Introduction to Optics for Embedded Vision

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Growing World of Embedded Vision

- Factory Automation Machine Vision + Robotics
- Medical Devices + Life Science Systems
- Defense, Space, Security
- Consumer!
  - Robots + Vision out of controlled environments
  - Benefit to every industry
    - Smaller, cheaper, accessible, more talent
- Autonomous Vehicles
  - Air, Land and Sea
- **<u>Crossover in all industries</u>**







Edmund
75 YEARS OF OPTICS

Goal of Presentation

- Introduce challenges & effects of optics on your final image
  - Basic theory related to root cause

- Why care about optical effects on image?
  - Include all variations in set of test images
  - Better image = less development time
    - Processing power, ISP cleanup & estimation of what info was lost

- Why care about optical root cause/theory?
  - Better architecture up front
  - Less surprise/$ during manufacturing and test

Outline: Embedded Optics Considerations

- Smaller, Cheaper Rugged and often wide angle
- Creates challenges + common design deviations during manufacturing
  - Boresighting/pointing accuracy and tip/tilt
  - Focal length/Field of View and Working Distance tolerance
  - Defocus and Focus shift
  - Ruggedized
  - Color aberrations
  - Coatings
  - Small pixels, Diffraction Limit, Chief Ray Angle (CRA)

Imaging System Basic Terms

FOV = Field Of View
PMAG = Primary Magnification
WD = Working Distance
FL = Focal Length
Res = Resolution
f/# = f-number
DOF = Depth of Field or Depth of Focus
NA = Numerical Aperture
MTF = Modulation Transfer Function

Imaging System Basic Terms

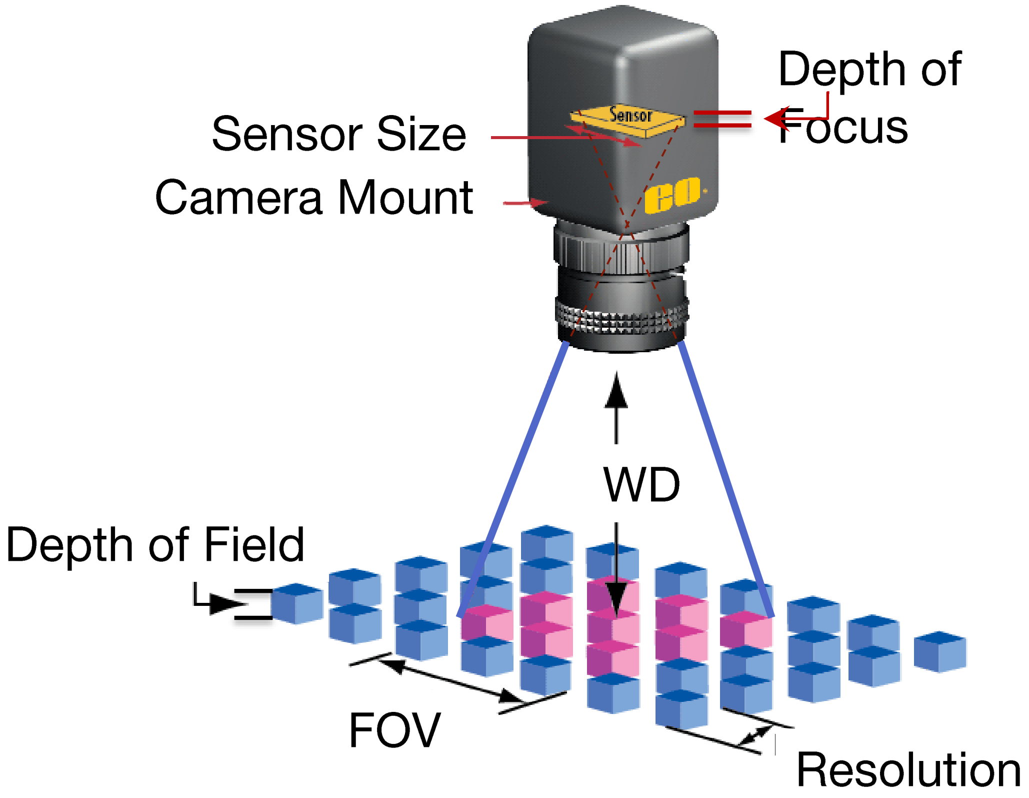
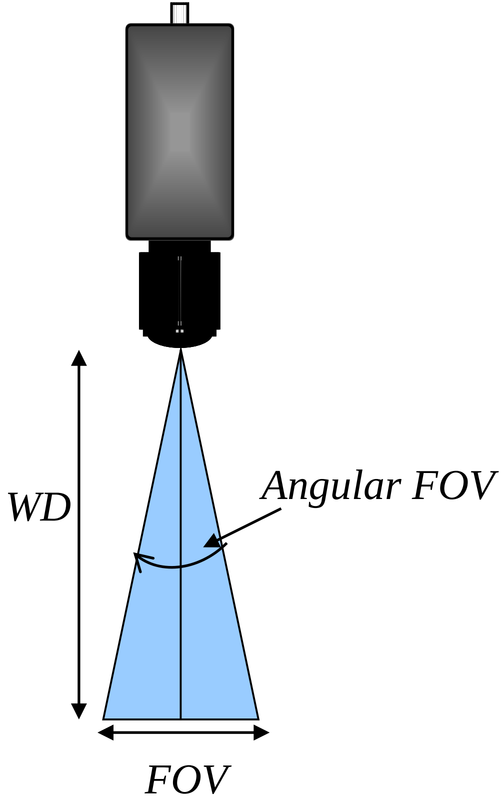


Image Space

Object Space

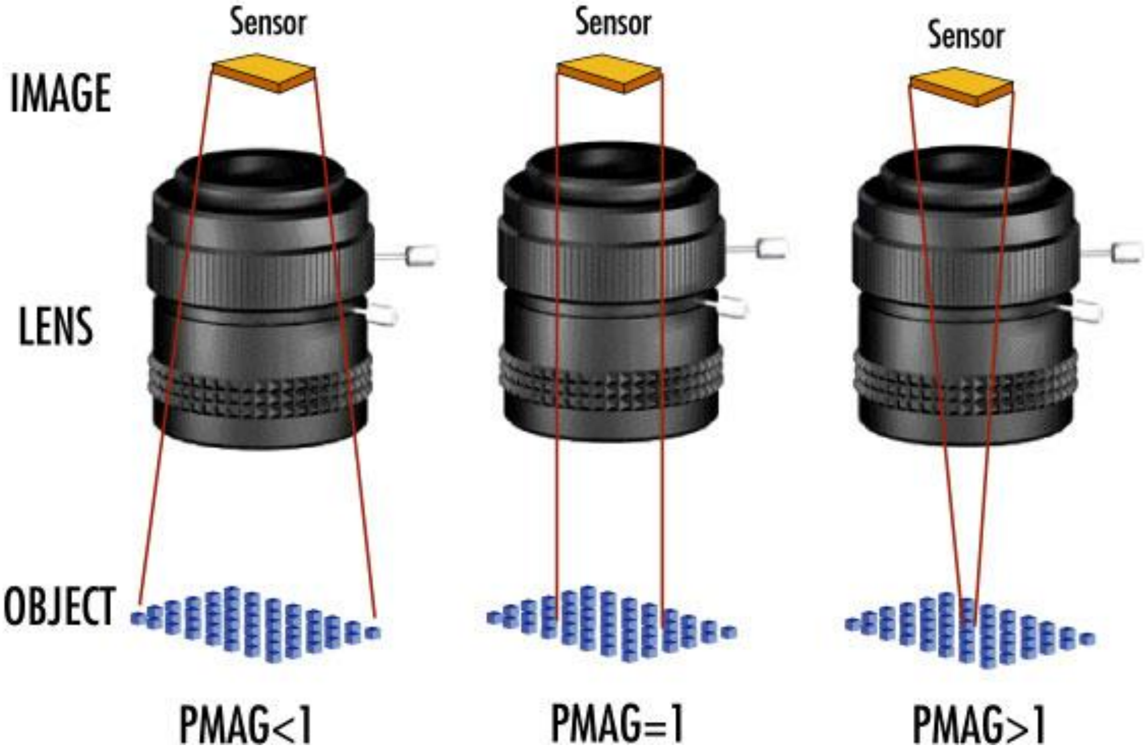
Basic Imaging Specs: Calculate FOV and WD



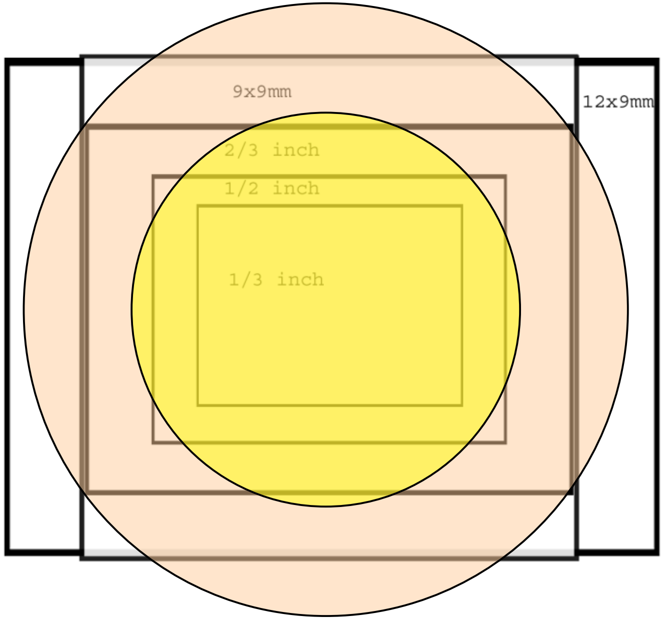
$$FOV = 2 * \left[WD * \tan\left(\frac{AngularFOV}{2} \right) \right]$$

$$WD = \frac{FOV / 2}{TAN\left(\frac{AngularFOV}{2} \right)}$$

Basic Image Specs: PMAG, Sensor Size

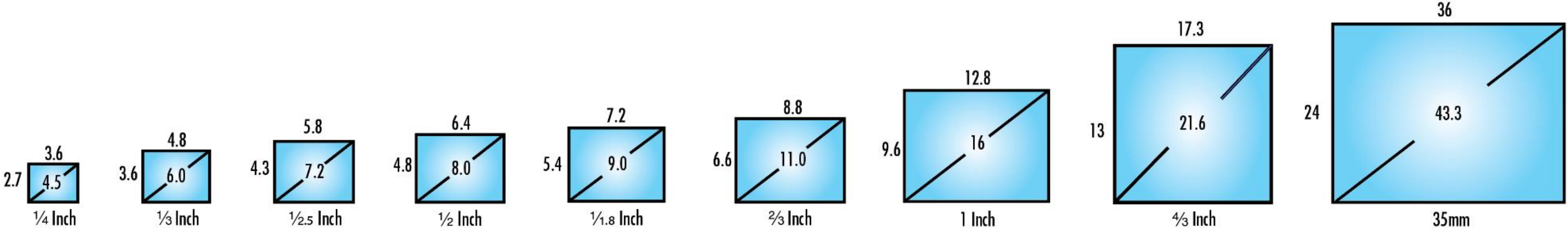


Short FL **Long FL**



Sensor Format Names

- Format names do not match sensor dimensions
- Format names relate to vacuum tube sizes



¼”

½”

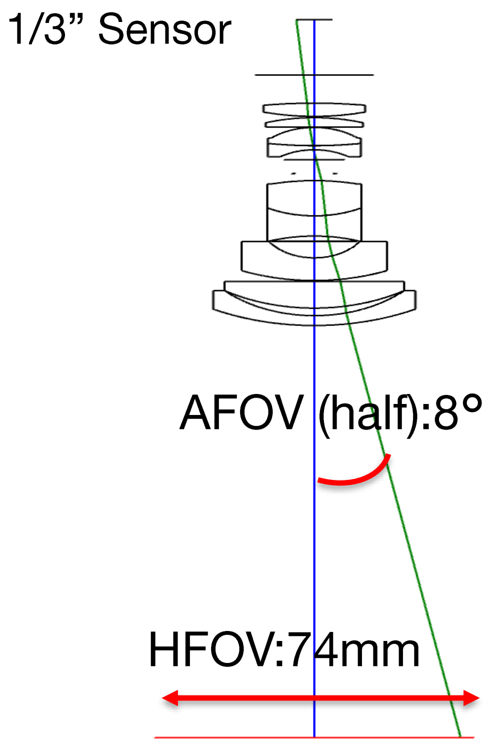
1”

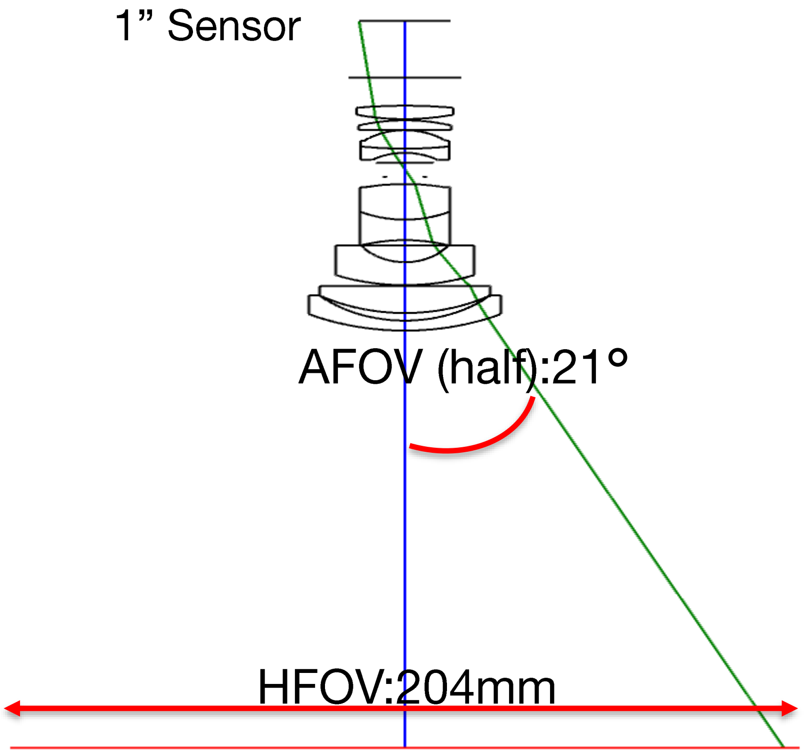
35mm

$$\frac{8mm}{4.5mm} = 1.78$$

$$\frac{16mm}{8mm} = 2$$

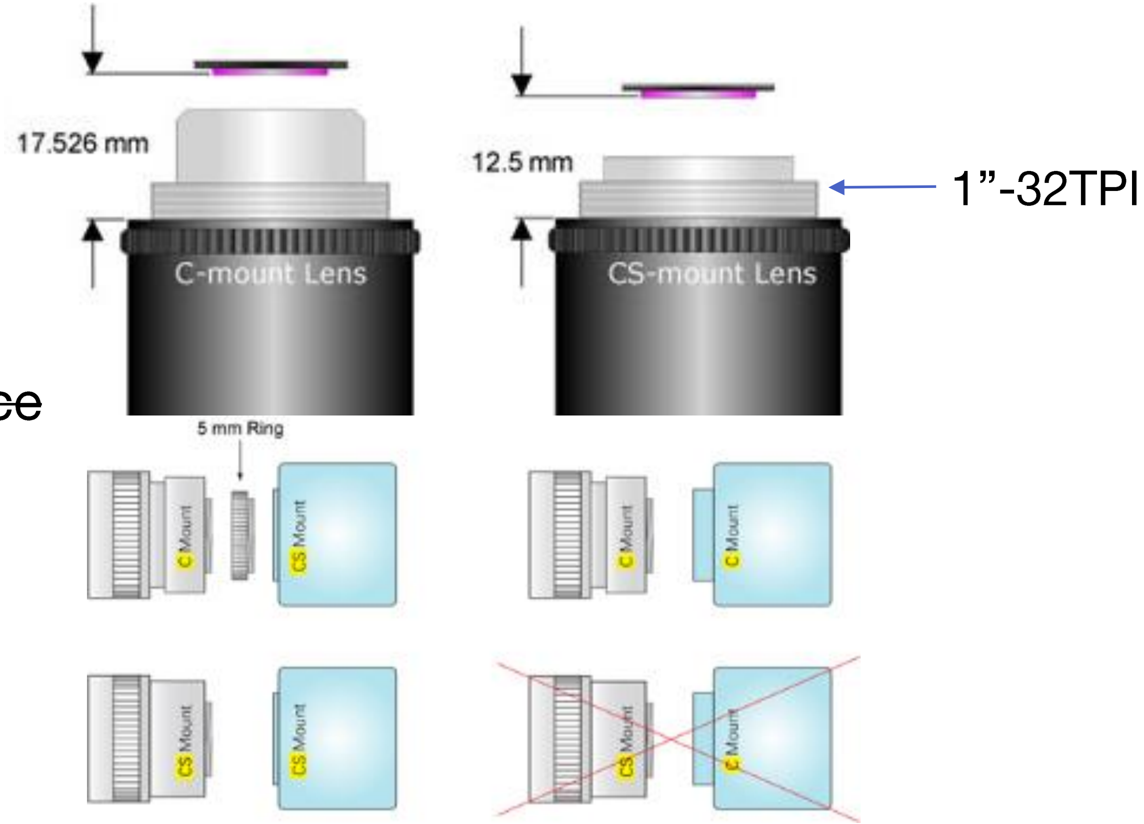
FOV and Sensor Size Dependency





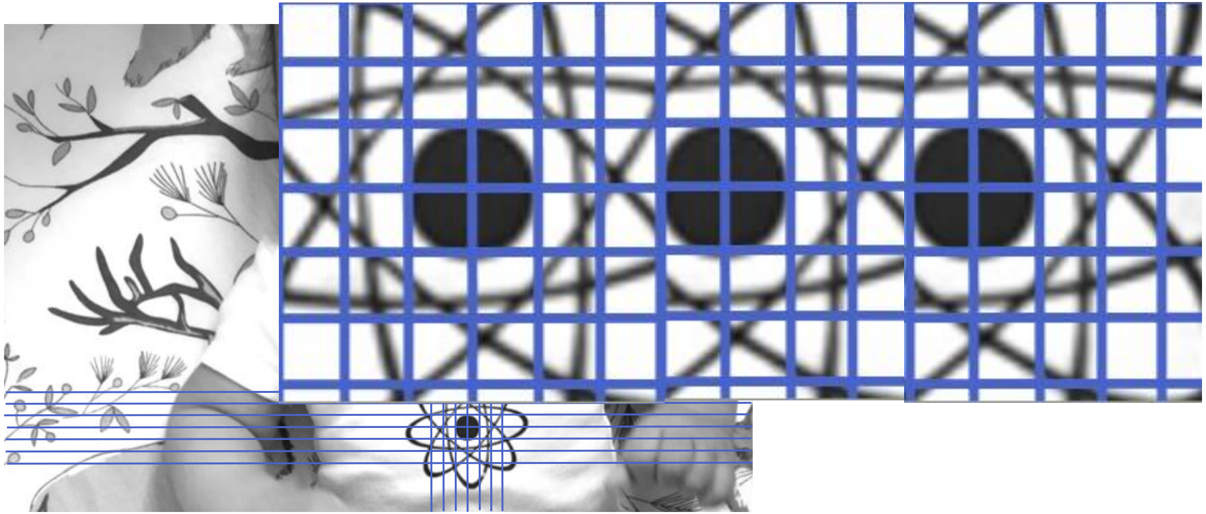
Basic Image Specs: Flange & Rear Protrusion

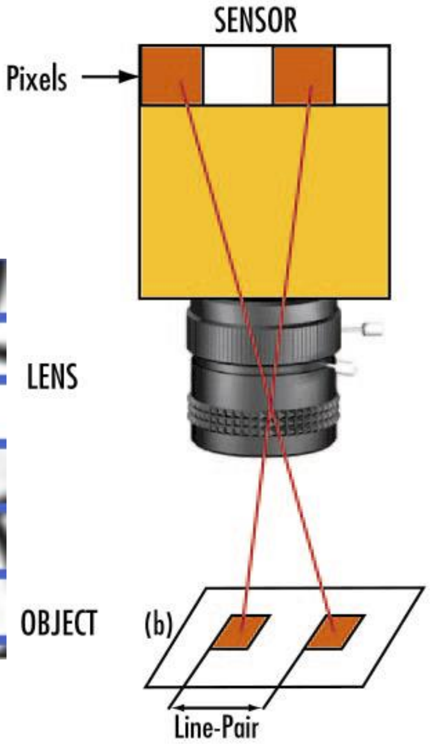
- C-mount
- CS-mount
- F-mount
- S-mount (M12)
  - ~~Standard Flange Distance~~
- M8, M6 and smaller



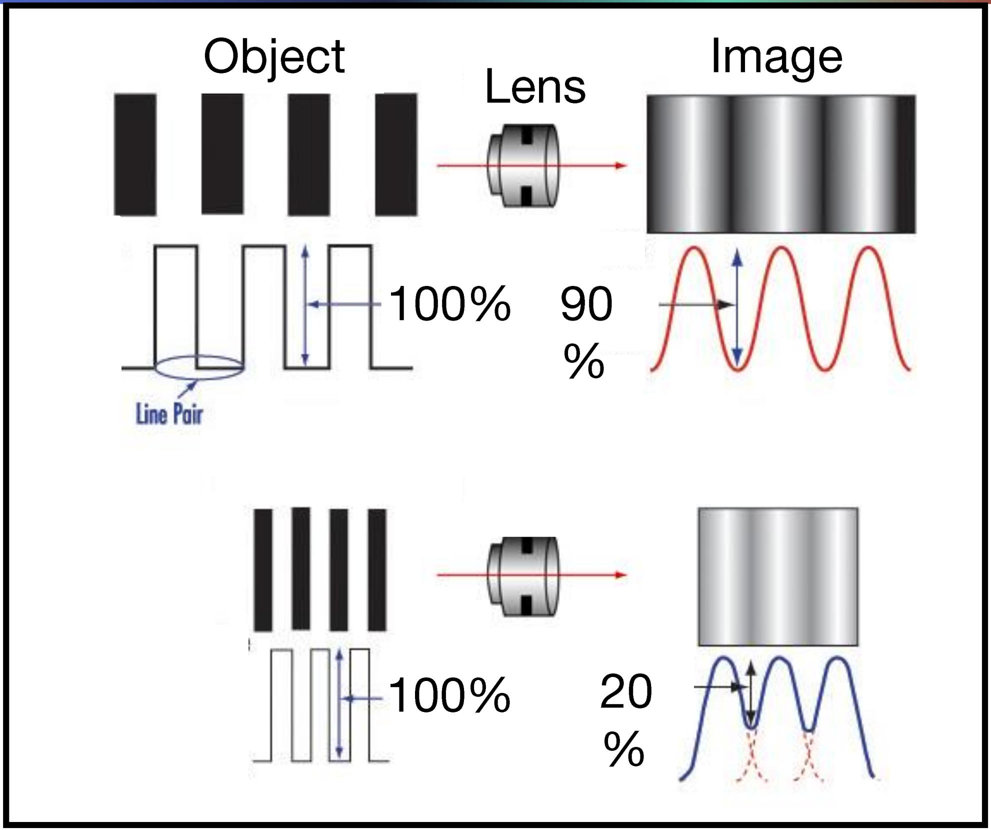
Basic Imaging Specs: Resolution

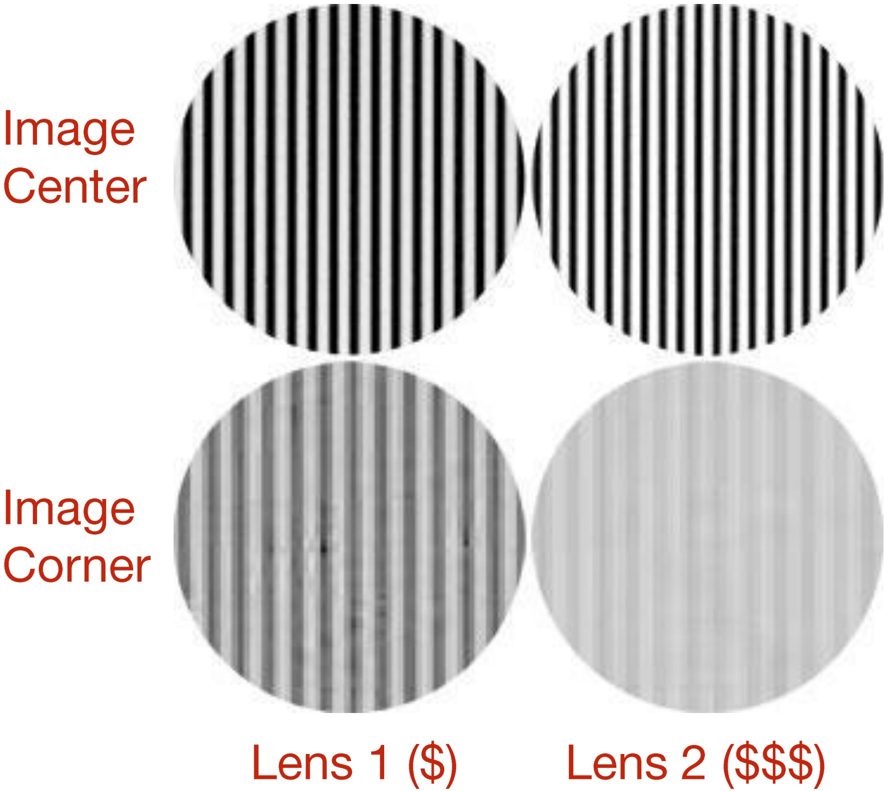
- Basic FOV/Feature Size mapping to pixels
  - 2 pixels = 1 line pair
  - Divide FOV by # pixels/2 = limiting resolution
  - PMAG used to convert Object to Image Space



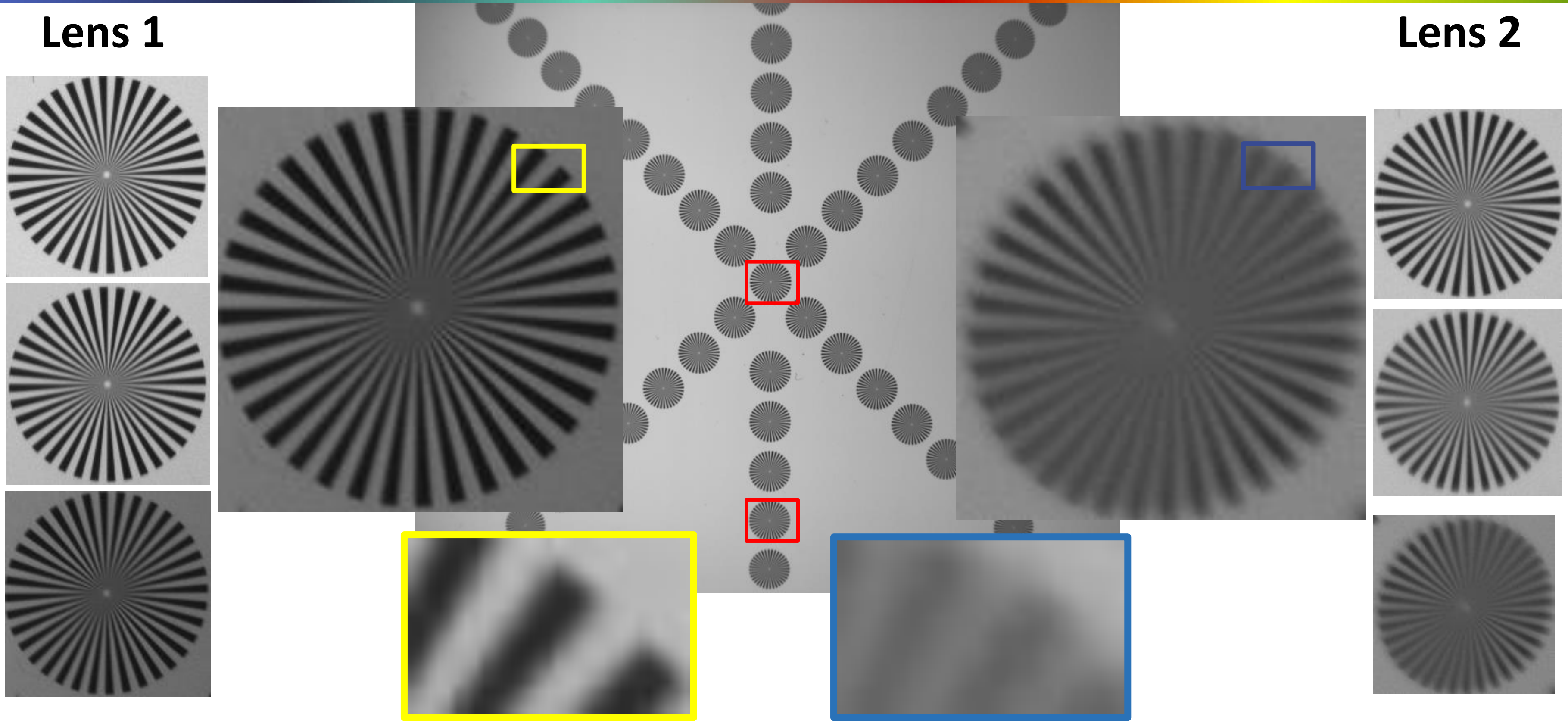


Resolution and Contrast



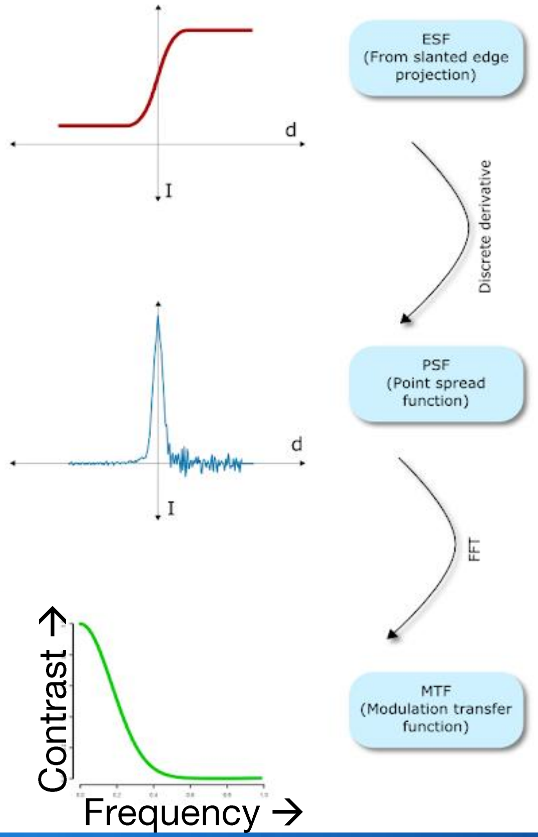


MTF: Resolution and Contrast



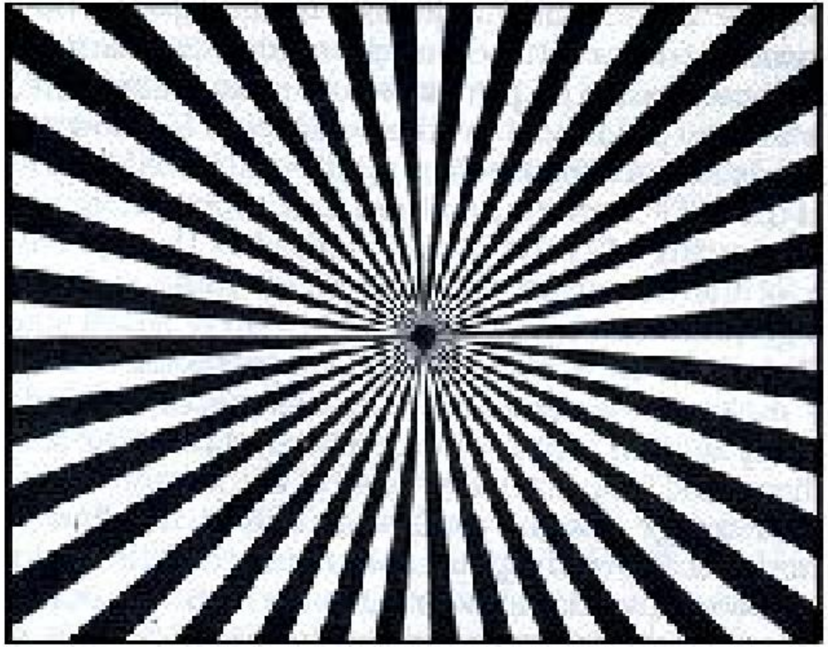
MTF (Modulation Transfer Function) Defined

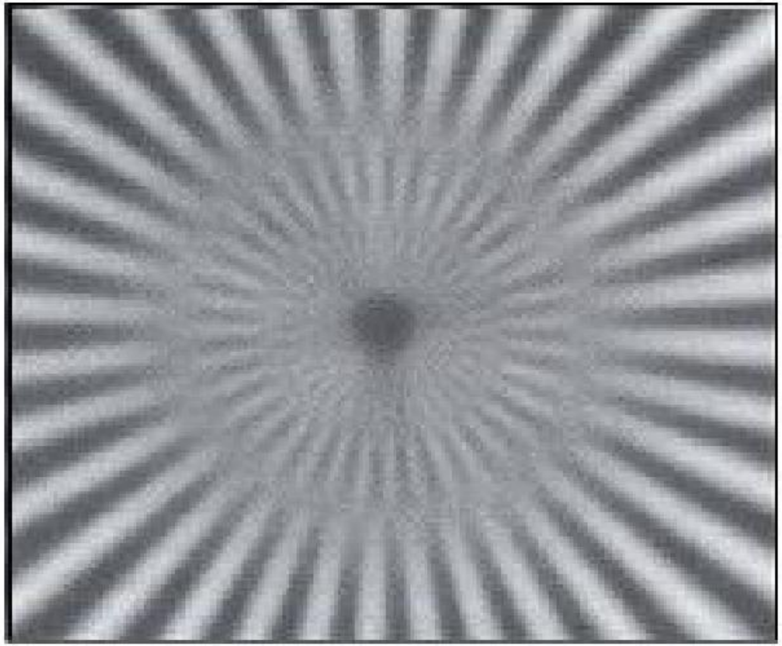
- MTF shows modulation (relative contrast) at many frequencies
- MTF is absolute value of OTF (Optical Transfer Function)
- OTF is calculated by taking FFT (Fast Fourier Transform) of PSF (Point Spread Function)
- PSF can be measured by imaging a Point Source c light or a Slanted Edge target



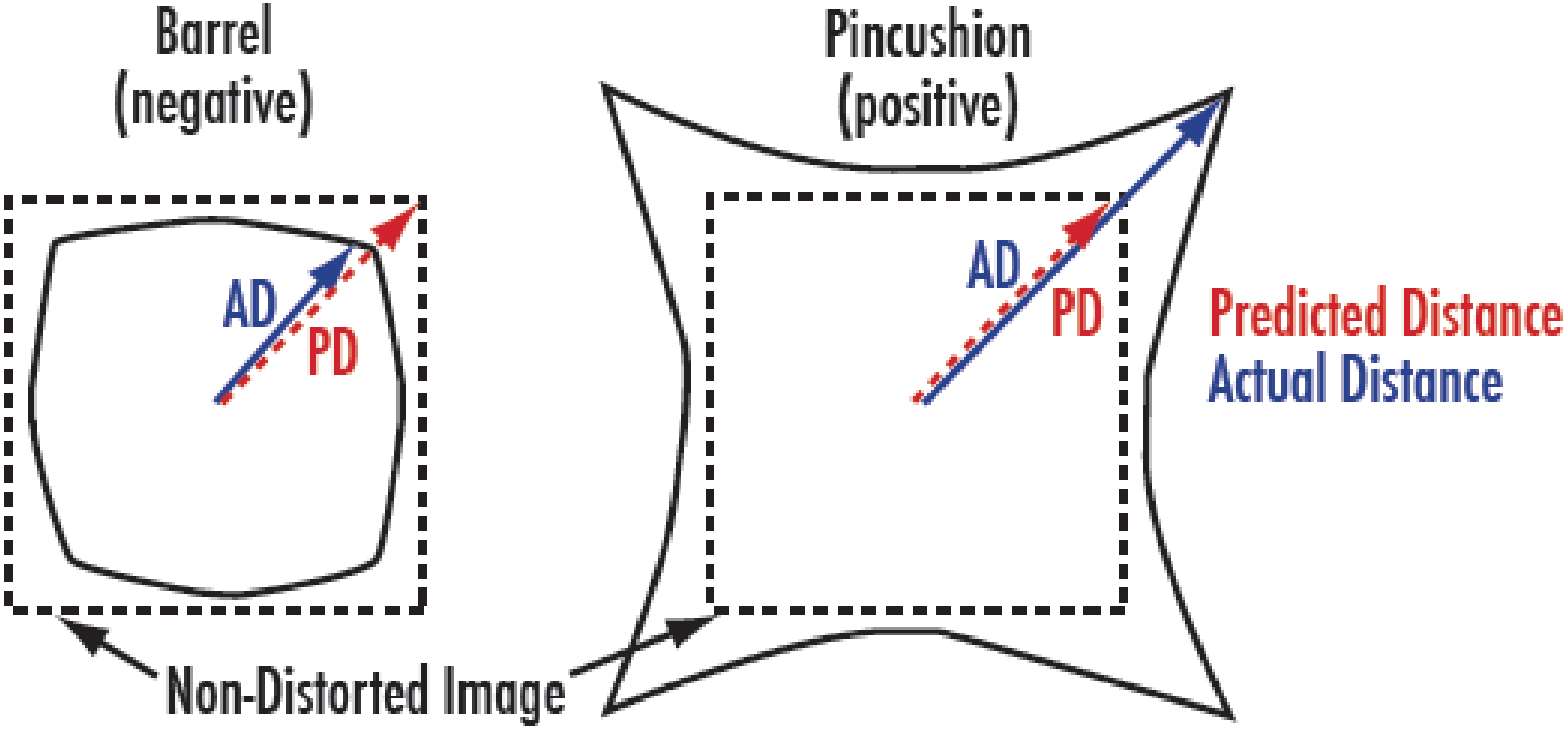
MTF describes some interesting affects

- Phase Reversal when OTF goes negative

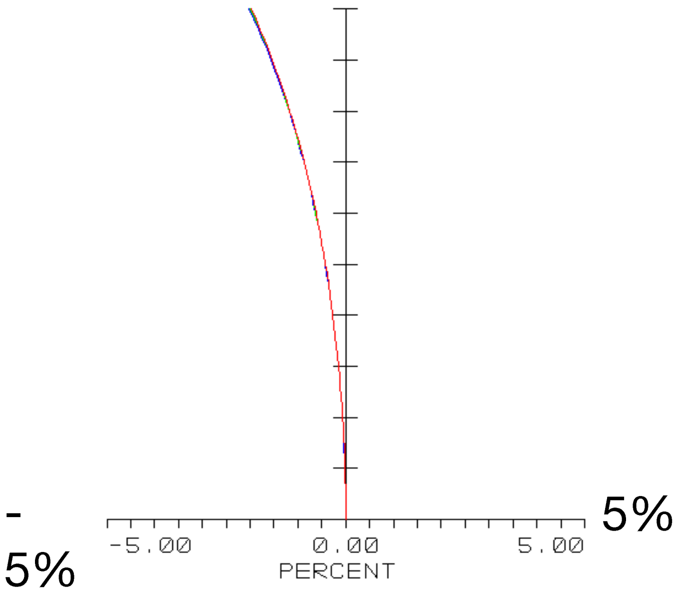




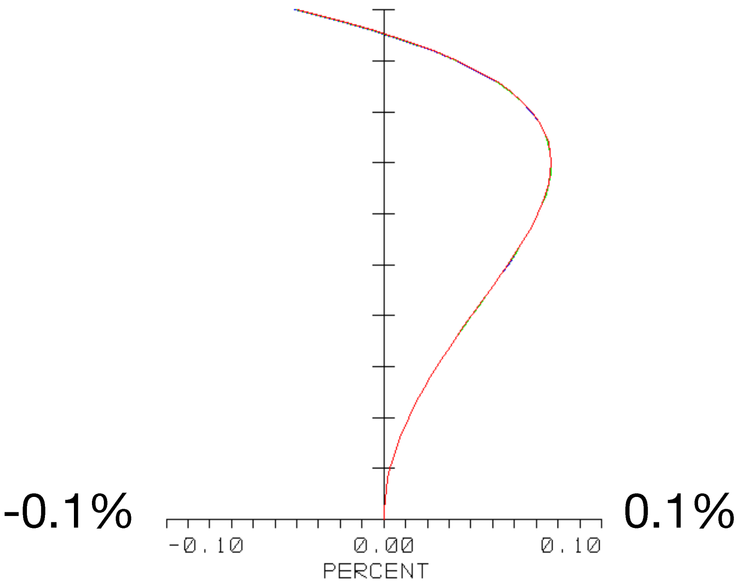
Distortion: Symmetric



Specifying and Calibrating Distortion



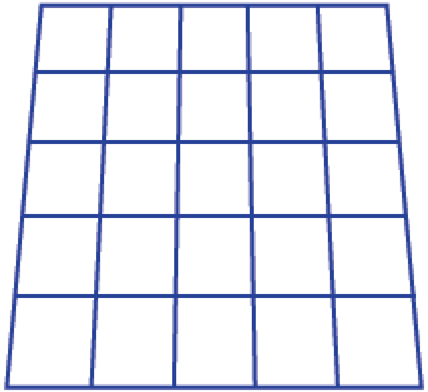
Monotonic
barrel (negative) distortion

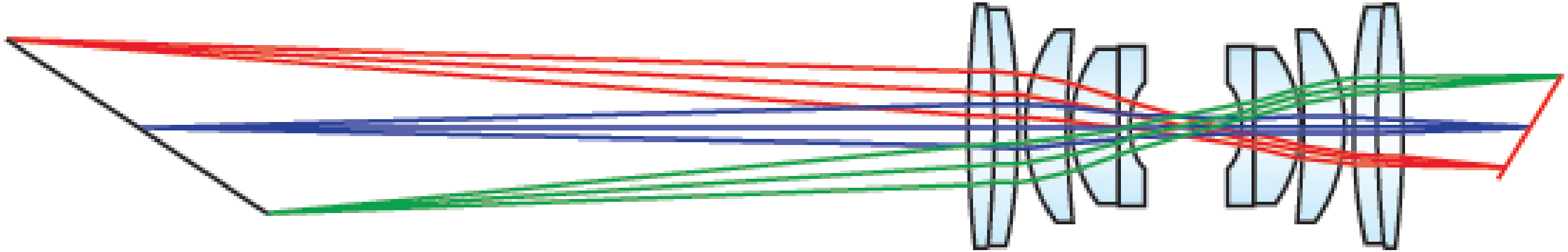


Non-monotonic
(mustache) distortion

Distortion: Asymmetric

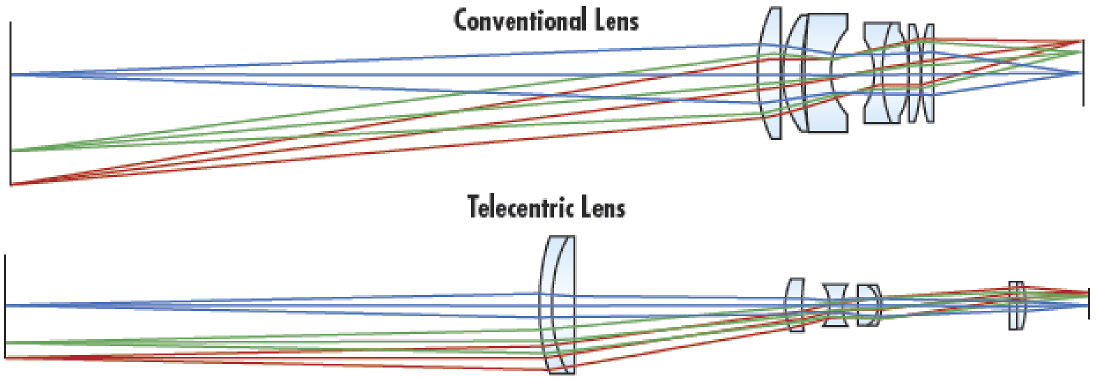
- Parallax/Keystone





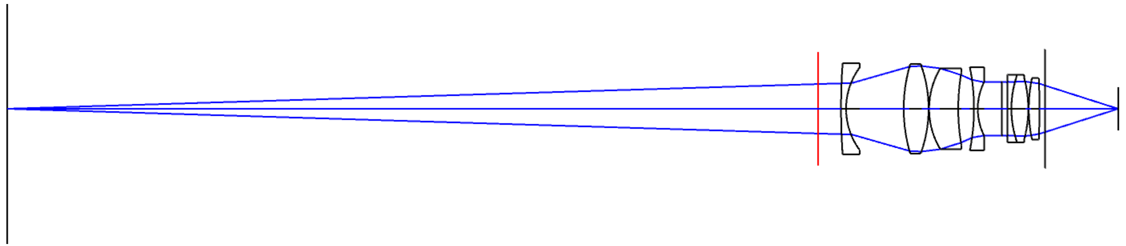
Telecentric Lenses

- 2 afocal systems with stop in between, located at common focus
  - Stop located 1 focal length from front and rear assemblies
  - Chief rays all parallel
  - Maintains same magnification as working distance changes
- Creates symmetric blur and low distortion

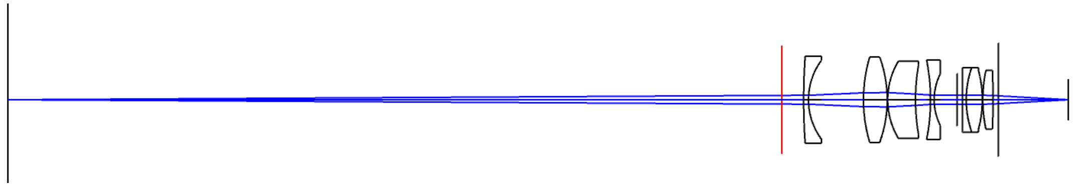


Basic Imaging Spec: F/# and Numerical Aperture

- Measure of how much light can enter the lens
- $\text{F/\#} = \dfrac{\text{Focal Length}}{\text{Entrance Pupil Diameter}}$
- Numerical Aperture (NA) $= \dfrac{1}{2*F/\#}$



Large NA means more light
larger apertures

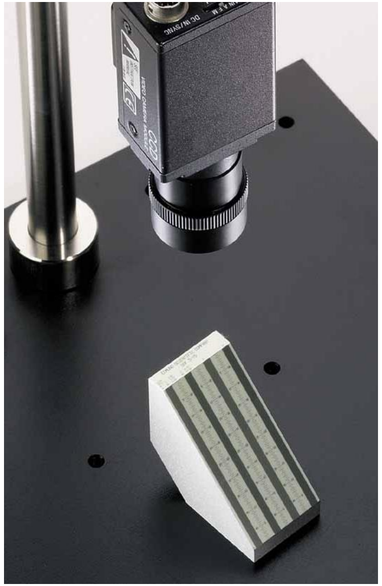


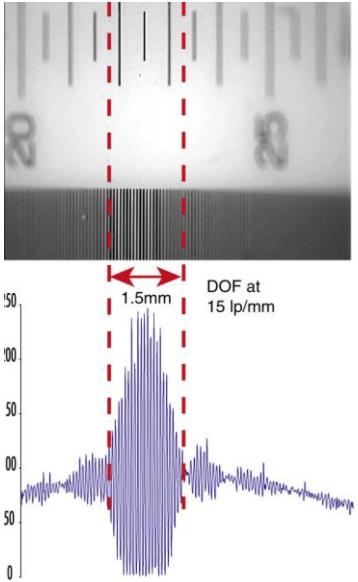
Large F/# means less light,
smaller apertures

Basic Imaging Spec: Depth Of Field

- Depth of Field is a measure of how much of an object is in focus measured along the working distance (Z-axis)

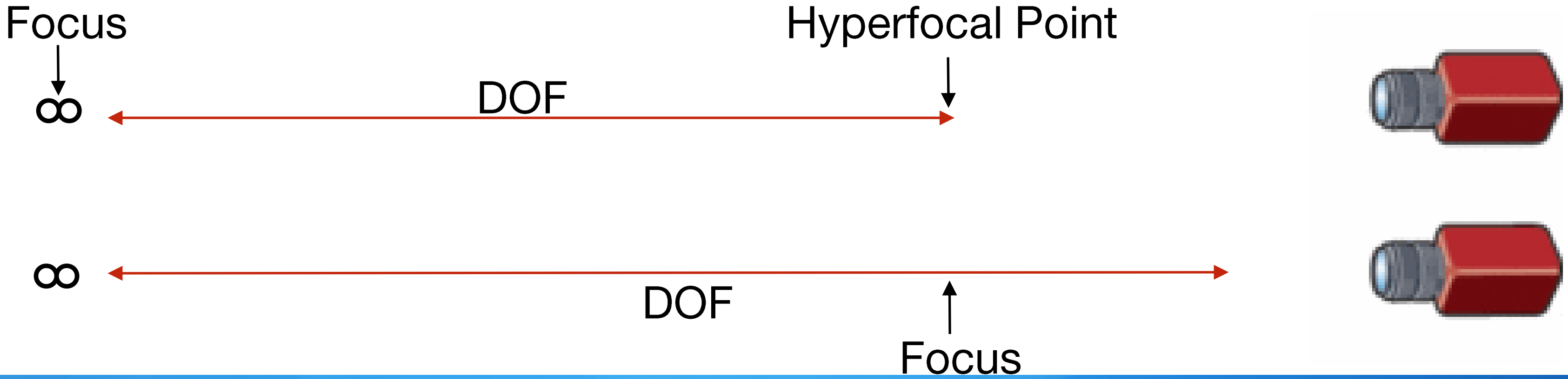
- Must be defined at a specific resolution





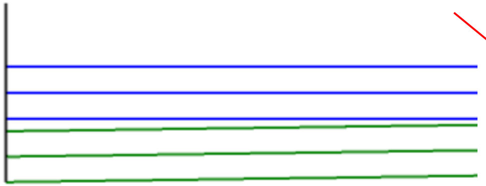
Maximizing DOF with Hyper Focal Distance

- Closest distance that appears sharp when lens is focused at ∞
- Closest distance that can be focused on while maintaining focus at ∞
- Circle of Confusion (CoC) is photographic term for limiting resolution in image space (equates to pixel size in digital imaging)

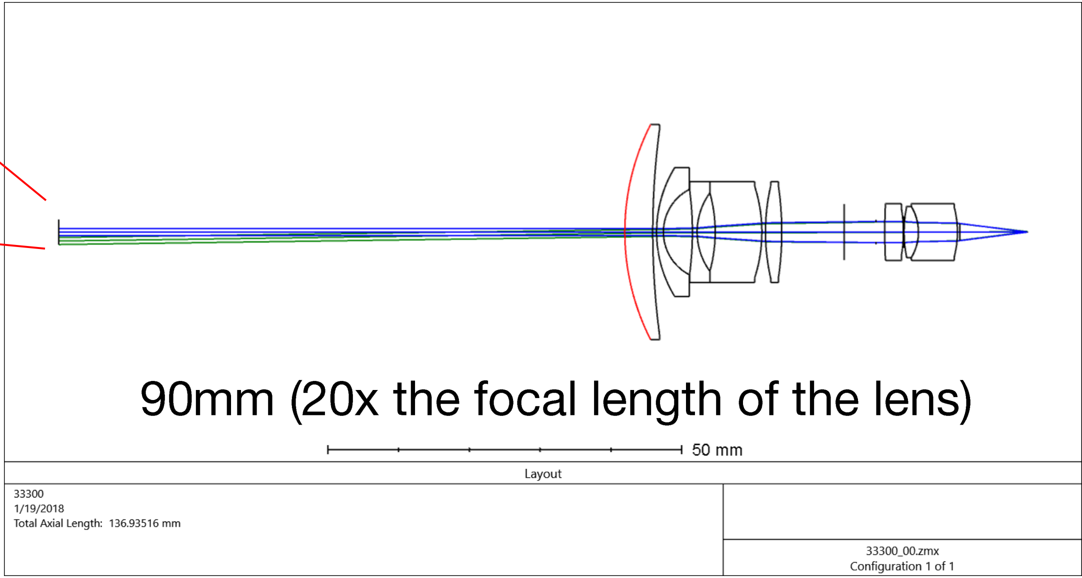


Focusing at Hyperfocal Distance Increases DOF

- If the lens is focused at infinity an object at the Hyper focal distance will have a smaller blur than the size of the pixel (blur is within CoC)

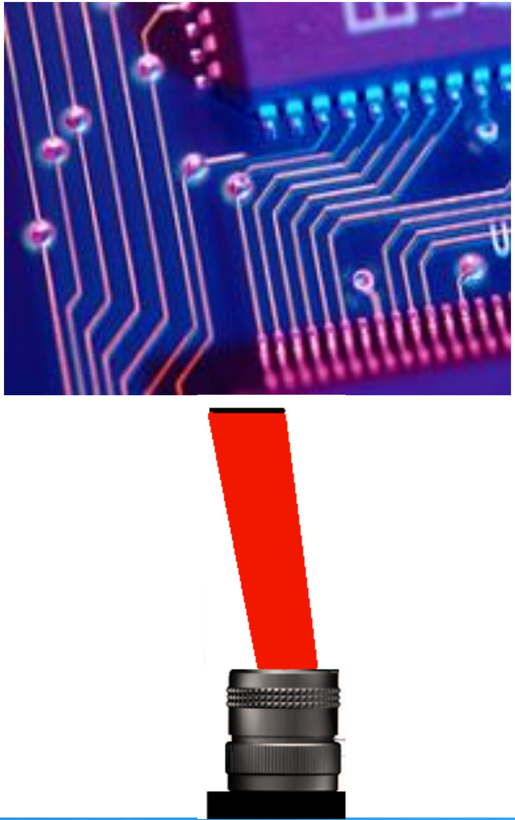


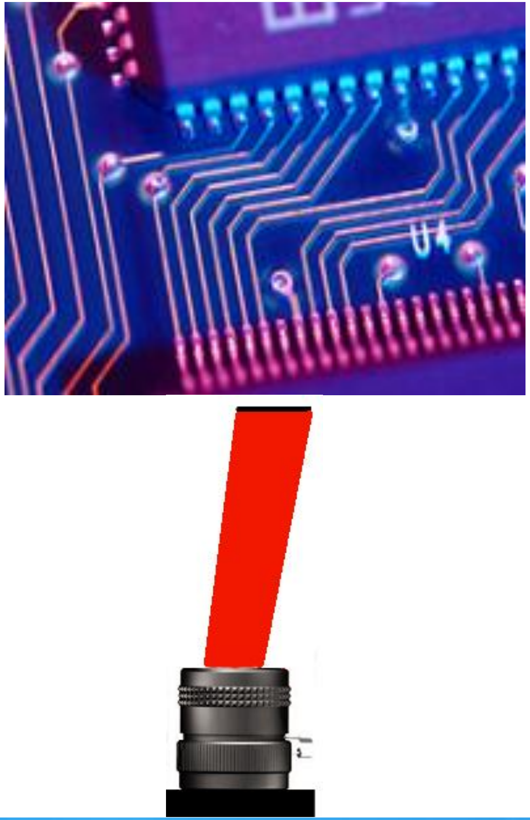
The green lines are the rays one 5.5um pixel away from the blue rays.

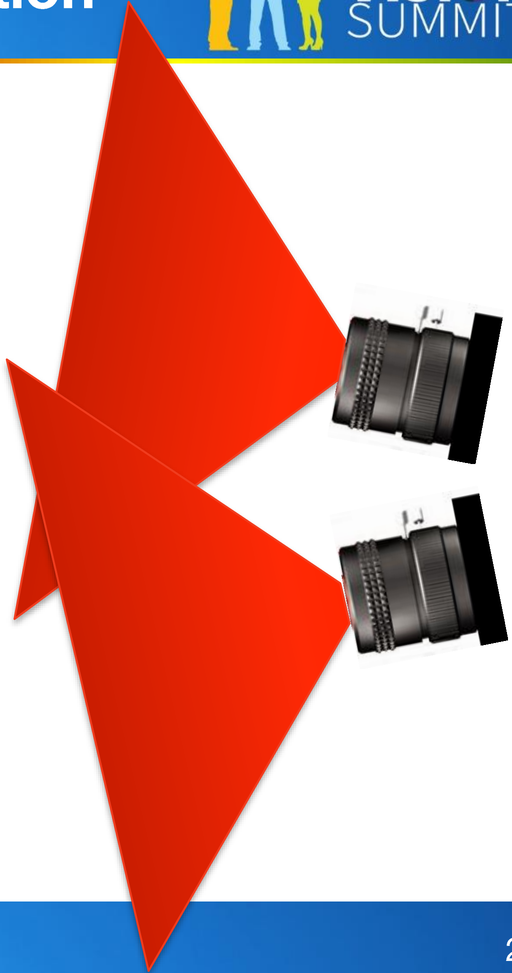


Pointing Accuracy and Tip/Tilt

Importance of Pointing Accuracy & Ruggedization

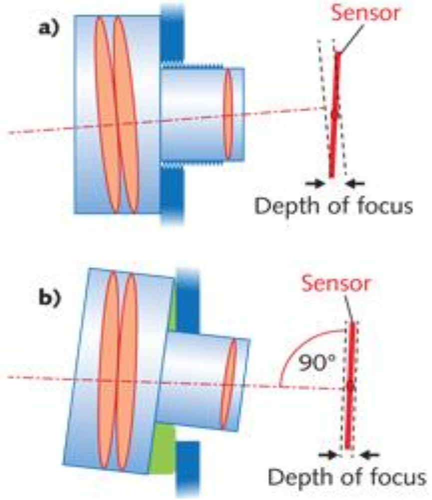


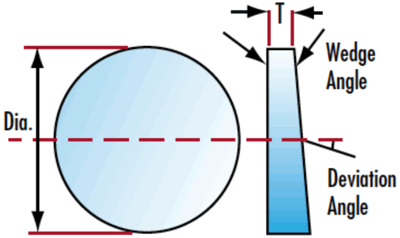


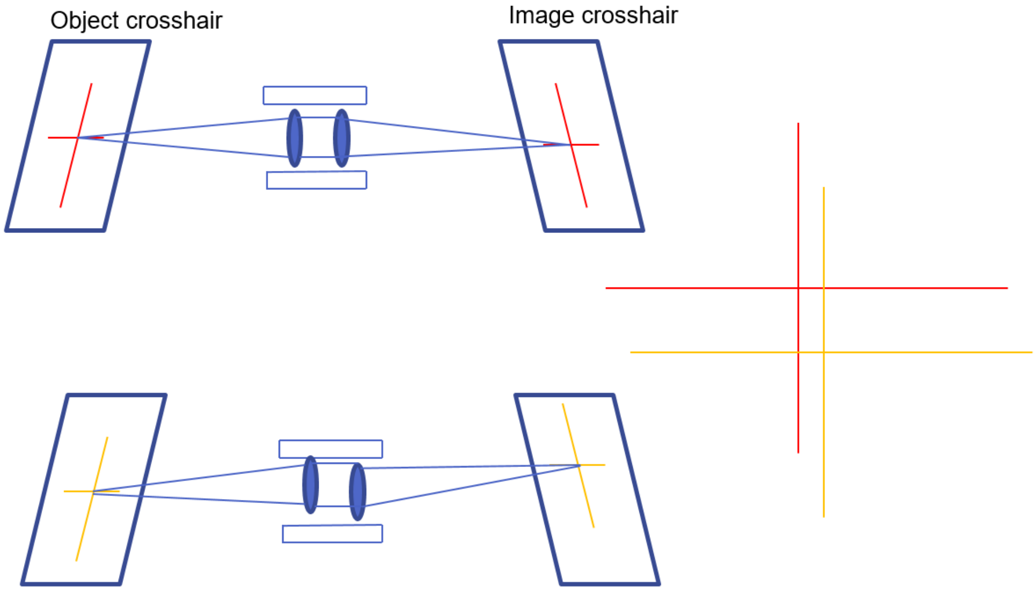


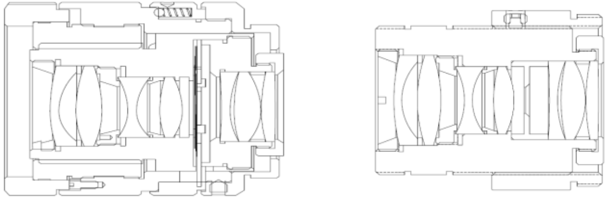
Causes of Pointing Variation

- Optical asymmetric tolerances
- Lens to Sensor alignment
- Opto-Mech tolerances
- Shock and Vibe





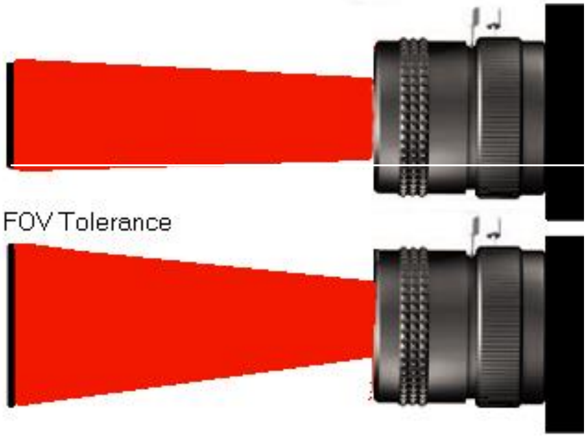




Focal Length/FOV

Focal Length Tolerance

- Causes of Focal Length variation = Axially Symmetric Tolerances
  - Power of Lens Elements
  - Spacer length

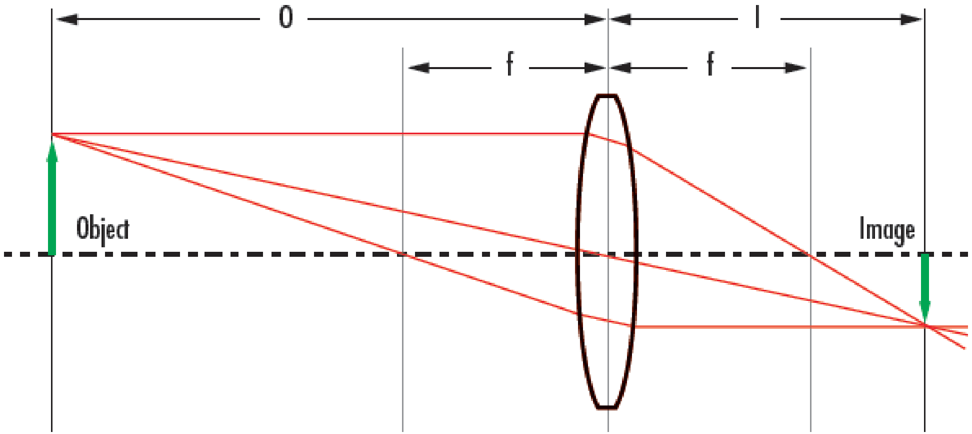


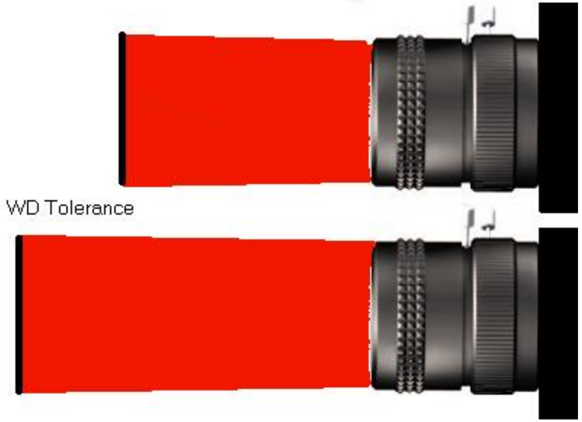
Working Distance

Working Distance Tolerances

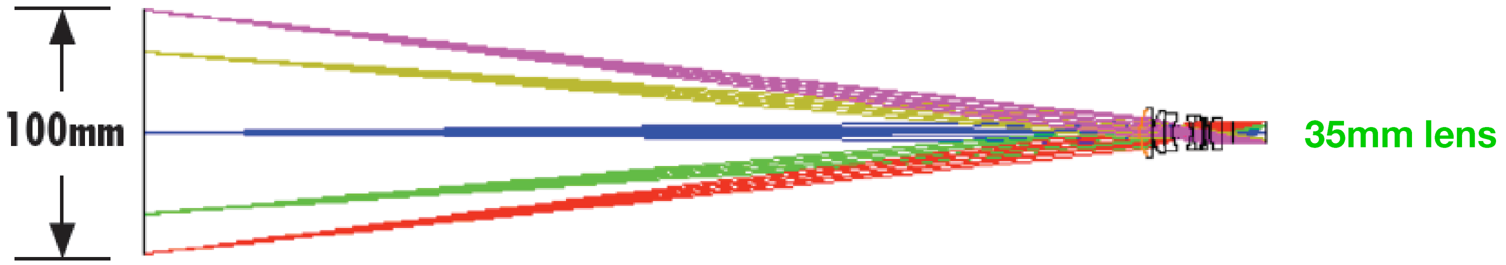
- Causes of Working Distance variation = Axially Symmetric Tolerances
  - Power
  - Spacer length
  - Sensor location

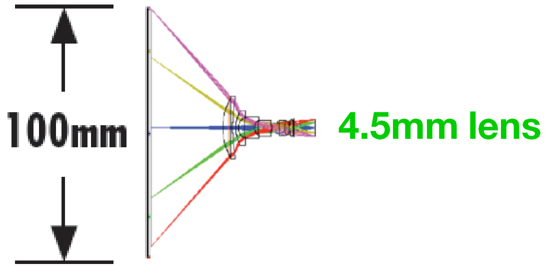
$$\frac{1}{I} = \frac{1}{O} + \frac{1}{f}$$





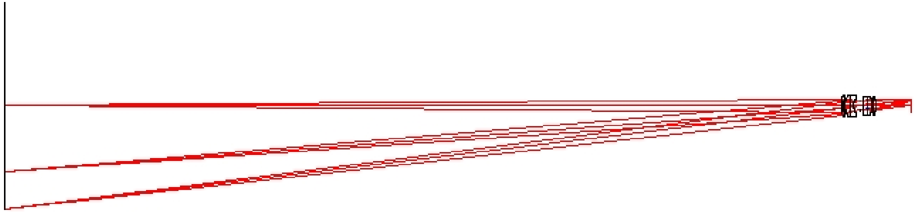
Your Application: FOV and WD Ratio



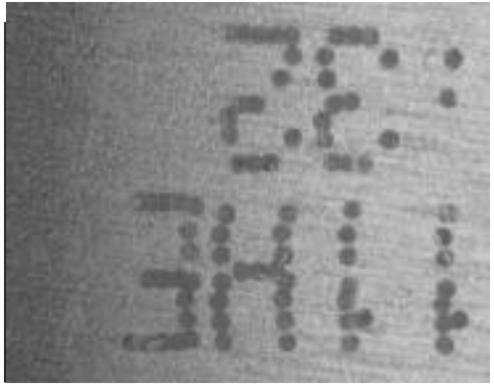


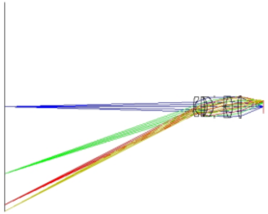
- It is possible to get wide fields of view at short working distances. However, performance usually drops severely
- A working distance to field of view ratio of between 2:1 and 4:1 is recommend to gain higher performance at the most reasonable price

Effects of Working Distance



75mm lens

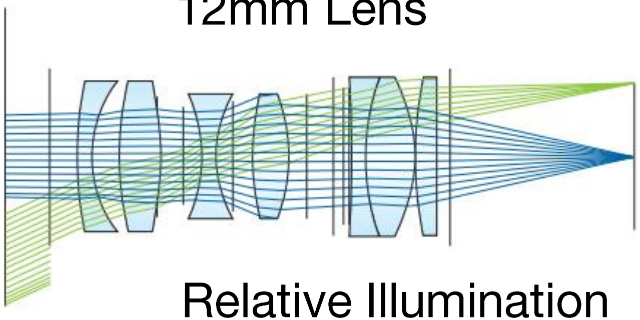




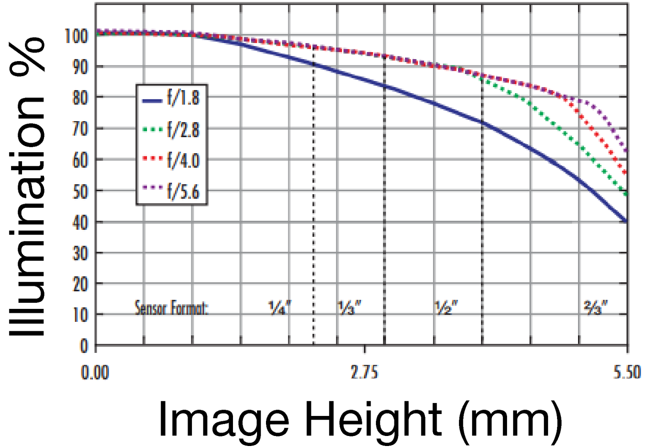
12mm lens

Relative Illumination (Vignetting/Lens Shading)

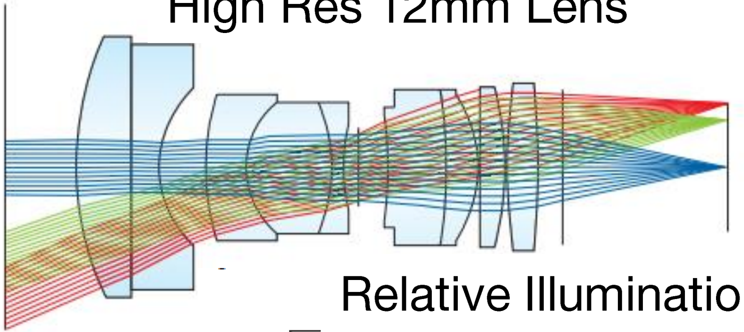
12mm Lens



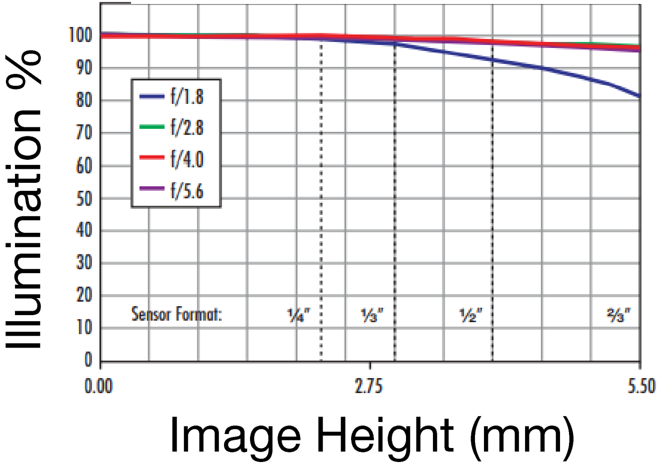
Relative Illumination



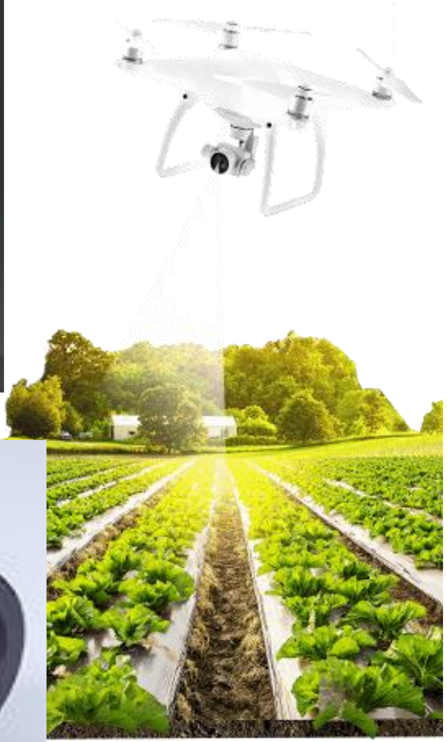
High Res 12mm Lens



Relative Illumination

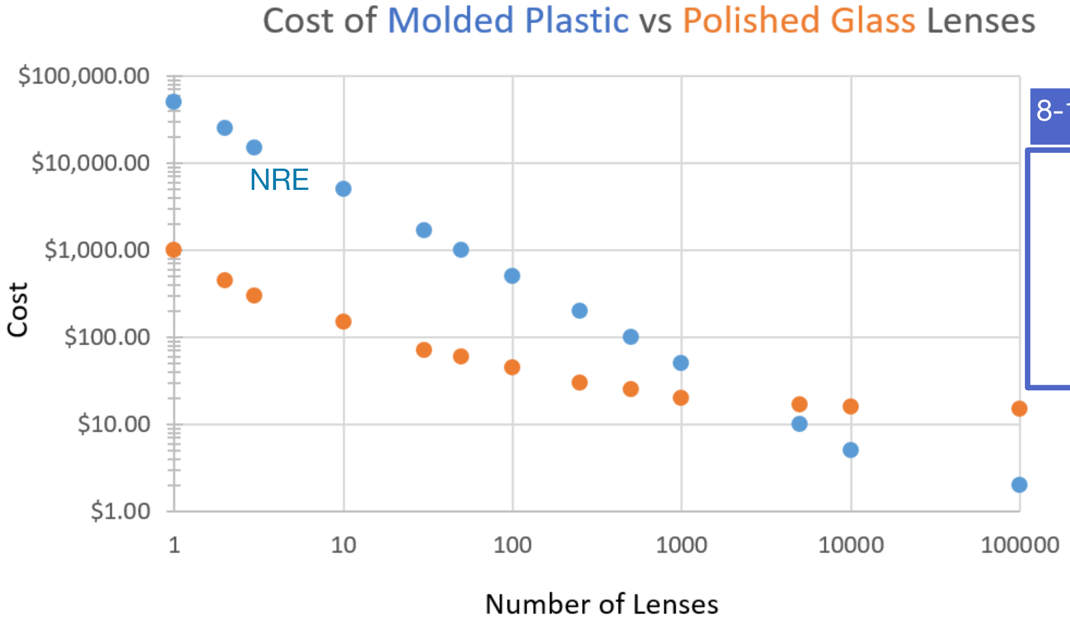


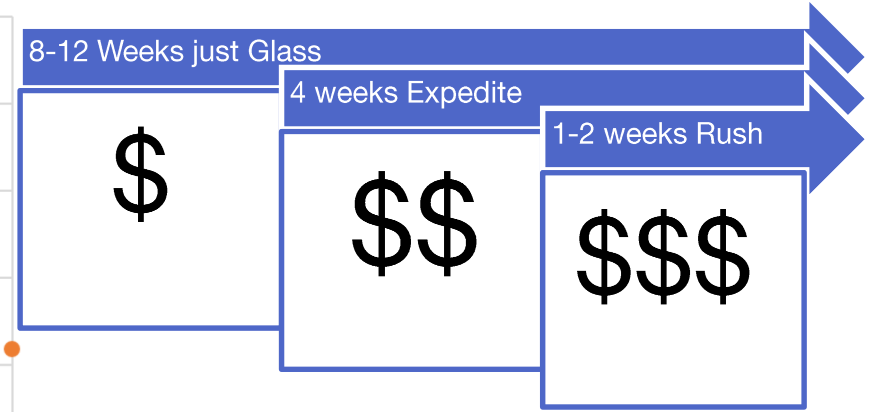
Consider Your Application



Consider Your Application

- Quantity and Cost
- Lead Time and Cost

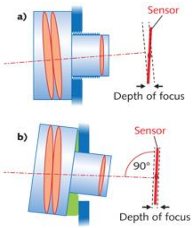


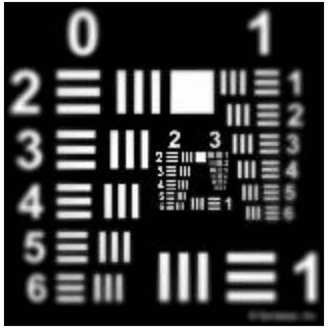


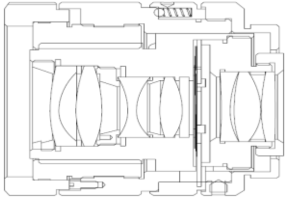
Focus Shift

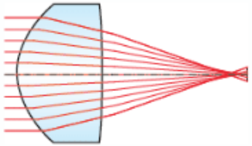
Sources of Focus Shift and Reduced MTF

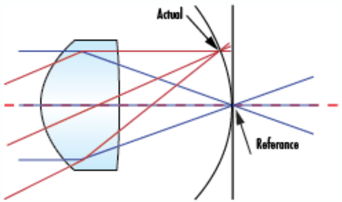
- Reduced MTF
    - spherical, field curvature, astigmatism, chroma
  - Lens spacing/index, flange distance, filter thickness
  - Veiling Glare
  - Manufacturing process
- Focus Shift
  - Thermal/Materials
  - Ruggedized

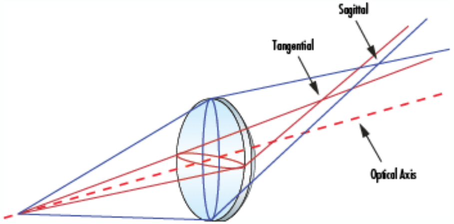


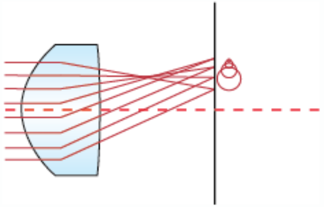


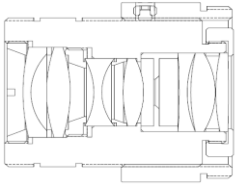








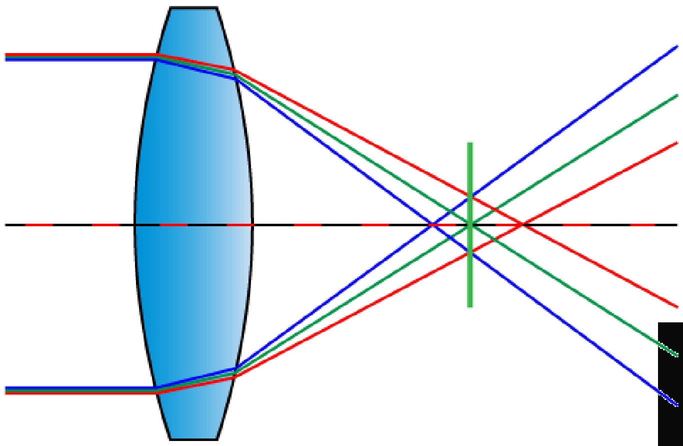




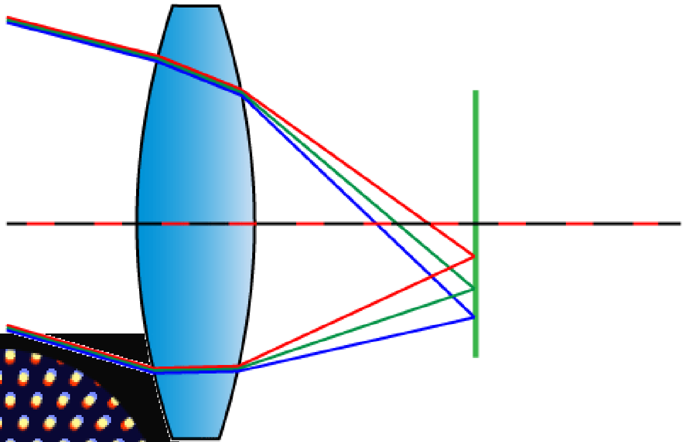
Color Aberrations

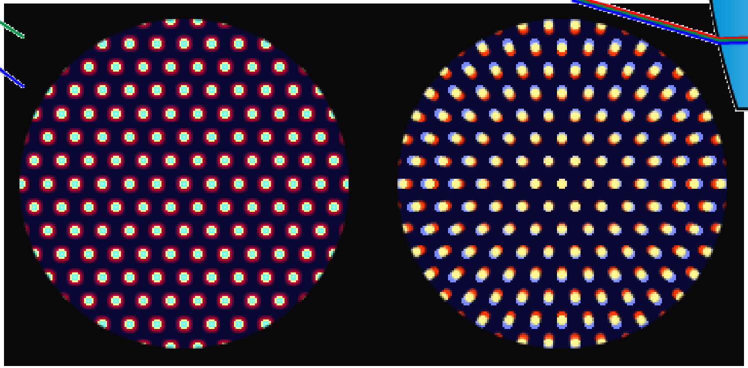
Color Aberrations

Longitudinal / Axial
Chromatic Aberration

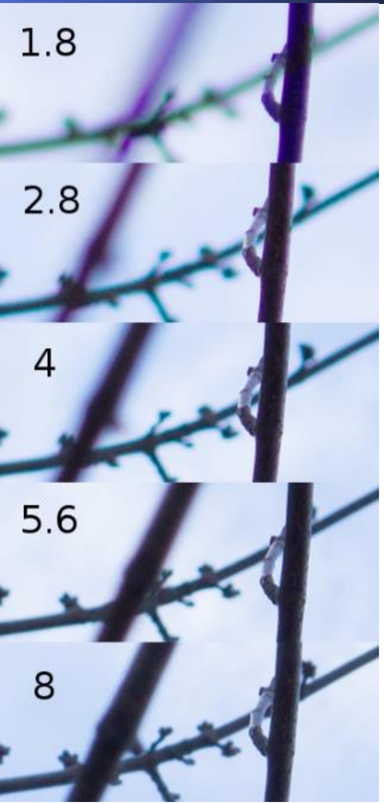


Lateral / Transverse
Chromatic Aberration





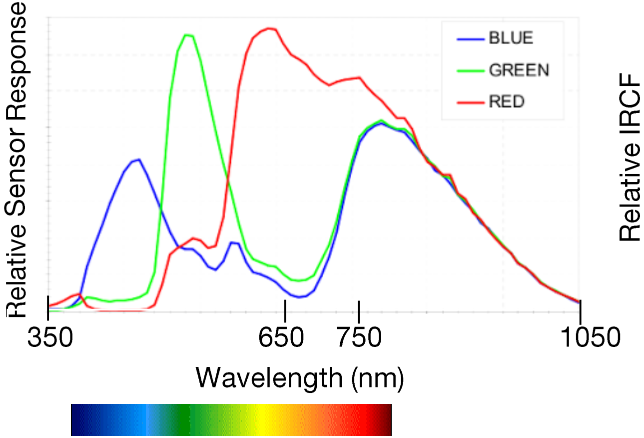
Purple Fringe

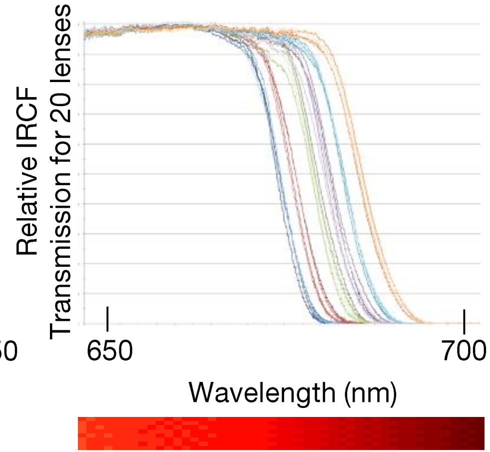


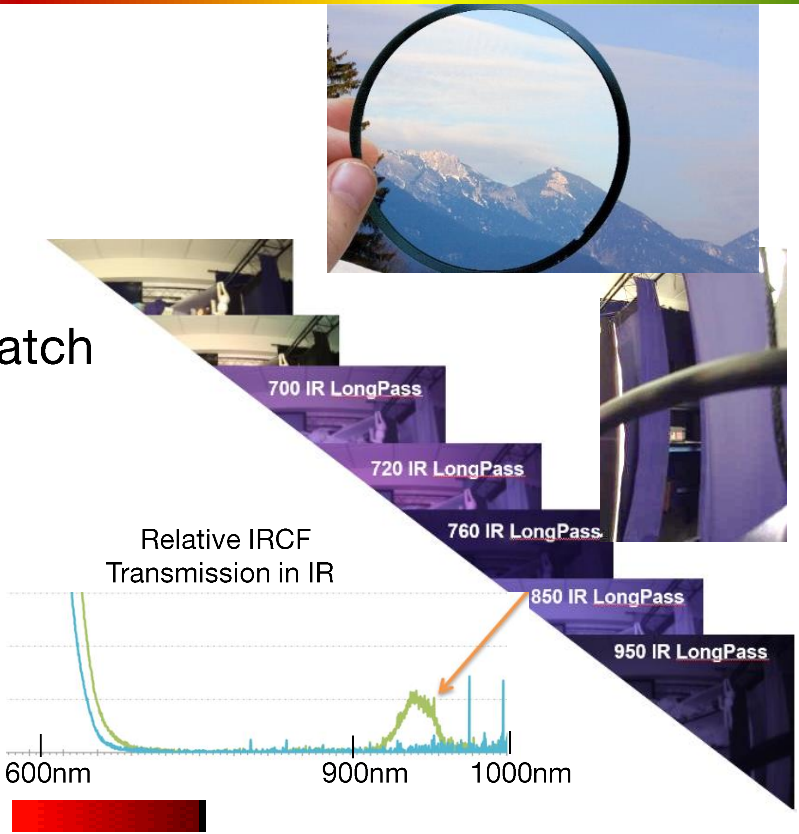
Coatings

Need for Coatings & Coating variations

- CFA (Color Filter Array) Curves
- UV or IRCF (Infrared Cut Filter)
  - Dichroic/Interference vs Blue Glass
  - Angle Dependence & batch variation/scratch







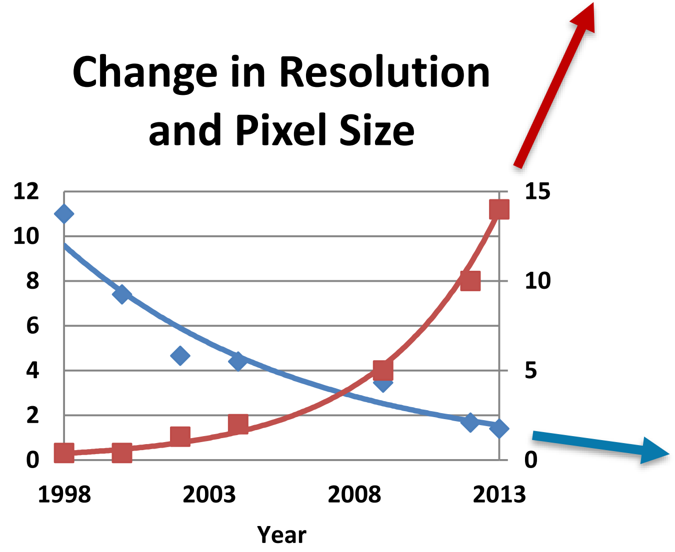
Pixel Size & Diffraction Limit

Challenges with Decreasing Pixel Sizes

- Standard Optics struggle to keep pace with sensor development
- Challenges are high resolution and light throughput

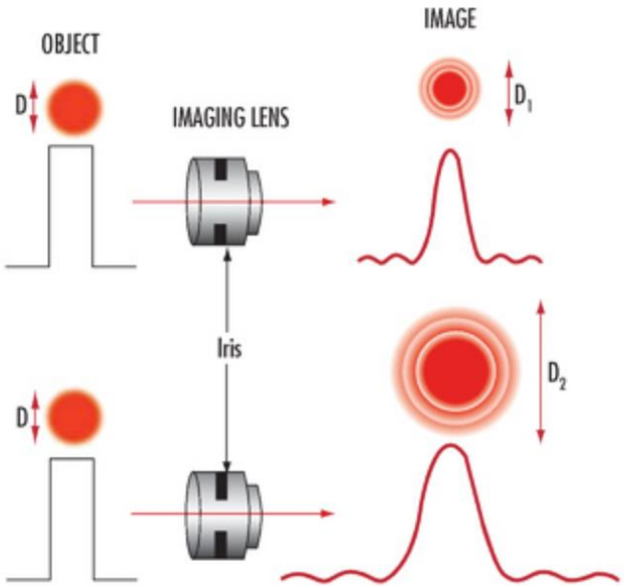
<u>The laws of physics create limitations</u>

- Manufacturability of high performance optics
- Higher performing optics have limited range of usability
- Higher performance will have come at the expense of depth of field and depth of focus

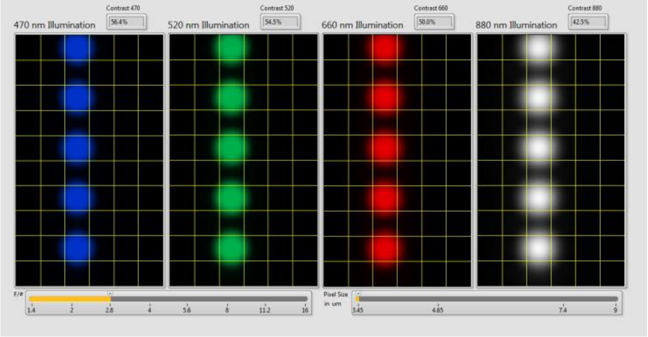


How Diffraction and f/# Affect Performance

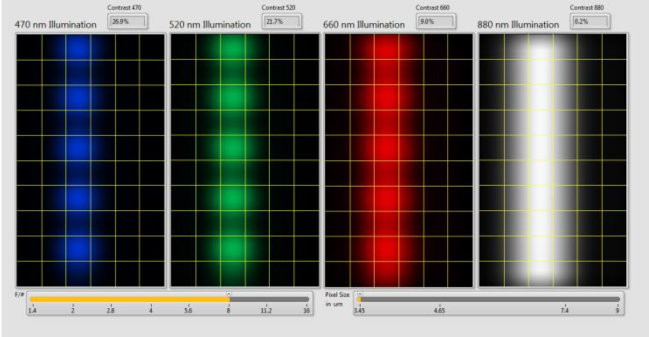
- Smallest achievable spot size = 2.44 * λ * f/#



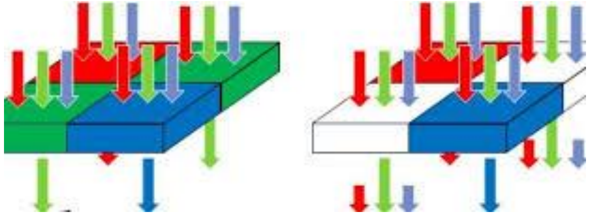
f/2.8



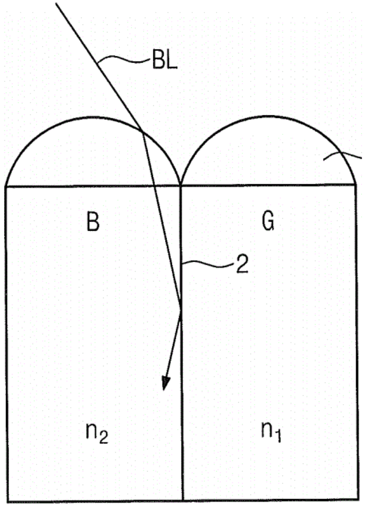
f/8



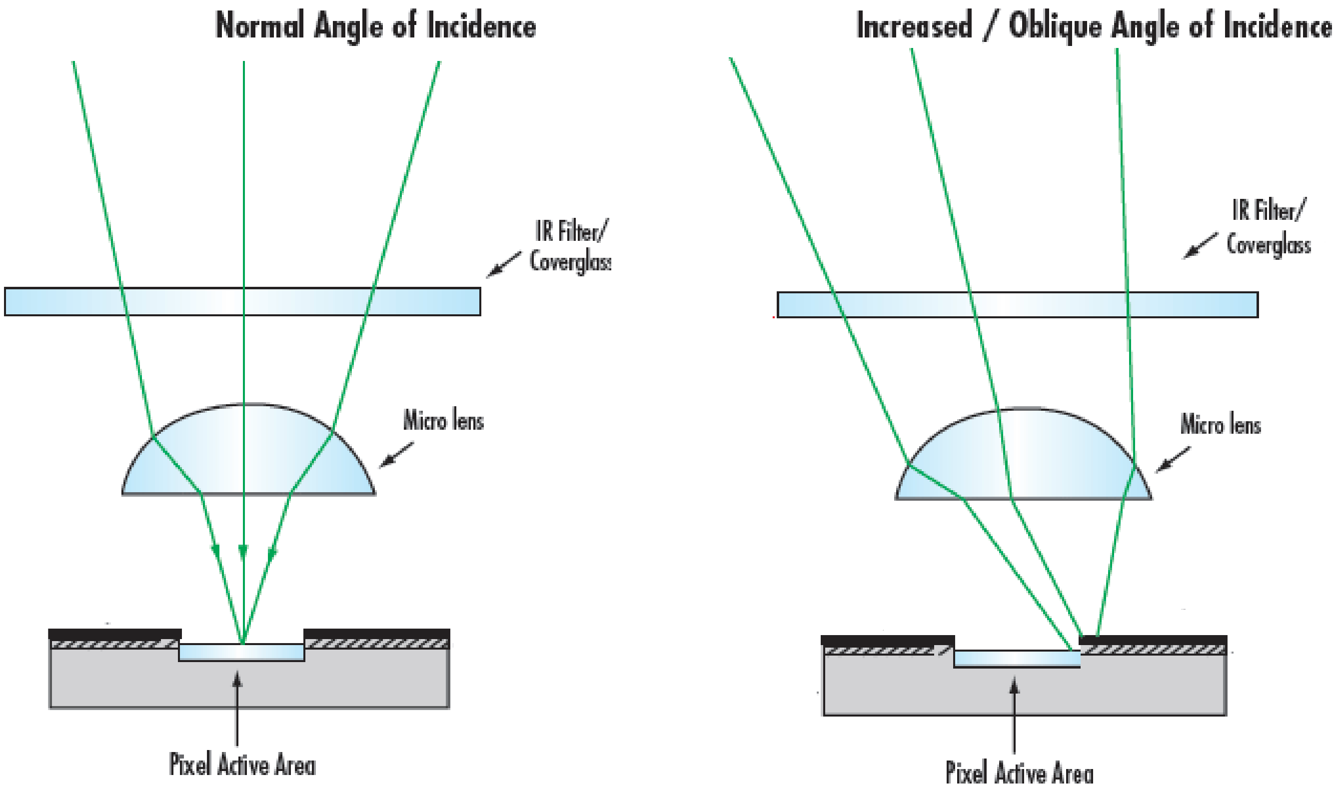
Larger Chief Ray Angles (CRAs) to Handle Extreme Sensor Demands



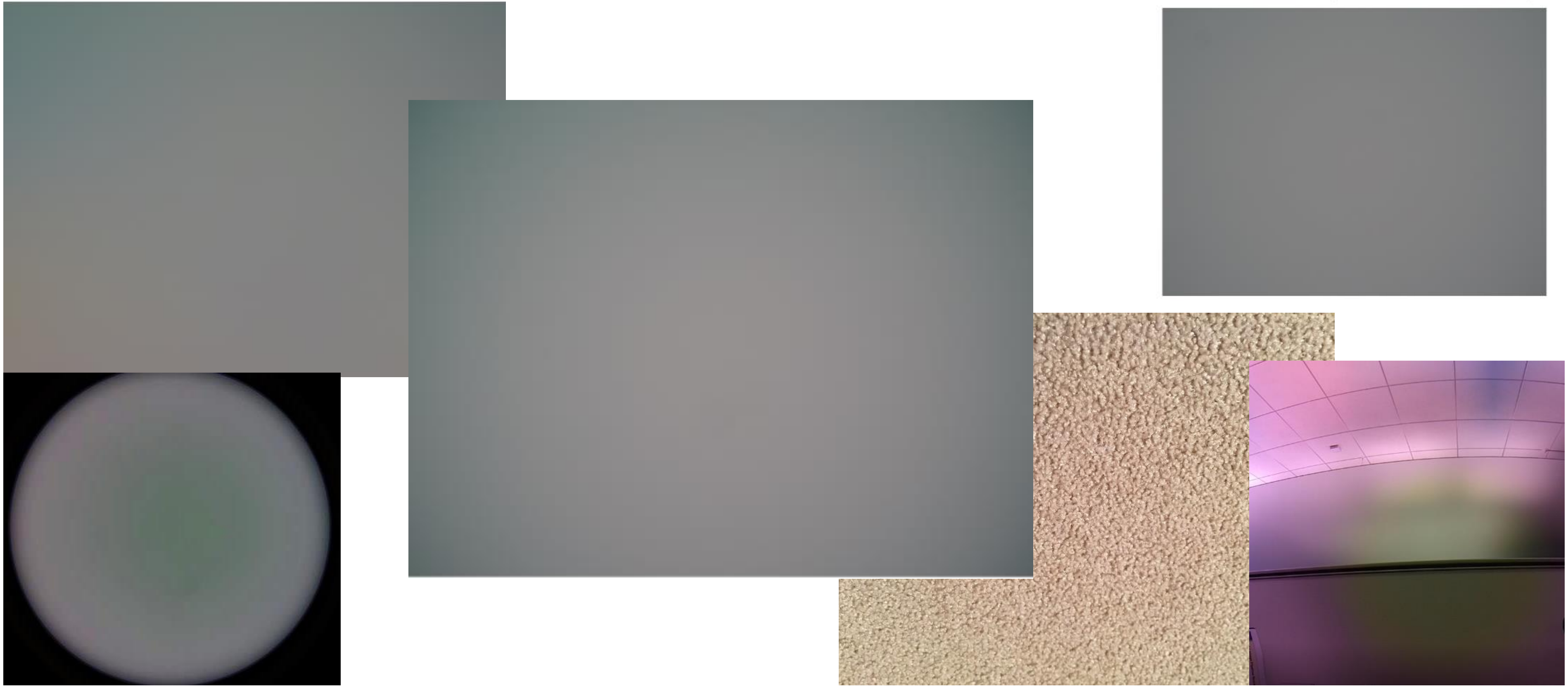
- Small pixels, large formats
  - Pixels < 6μ fill factor issue
  - Ratio of CFA thickness & pixel pitch = color crosstalk
- Wide angle lenses, short total track lengths (TTL)
- Add micro lens arrays
  - Offset of micro lens from pixels
  - Large CRA allows TTL to reduce
    - Pushes molded aspheres/other shapes



Larger Chief Ray Angles (CRAs)

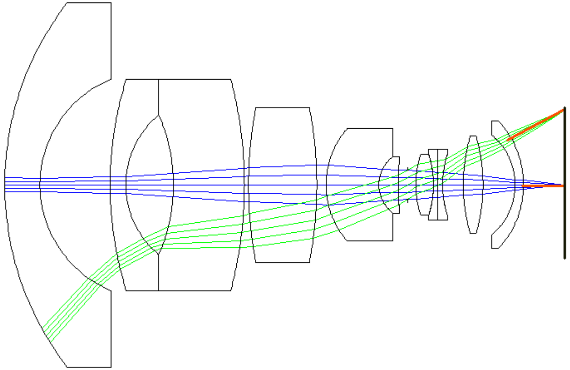


Color Shading due to CRA matching + Coatings



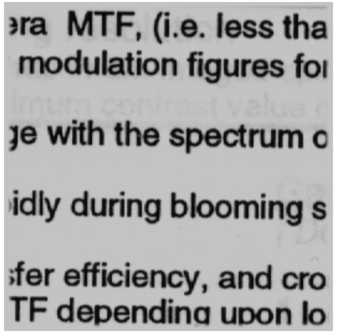
Lens Shading and Sensor Shading

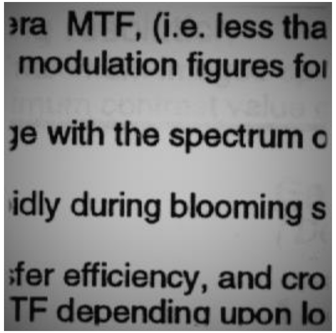
- Lens Shading/Relative Illumination used to reduce aberrations during design
- Combined with sensor shading/CRA matching + protective windows
- Calibrate/correct for color and lens shading = color noise in corners



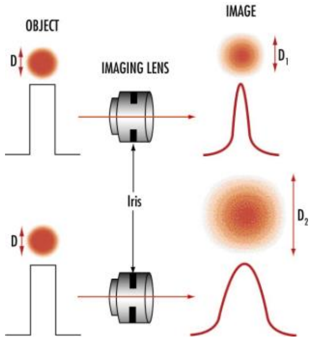
$$\boxed{RI \sim \cos^4\theta}$$

$\theta = 30° \rightarrow RI = .56$
$\theta = 45° \rightarrow RI = .25$
$\theta = 60° \rightarrow RI = .06$





Conclusions



- Choose right lens and sensor for your application
- Explore solutions from different industries
  - Match lens to sensor
  - Simple equations to get started
  - Remember required ‘resolution’ is more than just pixel calculation
    - Lens MTF, Aberrations, Diffraction Limit, Tolerances, DOF
- Many root causes for image to image variation
  - Isolate optical components, coatings, assembly, +mechanics, +sensor, + system integration & firmware
  - During design: think calibration requirements & manufacturing process

Resource Slide

- Image Credit and Active Alignment explanation
- Edmund Optics Tech Notes:
  - Fundamental Imaging System Parameters
  - Lens Design: Aberrations and MTF
  - Distortion
  - DOF
  - Athermalization
  - Aspheres
- Books for further reading:
  - Modern Optical Engineering, Warren J Smith
  - Principles of Color Technology, Roy S Berns