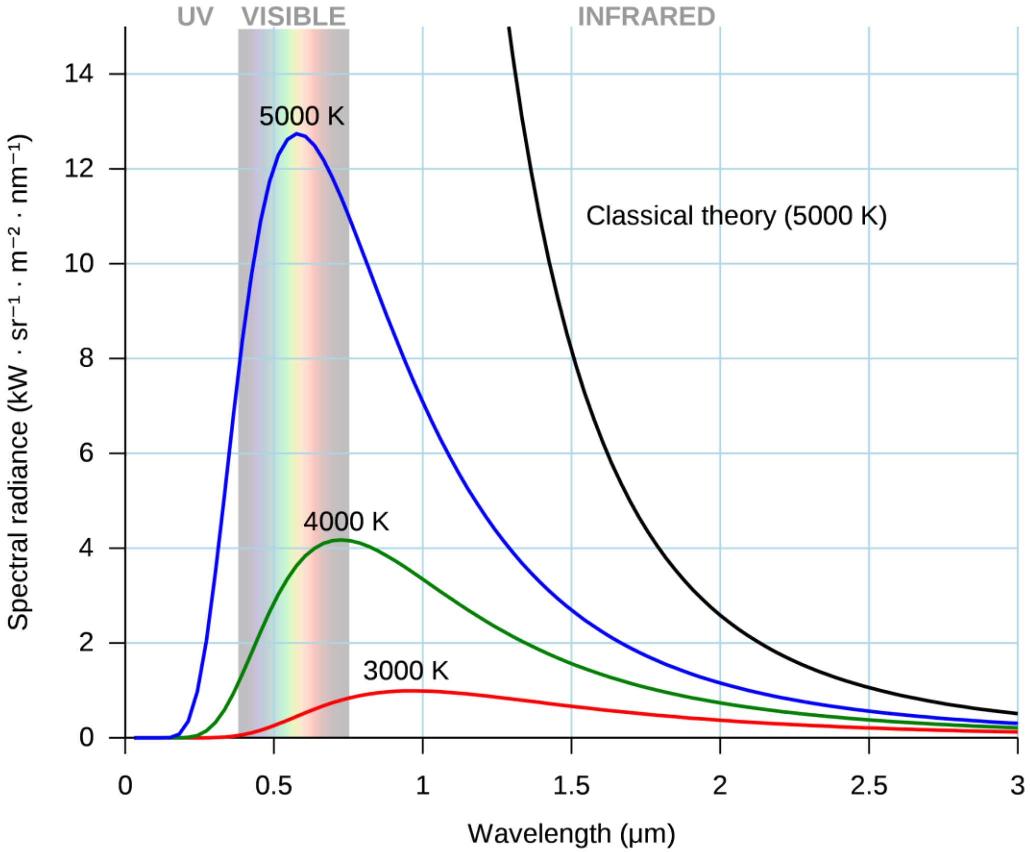
- Light is represented as both a particle and an electromagnetic wave
  - When discussing sensors we tend to rather casually switch between the two
- A photon = a light particle
- The energy determines wavelength (higher energy = shorter wavelength)
  - Energy (J) = Planck’s constant (Js) x speed of light (ms^{-1}) / wavelength (m)
- When visible (to human beings), we perceive wavelength as color
- Intensity of light = number of photons



Bands of Light

- **Visible: 380-740nm**
    - Sensors: CCDs and CMOS image sensors (CIS)
- **Near Infra Red: 0.74µm – 1µm**
    - Sensors: CCDs and NIR-enhanced CIS
- **SWIR: 1-2.5µm**
    - Sensors: InGaAs sensors
- **MWIR: 3-5µm**
    - Sensors: Indium Antimonide, Mercury Cadmium Telluride (HgCdTe), III-V semiconductor superlattices
    - Thermal imaging
- **LWIR: 8-14µm**
    - Sensors: Microbolometers, HgCdTe
    - Thermal imaging

Black body radiation as governed by Planck's equation



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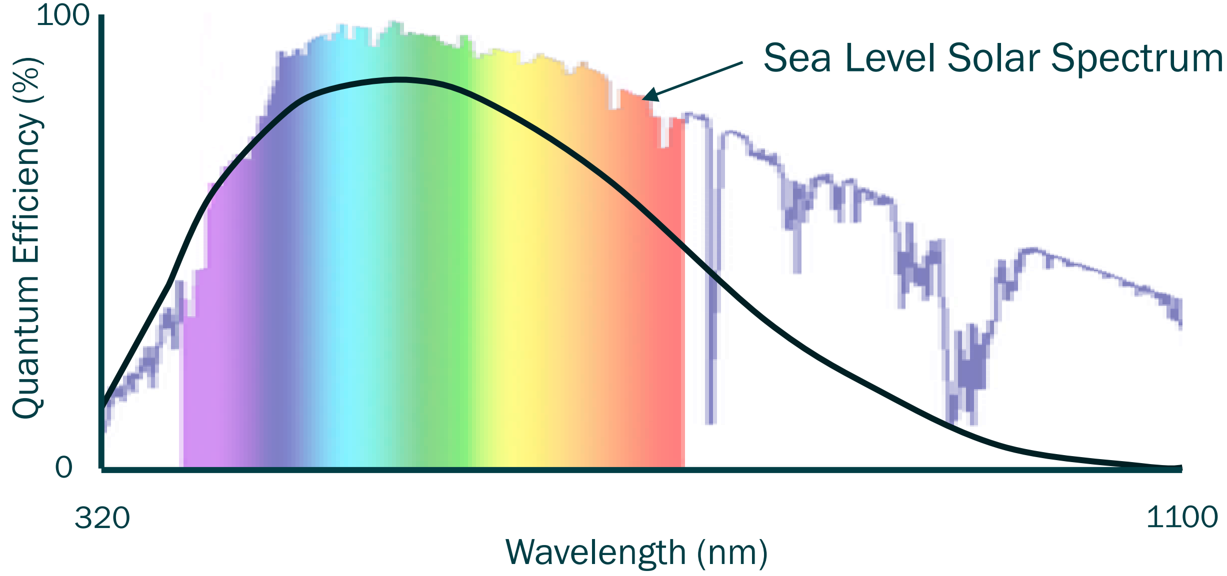
Quantum Efficiency

- Quantum Efficiency (QE) is the ratio of number of electrons collected to the number of photons incident
- QE is sensor specific, and is frequently normalized (“Relative QE”) to obscure IP
- The peak QE of silicon aligns nicely with the peak response of human vision @555nm



Typical Silicon Sensor QE

CMOS Image Sensors

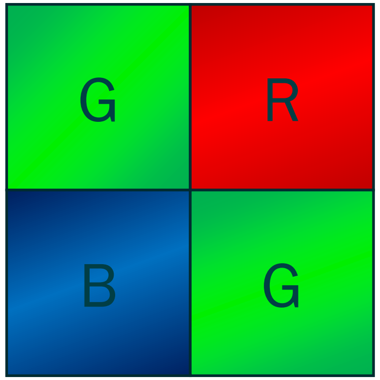
CMOS Image Sensors (CIS)

- Leverage Complimentary Metal Oxide Semiconductor (CMOS) manufacturing processes
- Each pixel contains a photodiode and a current amplifier ("active pixel sensor")
- Very high level of integration (SOC)
  - On-chip ADCs, timing control, voltage conversion, corrections (black level, defective pixels, etc.)
- **Major Types:**

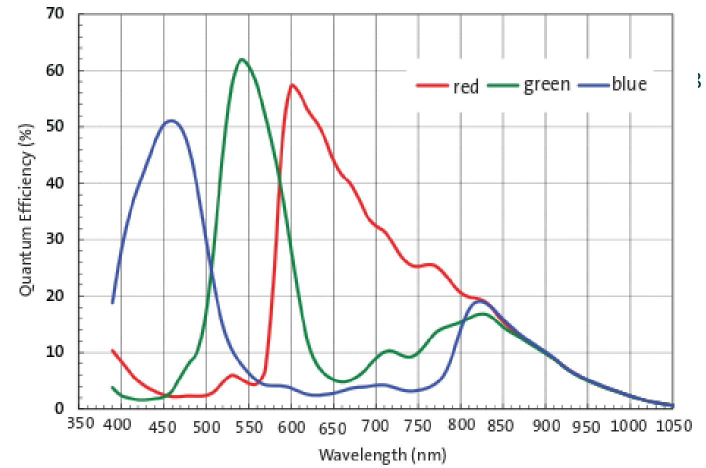
Type	What is it?
Rolling shutter	Each row of pixels start gathering light, and then are read out one at a time. Prone to motion artifacts
Global shutter	All pixels start gathering light and are then read out simultaneously. Avoids rolling shutter artifacts
Front-side illuminated	Wiring is built on top of the silicon. Light has to "navigate" this stack to reach the photodiodes
Back-side illuminated	The silicon is flipped over and thinned (to a few-microns). Light can now reach the photodiodes without having to pass through the wiring layers
Stacked sensors	Silicon wafers are bonded together. Interconnects formed between sensing layer and ASIC layer. Allows more sophisticated circuitry and functions, which can be fabricated using optimal processes

Sensor Color Filters & Micro-Optics

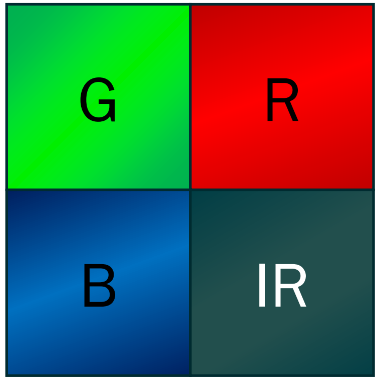
- Silicon cannot differentiate wavelengths
- To detect color, a filter is placed over each detector site
- Demosaic algorithm interpolates missing colors to generate RGB for each location
- Novel filters patterns can be used for specialist applications, like CCCR (C= clear), RGB+IR (IR = infrared pass filter)
- A “microlens” on top of each photodiode focuses light to maximize sensitivity
- Microlens positions often varied across the imaging array to compensate for incoming light angle



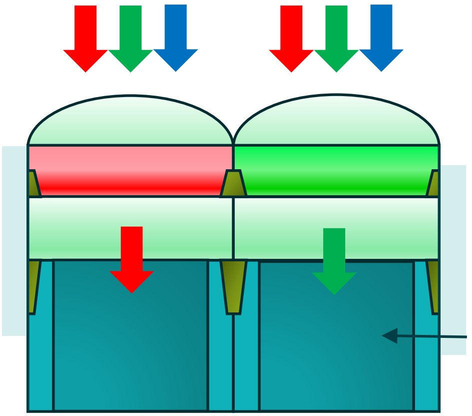
Bayer Color Filter Pattern



Quantum Efficiency for Color Sensor



RGB-IR Color Filter Pattern



Microlens Array

Color Filter Array (CFA)

Photodiode

Noise Sources in CMOS Image Sensors

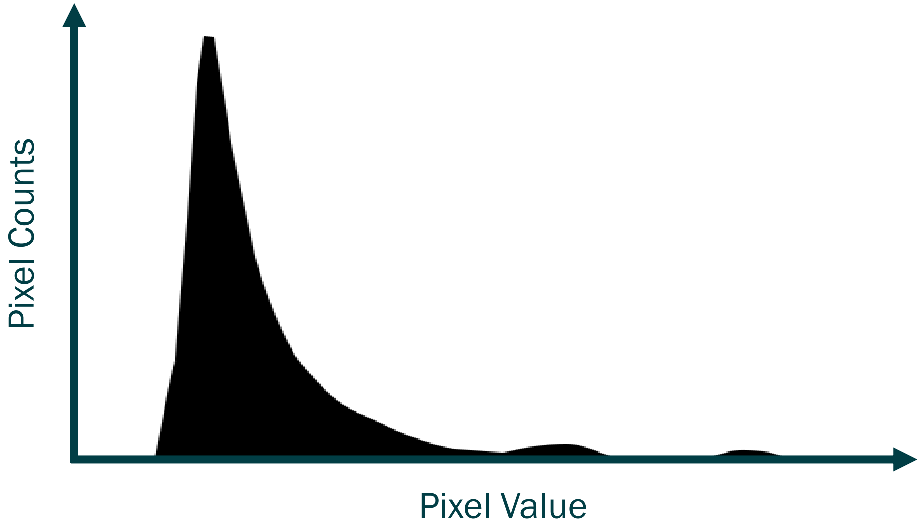
- CMOS sensors have characteristic noise sources that impact image quality, particularly in low light
- While most of these have improved from generation to generation, their impact on vision system performance should be considered
- Poor circuit design (power supplies and PCB layout) and sensor heat sinking can exacerbate some of these noise components
- Signs of poor circuit design:
  - Elevated row temporal noise
  - Elevated read noise
- Signs of poor thermal design:
  - Increased hot pixel counts (see slide 11)
  - Increased dark signal non-uniformity (DSNU)
  - Decreased black offset stability

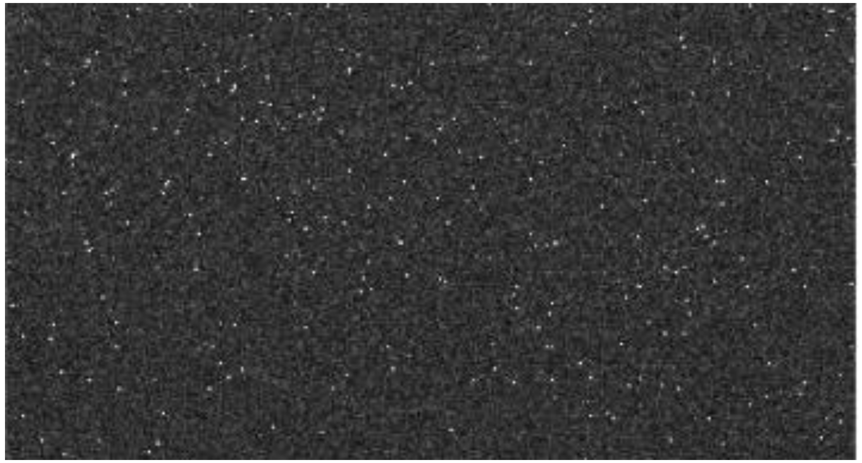
Noise Sources in CMOS Image Sensors (Continued)

Noise Type	Description
Photon shot noise	Noise that is intrinsic to the quantum nature of photons Uncertainty in measurement Shot noise is proportional to SQRT of number of photons
Read noise	Root mean square noise of the sensor circuitry
Row temporal noise	Per row variation in the black offset. Visible below the pixel temporal noise floor (e.g., visible down to ~1/15th read noise)
Column fixed pattern noise	Per column offsets in black level. Fixed in location due to semiconductor process variations. Visible well below the pixel temporal noise floor (e.g., visible down to ~1/20th read noise)
Photo response non-uniformity	Pixel to pixel variation in sensitivity (gain error). Tends to show up during camera pans. Can be corrected with a per-sensor gain correction (multiply per pixel), but this is rarely done
Black level flutter	Black offset (pedestal) changes from frame to frame. Mostly seen at high gains and in very low light

Hot Pixels

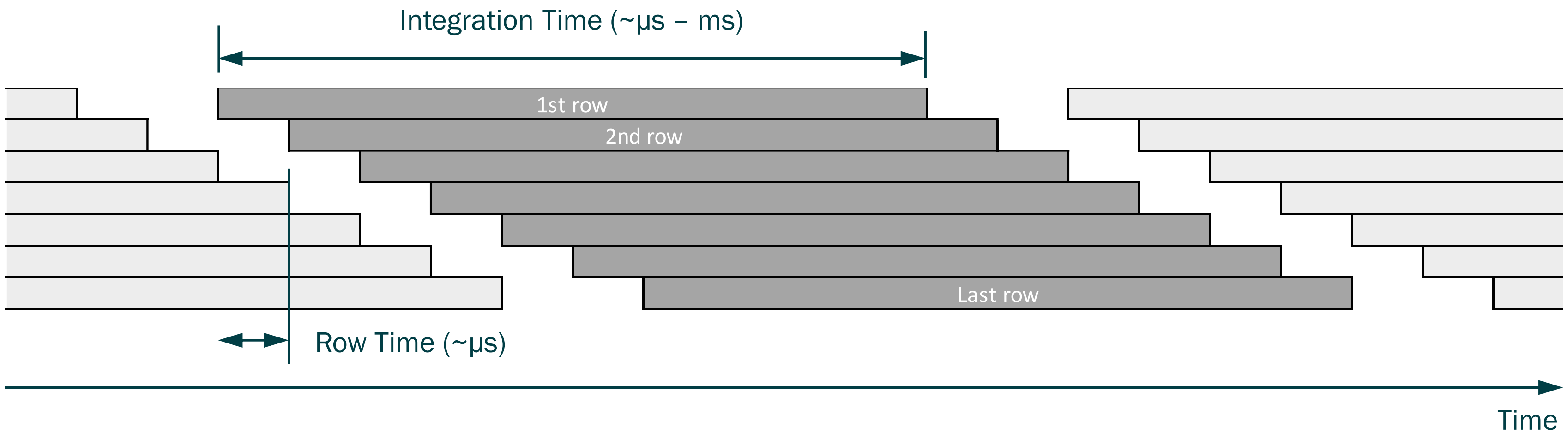
- Pixels with high leakage
- Bright pixels in images captured in the dark with long exposure and/or high temperature
- Need correcting (really hiding) by the image processing pipeline
  - Static map programmed at factory
  - Dynamic detection and correction
  - Replace with average of neighboring pixel values (in the same color plane)
  - See: “Adaptive pixel defect correction”, A. A. Tanbakuchi, et. al, *Proceedings Volume 5017, Sensors and Camera Systems for Scientific, Industrial, and Digital Photography Applications IV*; (2003)



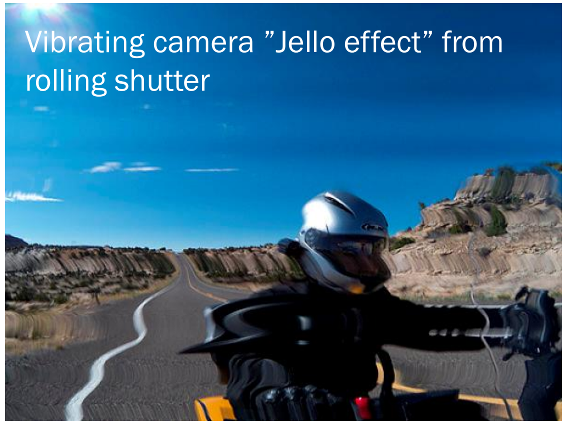


Global vs Rolling Shutter

- Global shutter:
  - All sensor rows capture light at the same time
  - Requires larger pixels, and (to date) has higher read noise
- Rolling shutter:
  - Each row reset one at a time, then read out n row periods later
  - Lowest read noise
  - Creates rolling shutter artifacts (moving object distortions, “jello effect” from camera vibration)



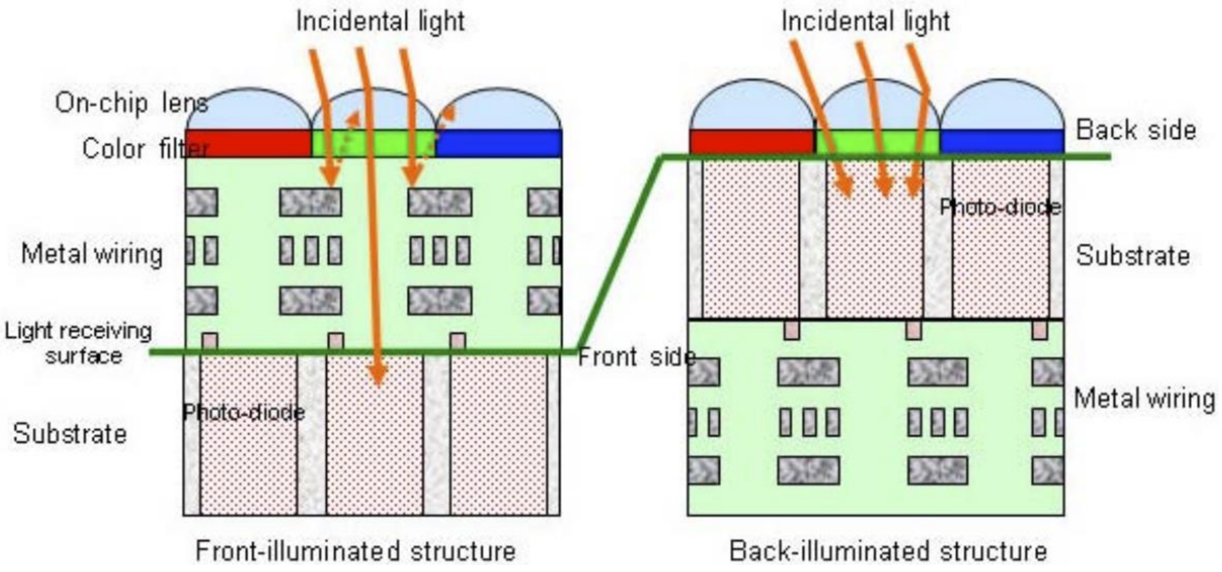
Rolling shutter temporal aliasing with spinning propeller



Vibrating camera ”Jello effect” from rolling shutter

Front-Side Illumination vs Back-Side Illumination

- Front-side illumination (FSI) sensors have the photodiode below the metal wiring
  - Impacts sensitivity, acceptance angle, optical cross talk (photons being captured by the wrong photodiode)
- In back-side illumination (BSI) sensors the wafer is flipped and bonded to a blank wafer, or an ASIC layer, and thinned
  - The color filter array and microlenses are built on top of the thinned photodiode layer



In FSI (left) metal impedes the optical path to the photodiode. In BSI (right), the optical stack height is minimized

Key Sensor Specifications Impacting Image Quality

- Full well capacity (really linear full-well capacity)
  - Small pixels: 5,000 electrons
  - Medium pixels: 10,000 electrons
  - Large pixels: 50,000 electrons
- Sensitivity
  - Voltage swing per lux-s
- Read noise
  - The noise floor measured in electrons
  - Small-pixel, low noise sensors have read noise ~2 electrons
- Resolution
  - Resolution is really a measure of linear resolving power, but colloquially it is equated with pixel count
  - Higher resolution means higher spatial sampling of the optical modulation transfer function (MTF)

Image Quality Metrics

- Signal to noise ratio
  - Ratio of the signal from photons collected to unwanted noise
  - SNR*n*: the number of lux (light flux per unit area) to achieve an SNR of *n*
- Dynamic range
  - Ratio between the max. output signal level and noise floor
  - Sensor companies typically misrepresent this as:
    - Max. output signal at minimum analog gain / noise floor at max. analog gain
    - This is unachievable within a single frame
  - $dB = 20 \times \log\left(\frac{Brightest\ Lux}{Darkest\ Lux}\right)$
- Resolution
  - Not just about number of pixels. More formally is a measure of the smallest features that can be resolved. Described in more detail later

Illuminance (Lux)	Scene
0.2 - 1	Full moon
100	Dim indoor
500 – 1,000	Office
10,000– 30,000	Outdoors, cloudy
100,000	Direct sunlight

Ratio of Brightest/Darkest	Dynamic Range (dB)
10	20
100	40
1,000	60
10,000	80
100,000	100

Image Sensor Interfaces

- MIPI:

MIPI Type	Key Attributes
D-PHY	Dominant interface in cell phones for last decade Up to 4 differential paired lanes, and separate clock lane Up to 10Gbps Adopted in automotive and other applications
C-PHY	Higher speed cell phone sensor interface Up to three 3-wire lanes (called "trios") Likely to become the dominant interface for high-speed sensors Up to 41Gbps in v2.0
A-PHY	New standard for automotive sensors Up to 16Gbps in v1.0, with a roadmap to 48Gbps 15 meter range Safety enhancements

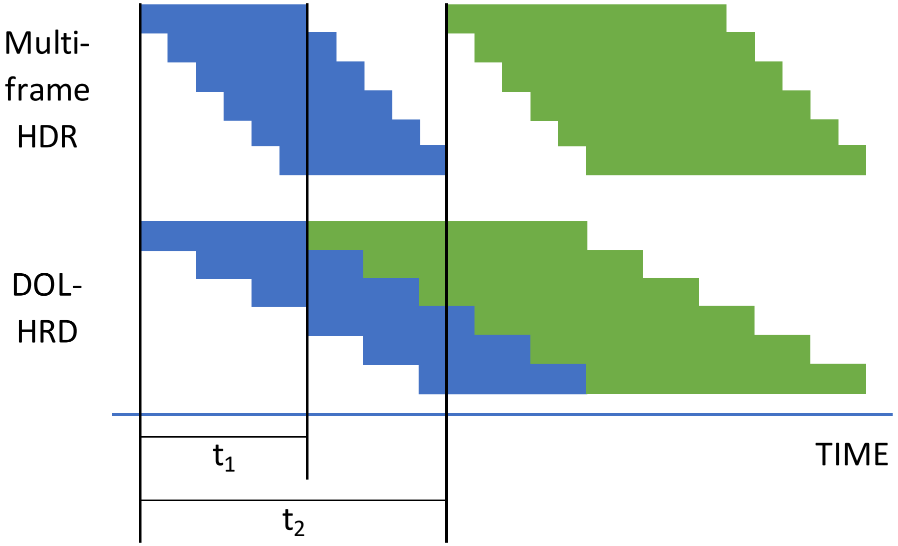
- Various proprietary LVDS, subLVDS, and SLVS interfaces
- It is important to select a sensor that interface directly with your SOC, or accept added cost and power of a bridge chip

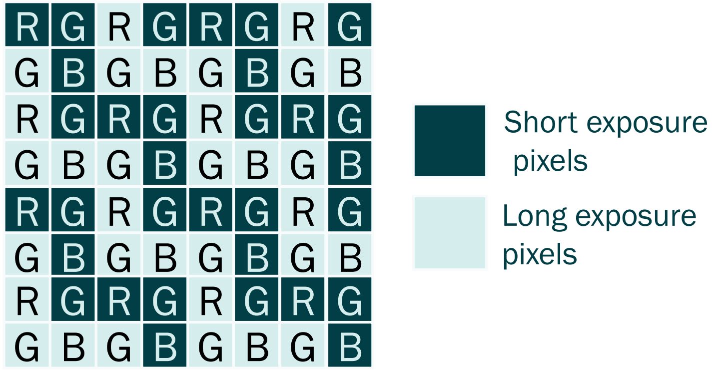
High Dynamic Range (HDR) Sensors

- Typical commercial sensors have a dynamic range around 70dB
- HDR sensors use a multitude of techniques to extend the dynamic range that can be captured
- Multi-frame HDR: capture sequential frames with long and short exposure times
  - Long exposure captures the shadows
  - Short exposure captures the highlights
  - Stitch the frames together to create a single higher dynamic range frame with higher bit depth
  - For scenes with motion, this technique can result in significant motion artifacts (ghosting)

High Dynamic Range (HDR) Sensors - II

- Overlapping multi-frame exposure
  - Multiple exposures are produced on a line-by-line basis, rather than frame by frame
  - Greatly reduces the motion artifacts by minimizing the time delta between the different exposure read outs
- Spatially interleaved methods
  - Multiple exposure times are captured simultaneously by varying the exposure time of different groups of pixels (alternate lines, zig-zag pattern, etc.)
  - Almost eliminates HDR motion artifacts, but reduces resolution and creates aliasing artifacts on high contrast edges





R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B

■ Short exposure pixels

□ Long exposure pixels

Sony SME HDR

High Dynamic Range (HDR) Sensors - III

- Dual conversion gains
  - Technology that allows the pixel gain (µV/e-) to be switched between two values
  - Can be used in a multi-frame, or spatially interleaved manner with similar characteristics, but improved noise (as there is no short exposure throwing away photons)
- Logarithmic pixels
  - Pixel has a logarithmic response, or a logarithmic response region, that extends dynamic range compared to a linear pixel
  - Mismatches between the pixel response curves and changes with temperature can create high fixed pattern noise and high photo-response non-uniformity
- Overflow pixels
  - Pixels that contain an overflow gate that allow charge (electrons) to flow to a secondary overflow node
  - Requires additional per-pixel storage node, and control line. Means the technology only works for larger pixels (~6µm)

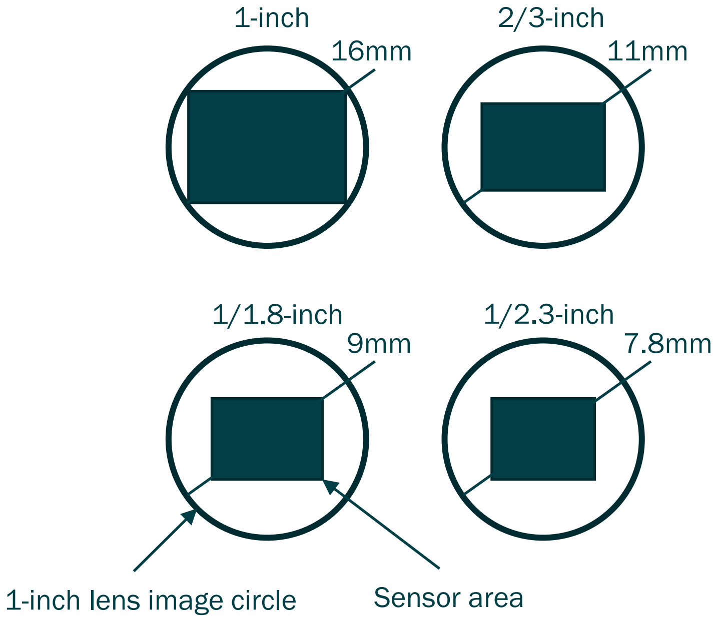
Optics for Image Sensors

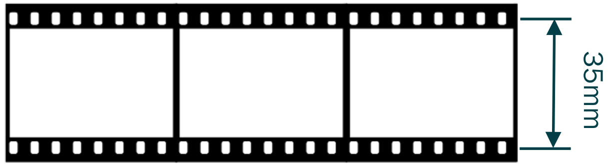
Matching Optics with a Sensor: Overview

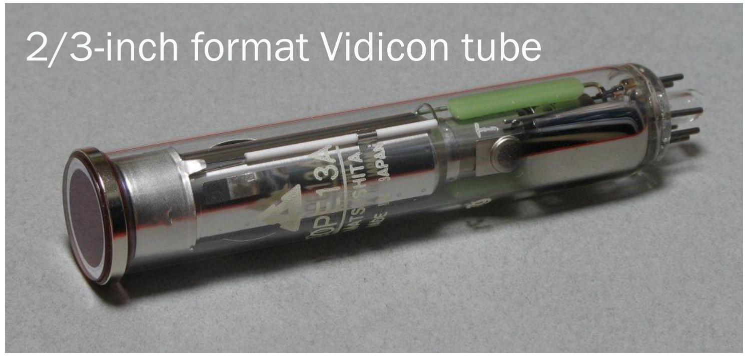
- Optical format
- Chief ray angle
- Focal length
- Magnification
- Field of view
- F-number
- Depth of field
- Wavelength range
- Modulation transfer function
- Relative illumination
- Stray light

Optical Format

- Optical format is probably not what you think!
- A 1/2.3-inch format sensor does not have a diagonal of 1/2.3” (11.04mm). It’s actually 1/3.2” (7.83mm)
- Convention is legacy of imaging tube technology, where the stated format was the mechanical diameter of the tube
- Optical format ~3/2 x sensor diagonal
- From film cameras, “35mm format” is 36mm x 24mm (43mm diag.)
  - 35mm is the pitch between the feed sprocket holes
- The lens and sensor optical formats must be matched
- Smaller sensor optical format is okay, but this will crop the field of view, and may create a CRA mismatch issue (more on this later)







2/3-inch format Vidicon tube

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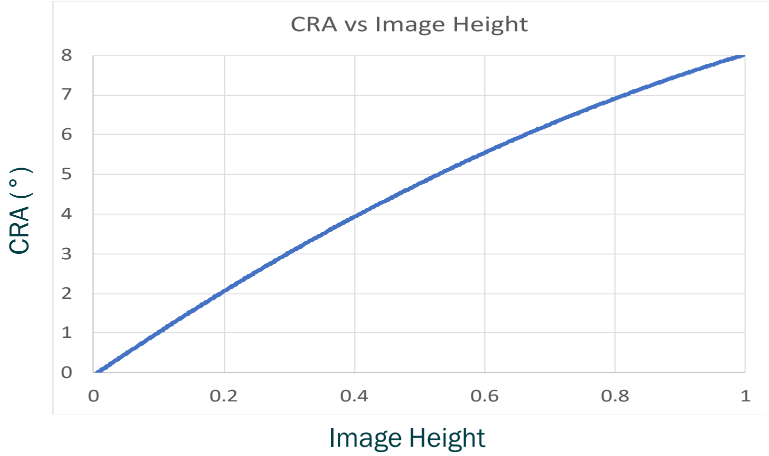
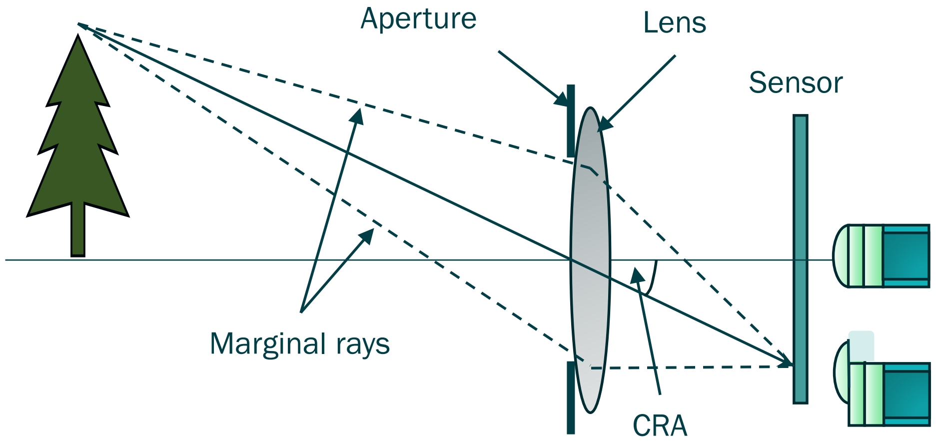
Chief Ray Angle (CRA)

- The angle of light rays that pass through the center of the exit pupil of the lens relative to the optical axis
- Often quoted as a number (for the maximum CRA), but it’s actually a curve
- The microlenses on a sensor are (typically) shifted to compensate for the anticipated change in CRA across the array
- Mismatched lens and sensor CRA can lead to luma and chroma shading
  - Match for 1µm pitch pixels should be within ~2°
  - Match for 2µm pitch pixels should be within ~5°





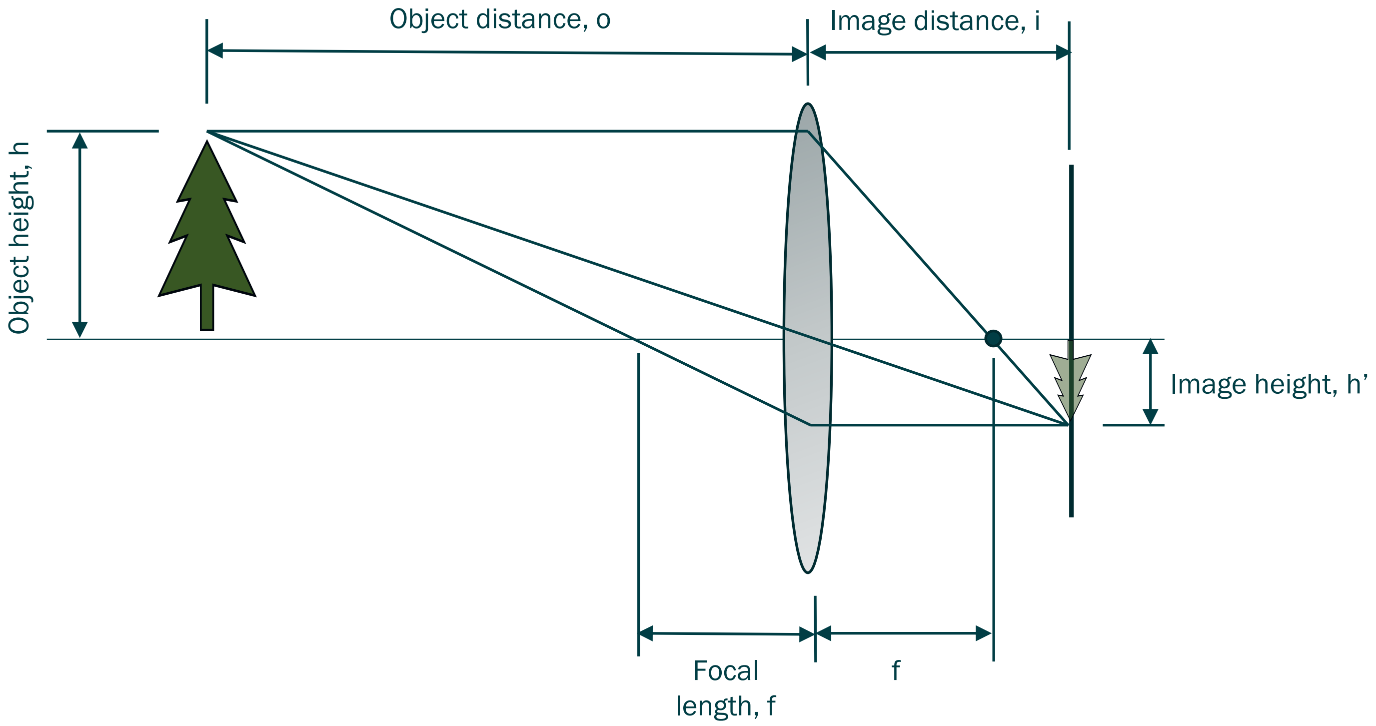
Focal Length & Magnification

- Focal length is a measure of how strongly the system converges (or diverges) light
- Thin lens approximation:

$$\frac{1}{o}+\frac{1}{i}=\frac{1}{f}$$

- Magnification, M:

$$M=\frac{-i}{o}=\frac{h'}{h}$$

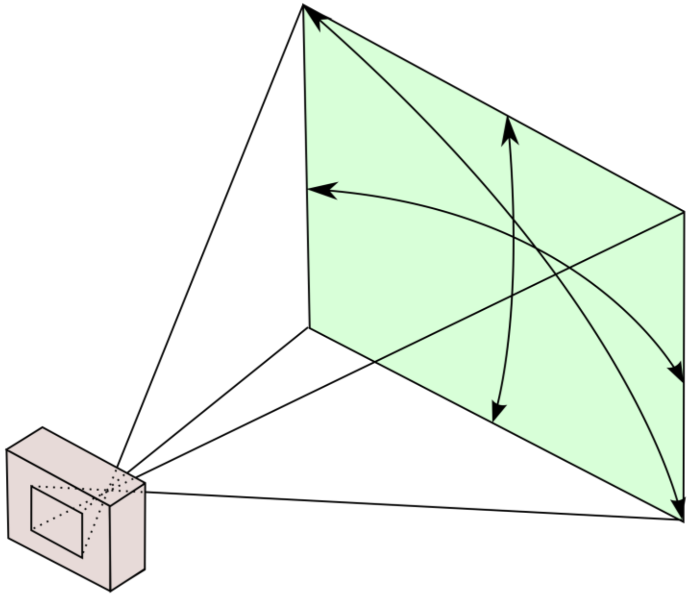


Field of View (FOV)

- FOV is determined by focal length and distortion
- For a rectilinear lens (one where straight features form straight lines on the sensor) the field of view, α, is:

$$\alpha = 2\arctan\frac{d}{2f}$$

- Where d = sensor size, and f = focal length
- This is true so long as the object distance >> the lens focal length
- For lenses with non-rectilinear distortion (like GoPro lenses) the calculation gets more complex
- FOV is quoted as the diagonal FOV (DFOV), horizontal FOV (HFOV), or vertical FOV (VFOV)
  - Sometimes without defining which is being used



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F-Number

- Ratio of focal length to the diameter of the entrance pupil
  - Entrance pupil is the image of the physical aperture, as “seen” from the front (the object side) of a lens

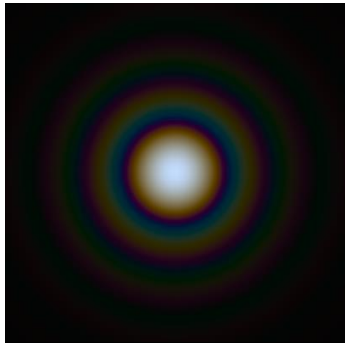
$$N = \frac{f}{D}$$

- The smaller N, the more light reaches the sensor
- A lens with a smaller f-number is often referred to as a “faster” lens, because it permits a faster shutter speed
- “Stop” scale for f-number with each stop being 1/2 the amount of light passing through the optical system:

N	1.0	1.4	2	2.8	4	5.6	8	11	16	22	32

F-Number & Resolution Limits

- Diffraction of light by the aperture creates a lower “diffraction limit” to the resolution of the camera
  - This is another quantum mechanical effect
- A circular aperture creates an “Airy disc” pattern of light on the image sensor
- The smaller the aperture, the larger the airy disc
- For small pixels, or lenses with high f-numbers, real world performance can be limited by the diffraction limit
- Diameter of Airy disc to first null, d:
  - $d = 2.44\lambda N$
  - Where λ = wavelength and N f-number
- Table on right shows minimum resolvable pixel size vs f-number
  - This is for edge detection. For imaging points (like stars) the limits are higher



Simulated Airy Disc for white light

By SiriusB - Own work, CC0, https://commons.wikimedia.org/w/index.php?curid=68302545

F-Number	Blue (430nm)	Green (550nm)	Red (620nm)
1.0	0.41µm	0.50µm	0.56µm
1.4	0.57µm	0.70µm	0.78µm
2	0.81µm	0.99µm	1.12µm
2.8	1.14µm	1.39µm	1.57µm
4	1.63µm	1.99µm	2.24µm

Depth of Field (DoF)

- Depth of field is the distance between the nearest and farthest objects that are acceptably in focus
- $DoF \approx \frac{2o^2\mathrm{Nc}}{f^2}$
- Where o = object distance, N = f-number, c = circle of confusion (acceptable blur circle), f = focal length
- DoF increases with:
    - Focus distance (squared)
    - Circle of confusion
    - F-number
        - At the cost of light reaching the sensor, and the diffraction limit
- DoF decreases with:
    - Focal length (squared)
        - A shorter focal length lens has a larger depth of field. So either a wider FOV, or a smaller sensor will increase the DoF

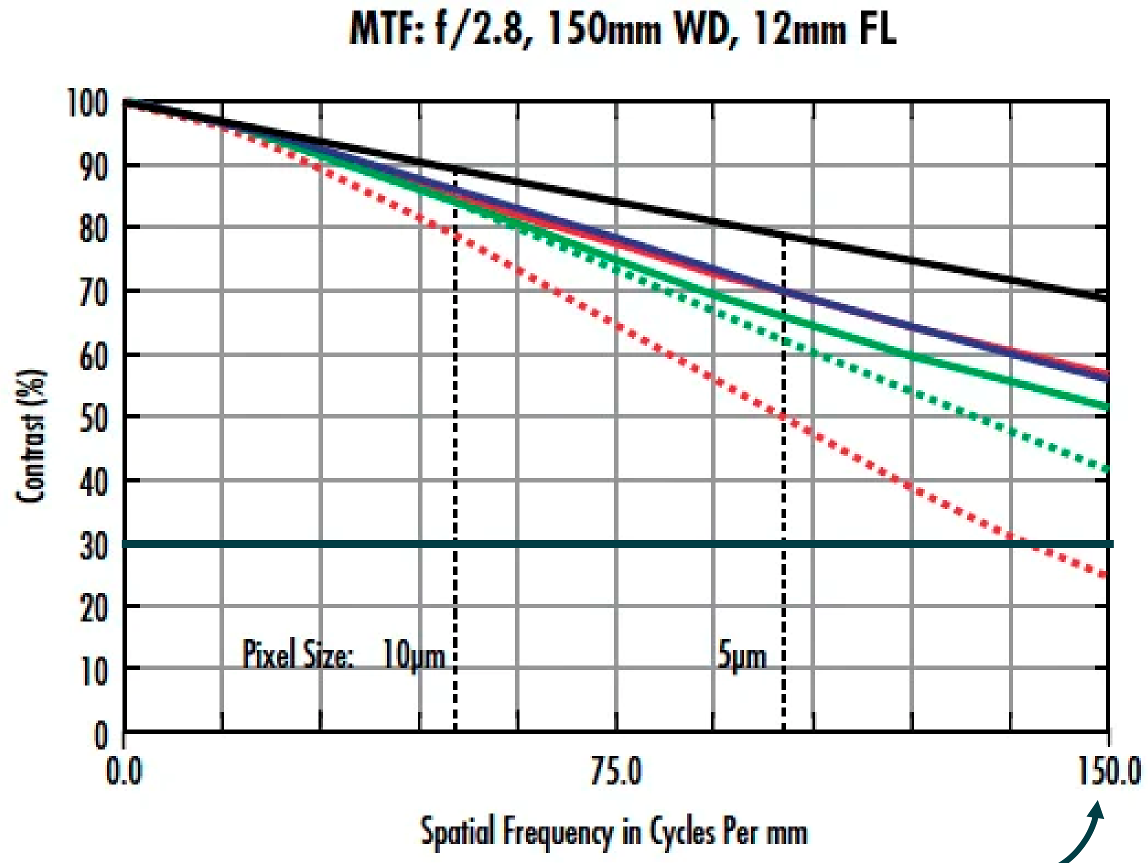
Wavelength Range

- A lens is designed for a specific wavelength range
- The wider the wavelength range the more difficult the design becomes
  - Leading to higher cost/performance ratio
- A lens designed for visible light will have poor performance in the NIR, and visa versa
- So a lens should be selected to match the application
- A camera for NIR only, should use a NIR lens
- If using visible + NIR, a lens designed for the full wavelength range should be selected

Modulation Transfer Function (MTF)

- MTF is a measurement of the sharpness and contrast of a lens over a range of spatial frequencies (starting at 0)
- MTF plots allow a lens to be evaluated for a particular application, and lenses to be compared
- A MTF score of 30% means that an edge will be well resolved
- Horizontal axis is line pairs per mm. Higher lp/mm -> smaller features
- The highest spatial frequency that can be sampled by the image sensor is:

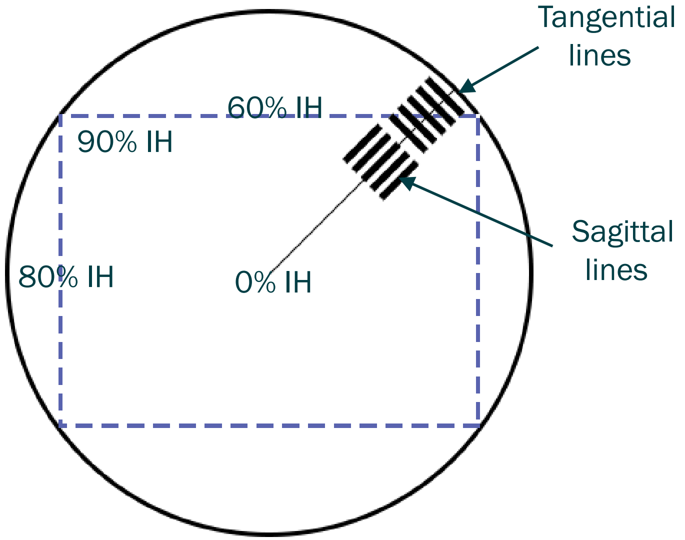
$$\frac{lp}{mm} = \frac{1000\,\frac{\mu m}{mm}}{2\ x\ Pixel\ Size\ (\mu m)}$$



Resolving limit for 3.45µm pixels

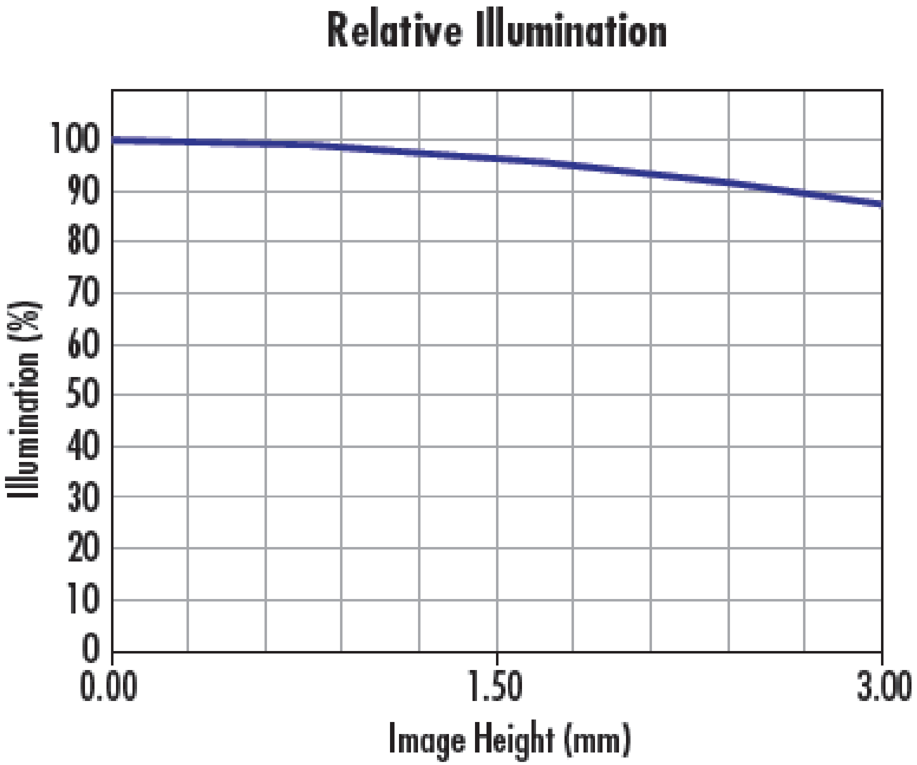
MTF (Continued)

- This type of MTF plot typically contains lines for various image heights
  - For example 0% IH, 60%IH, 90% IH
  - This allows MTF in the center, middle, and corners of the image to be assessed
- Plots typically show different lines for sagittal and tangential directions
- Alternative plots show MTF vs image height for specific spatial frequencies
- Warning on MTF:
  - Unless stated, quoted MTF is for an “as designed” lens, without manufacturing tolerances
  - Actual ”as built” MTF will always be worse that this
    - This can be simulated using Monte Carlo simulations, and measured on optical test equipment



Relative Illumination (RI)

- Relative illumination (RI) is a measure of the roll-off in light intensity from the center to the edge of the lens image circle
- Often stated as a single number, being the RI at 100% image height
- Plot on right is for a lens with a 88% RI
  - This is very good, a typical mobile phone lens, by contrast, will have an RI <30%
- This shading effect means corners will be noisier (lower SNR) than the center of the image
- The sensor will also have some roll-off in sensitivity with CRA, so camera RI is the product of the lens RI and the sensor roll off
- RI can be corrected by applying a spatially-varying normalization function, but this amplifies noise in the corners



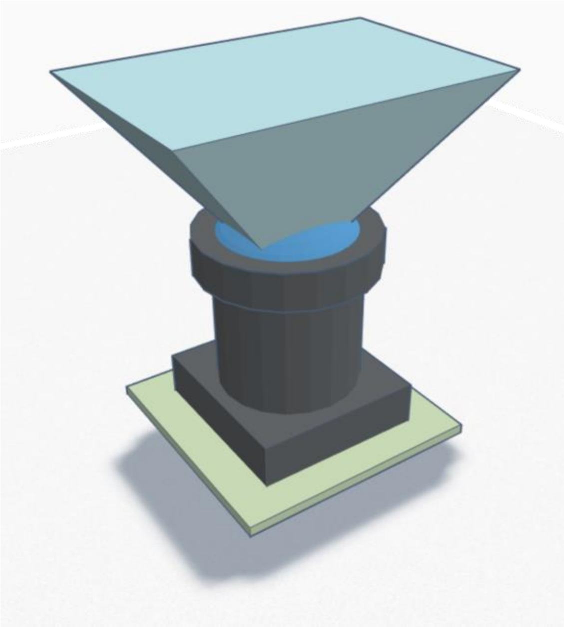
Stray Light & Ghosts

- Stray light is light scattered within the optical system that reduces contrast
- Ghosts are spatially localized reflections that can obscure details or confuse machine vision
- Sources include:
  - Imperfect anti-reflective coatings
    - Typical coatings on glass lens elements reflect <0.3% of normal incident light
    - Typical coating on plastic lens elements reflect <0.4% of normal incident light
  - Edges of lens elements (sometimes inking helps)
  - Mechanical surfaces (can be blackened or textured)
  - Diffraction off the image sensor
  - Dirt and oils on optical surfaces
- Can be simulated using full lens design and special tools (Fred, LightTools, ASAP)
- Can be measured in lab using a point light source (fiber bundle) and a robotic stage to rotate the camera

Faux stray light rendered in Adobe Photoshop. Subjectively good for art, bad for object recognition

Vignetting

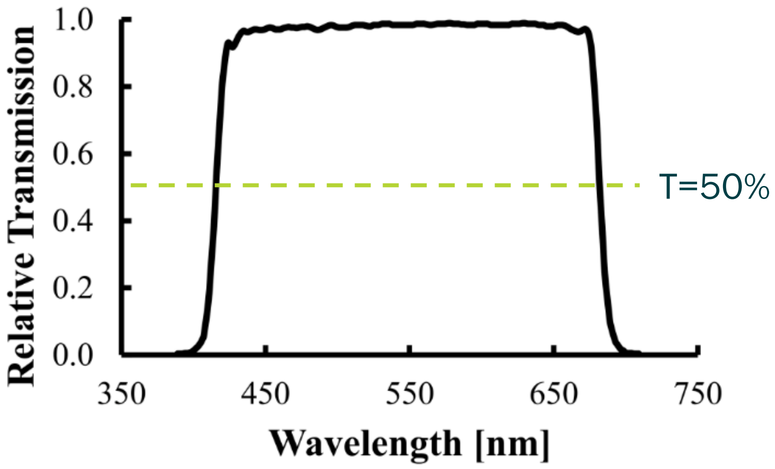
- Vignetting is unintended blocking of light rays towards the edge of the image
- Check all mechanical features for possible blocking
  - Filter/window holders
  - Main product housing
- Have an optical engineer generate a mechanical FOV for importing in to CAD
- Include mechanical tolerances in determining clear window sizing
  - Lens to sensor centration
  - Lens to sensor tip/tilt
  - Camera module to housing alignment tolerances (x, y, z, tip/tilt)

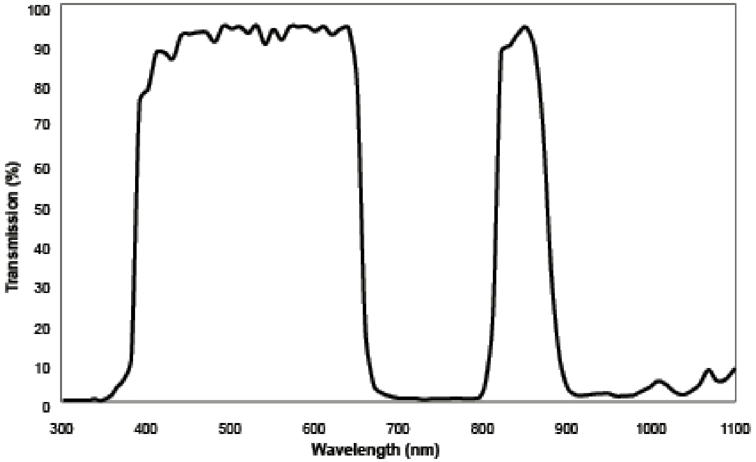


Optical Filters

- Most systems require an optical filter to reject light outside the desired spectral range
- Cut-on and cut-off wavelengths are quoted at the 50% (T=50%) relative transmission
- Full color imaging:
    - IR cut to reject light beyond 740nm
    - T=50% typically ~650nm
- Near IR LED illumination:: narrow bandpass filter centered at 850 or 940nm
- Visible + NIR: dual bandpass filter like DB850/DB940
- Interference-type filters have well controlled (sharp) cut on/off curves, but are sensitive to incident light angle
- Absorptive-type filters do not shift with angle, but have shallow cut on/off gradients
- Hybrid filters combine absorptive + interference filters for optimum performance

Bandpass filter for visible





DB850 Dual bandpass filter for visible + NIR

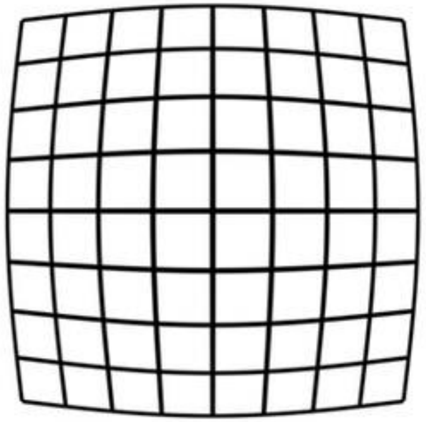
Correcting for Optical Aberrations

Image Processing Corrections for Optics

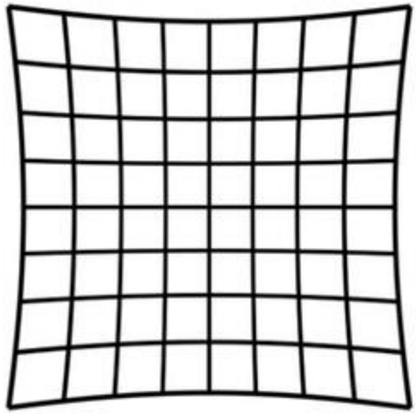
- The image signal processor (ISP) can be used to correct or mitigate certain optical aberrations
- Lens shading correction:
  - Corrects for lens relative illumination, and other low-spatial frequency shading effects
  - Uses a “golden lens” calibration map, or per unit calibration (requires additional factory calibration process)
  - Typically uses a low resolution map (say 16 x 16) with polynomial interpolation
  - Multiply each pixel value by the inverse of the local shading value
  - For color cameras, this should be performed separately for red, blue, and each of the two green channels in the Bayer filter pattern (as the two greens can have different characteristics)
- Chromatic aberration correction:
  - The refractive index of a medium changes with wavelength. Effort is made in the optical design to bring each color to focus at the imaging plane, but some splitting of the colors towards the corners can remain
  - Chromatic aberration correction attempts to mitigate this color splitting
  - For an example algorithm, see: “Removing chromatic aberration by digital image processing”, S Chung, et. al, Optical Engineering 49(6), 067002 (1 June 2010)

Image Processing Corrections for Optics (Cont.)

- Distortion correction
  - Even "rectilinear" lenses typically have a few percent distortion
  - Positive distortion is called "barrel distortion"
  - Negative distortion is called "pincushion distortion"
  - A geometric warp can correct for this distortion
  - If barrel distortion is corrected, the image must then be cropped to eliminate areas where there is no data
  - Correcting for pin cushion distortion stretches parts of the image, reducing linear resolution
  - Distortion correction map generated from a checkerboard target
  - Distortion correction algorithm available within OpenCV



Barrel Distortion



Pincushion Distortion

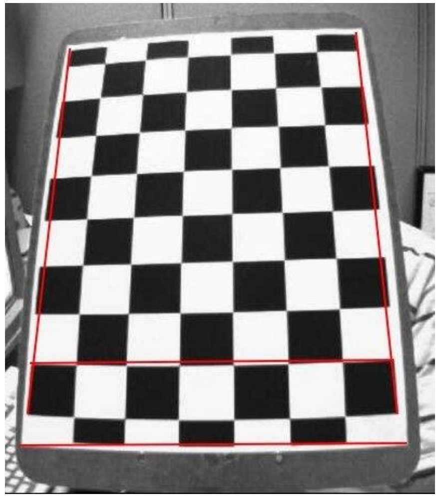
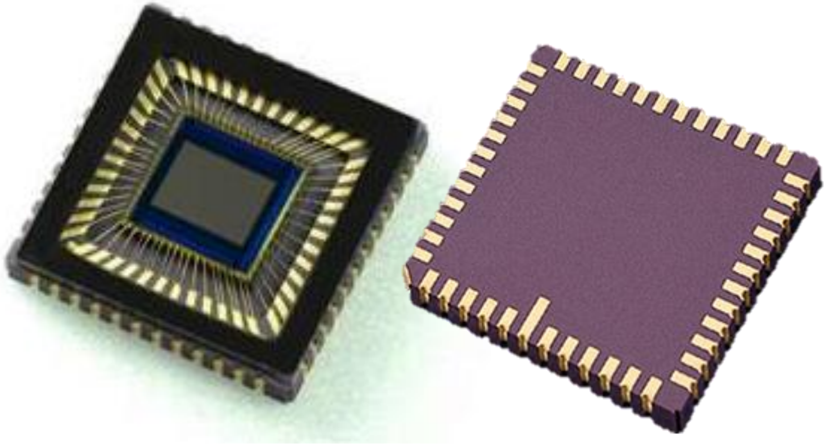
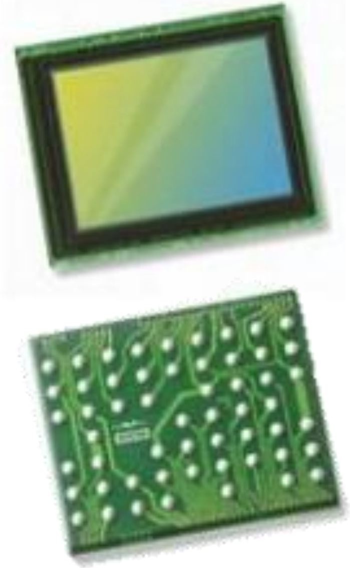


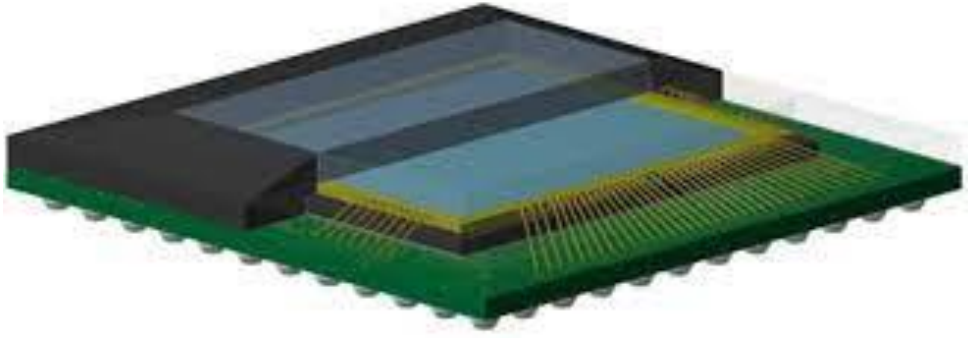
Image Sensor Packages

Sensor Package Types

- Common package types:
    - Ceramic leadless chip carriers (CLCC)
        - Ceramic package with solderable lands/castilations
    - Imaging ball grid array (iBGA)
        - Ball grid array package with an organic, laminated substrate
    - Chip-scale package (CSP)
        - Micro BGA with a footprint the size of the sensor silicon

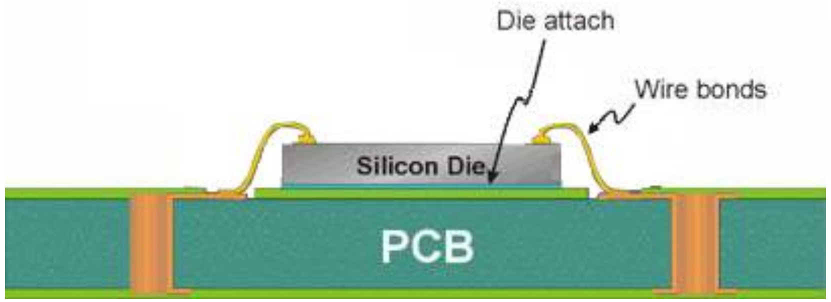


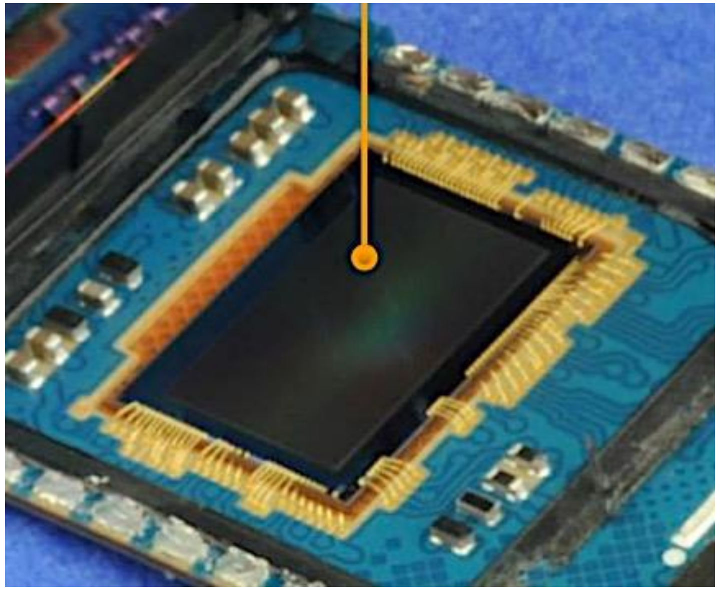




Chip-on-Board (COB)

- Chip-on-board (COB)
  - Bare silicon die mounted to PCB using thin (~25µm) die attach adhesive and connected using gold wire bonding
  - PCB must have a special wirebondable pad finish. Electroless nickel electroless palladium immersion gold (ENEPIG) most commonly used
    - Not the same as the immersion gold finish sometimes used on PCBs
  - A protective cover should be placed over the COB sensor to protect it from dust and damage
    - If this is a filter glass, it eliminates an additional glass in optical path
  - Thermal expansion mismatch between the silicon die and the PCB can lead to warpage. This will affect focus
    - Use low CTE PCB material, and low stress die attach adhesive





Samsung GS6 Camera COB

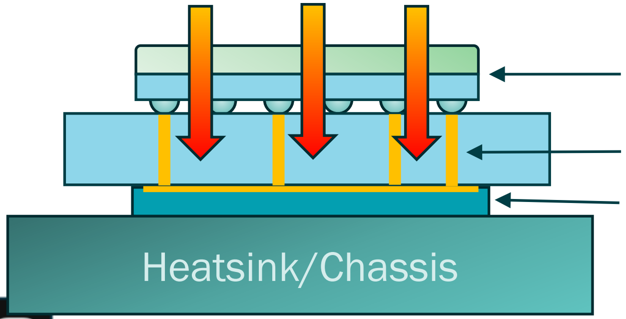
Image Sensor Package Comparison

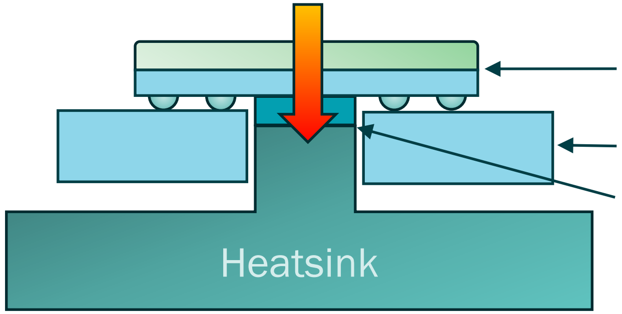
	CLCC	iBGA	CSP	COB
Cost	High	Moderate	Low for small sensors	Low
Moisture resistance	Good	Poor	Moderate	Poor
Reliability	High	Moderate	Moderate	Low
Size	Large	Moderate	Very small	Small
Module flexibility	Low	Low	Medium	High

Other Design Factors

Thermal Considerations

- Dark current doubles about every 6°C
- Dark signal non-uniformity increases with temperature
- Dark signal shot noise (= SQRT number of dark signal electrons) can become a factor at high temperatures
- Hot pixels increase with temperature (defect thermal activation)
- Black level corrections get worse with temperature
- Thermal design of a camera should be considered *up front*
- Design a low thermal resistance path from the sensor die to ambient


Sensor Package
PCB with thermal vias
Thermal pad
Heatsink/Chassis


Sensor Package
PCB with hole
Thermal pad
Heatsink

Electrical Factors (Keep it Quiet)

- Image sensors are mixed signal devices
- Care must be taken to ensure low power supply noise, particularly on analog supply rails
  - Dedicated supply (LDO) for sensor V_{ANA} is a good idea
- Careful placement and low-impedance routing of decoupling capacitors is essential
  - Ask sensor supplier for a module design reference guide
  - Prioritize placement of analog rail decoupling capacitors (place as close to the sensor as possible) with minimal vias
- Analyze the noise
  - Capture dark raw images (no image processing) and extract noise components
  - Analog supply noise is particularly prone to creating temporal row noise
    - Compare with sensor noise on manufacturers evaluation system, or other reference design

Selecting a Sensor & Lens

Selecting a Sensor - Determine Key Requirements

1. Determine resolution requirements:
    - Object space resolution
    - Field of view
    - Max. object distance
    - Min. linear pixels for feature recognition

- $$Pixel\ Size\ (\mu m) = Object\ Space\ Resolution\ (\mu m) \times \frac{FOV\ (mm)}{Sensor\ Size\ (mm)}$$

2. Wavelength of light to be imaged: visible or NIR-enhanced sensor
3. Color (full RGB, mono + R, etc.), or monochrome
4. Dynamic range requirements
5. High-speed motion (camera or scene): rolling/global shutter
6. Interface requirements for SOC

Selecting a Sensor – Evaluate using Sensor Evaluation Kit

- Use requirements from previous slide to select a sensor evaluation kit (EVK)
  - Look for sensors intended for similar applications
  - Many sensor companies have online product selection tools, or can support at the sales/application engineering level
- If possible, pair EVK with lens that's a close fit for final application (see following section)
- Test EVK in your application including with minimum illumination conditions
  - If lens FOV does not match, adjust object distance, or chart size to compensate
- If low light SNR is acceptable proceed to lens selection
- If low light SNR is not acceptable:
  - Can required SNR be achieved by adjusting the lens aperture?
    - Trade-off = depth of field, lens size/cost
  - Can required SNR be achieved by increasing exposure time?
    - Trade-off = motion blur
  - If SNR requirements cannot be achieved, select a larger sensor (more light collection) and repeat process
    - Trade-off = depth of field, sensor cost, lens size/cost
- Evaluate dynamic range
  - This is one of the more difficult tests to perform correctly, but online resources exist like Imatest test software tutorials

Selecting a Lens

1. Determine optical format (from sensor size)
2. Select field of view ⬄ focal length
3. Determine target f-number
4. Check depth of field
5. MTF
    - From resolution study, determine line pairs/mm resolution needed
    - An MTF ≥ 30% at the target lp/mm is a good rule of thumb for the detection of edges
    - Check MTF across field: center, mid, corner regions
6. Pick a lens with a CRA that closely matches the sensor CRA specification
7. Check the impact of relative illumination on performance in corners (SNR decrease)
8. Determine if the lens includes a filter (IR-cut, IR passband, etc.), if one is needed
9. Check if the lens is suitable for the dynamic range requirements (HDR requires very good anti-reflective coatings)

Resources

- **Image Sensor Manufacturers**
- ON Semiconductor: ON Semi Image Sensors
- Sony: Sony image sensors
- Omnivision: https://www.ovt.com/
- Samsung: Samsung image sensors
- Fairchild Imaging (BAE Systems): https://www.fairchildimaging.com/
- ams: ams CMOS Image Sensors

Interfaces, Optics, and Imaging

MIPI Alliance: https://www.mipi.org/

Edmunds Optics Knowledge Center:

- Optics: Edmund Optics Knowledge Center - Optics
- Imaging: Edmund Optics Knowledge Center - Imaging

Cambridge in Colour imaging tutorials: Cambridge in Colour

Imaging Test Software and Charts

Imatest: https://www.imatest.com/

Algorithms and Image Processing

“Adaptive pixel defect correction”, A. A. Tanbakuchi, et. al: SPIE Digital Library

“Removing chromatic aberration by digital image processing”, Soon-Wook Chung, et. Al: Removing Chromatic Aberration

OpenCV distortion correction tutorial: https://docs.opencv.org/master/dc/dbb/tutorial_py_calibration.html