# Advanced Optics for Vision

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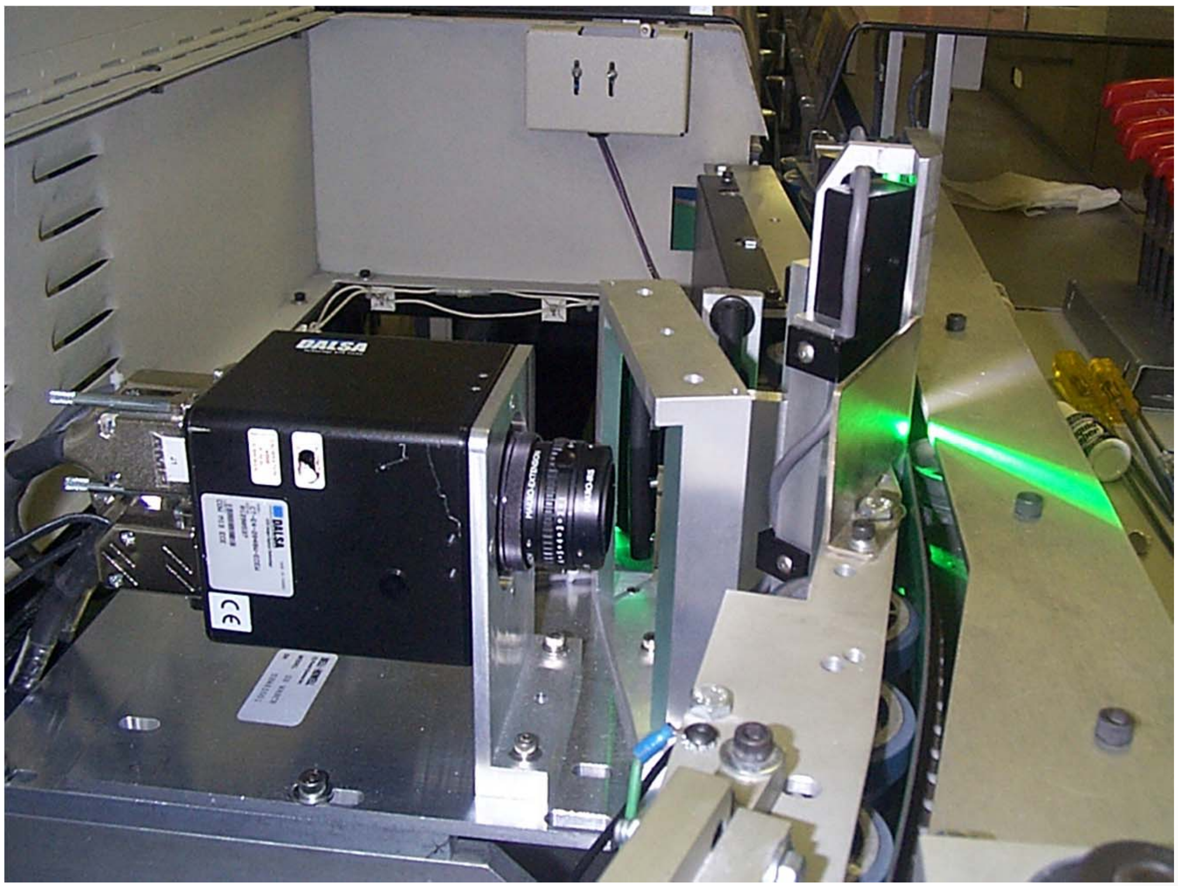
# Machine Vision

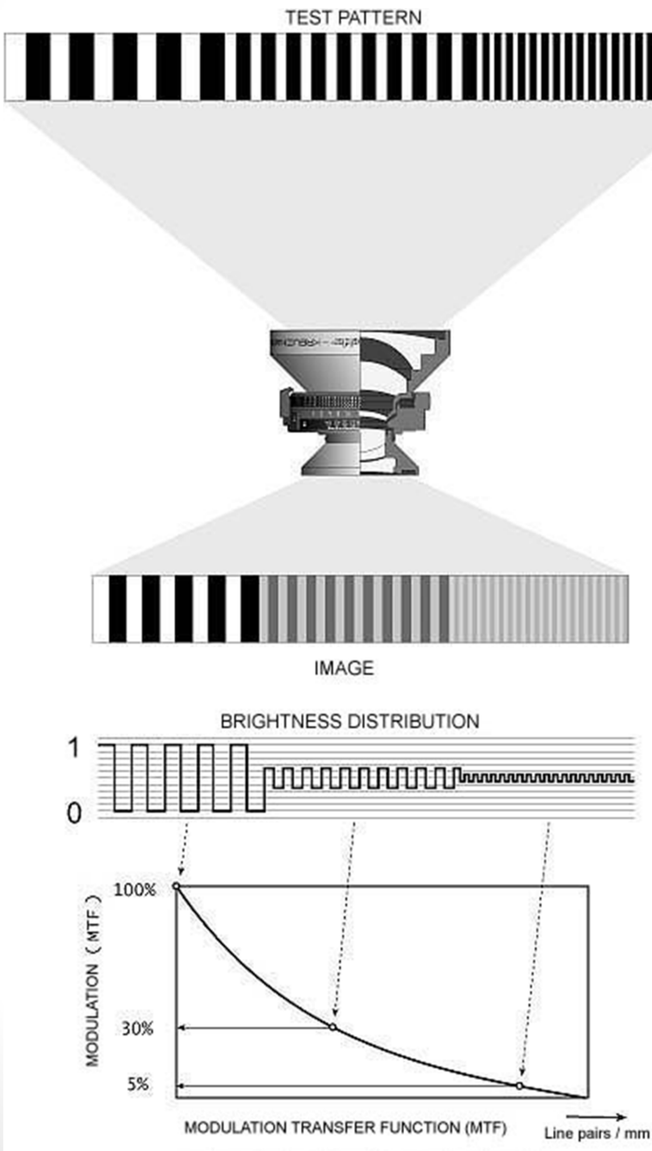
**Machine Vision (MV) ≡** Interpretation of an image of an object or scene through the use of optical non-contact sensing mechanisms for the purpose of obtaining information and / or controlling machines or processes.



# MTF / Lens Performance

- **Modulation Transfer Function (MTF)**
  - What is it
  - Aberration effects
  - f/number effects
  - Manufacturing effects
  - How should you use it

# MTF Cont…




The MTF (Modulation Transfer Function) describes the quality of an imaging system with respect to sharpness and contrast.

**Brightness Distribution: 1 = white 0 = black**
**Modulation (MTF) = "Difference in Brightness" Modulation as a function of the fineness of lines (No. of line pairs/mm)**

$$\text{Modulation} = \frac{I(MAX) - I(MIN)}{I(MAX) + I(MIN)}$$

## Intensity / Brightness

$$\text{MTF} = \frac{\text{Modulation In Image}}{\text{Modulation In Object}}$$

# MTF – Radial and Tangential Orientation

The MTF depends on the orientation of the object structures. Therefore the MTF is typically stated for test grids orientated in tangential and radial direction to the optical axis.

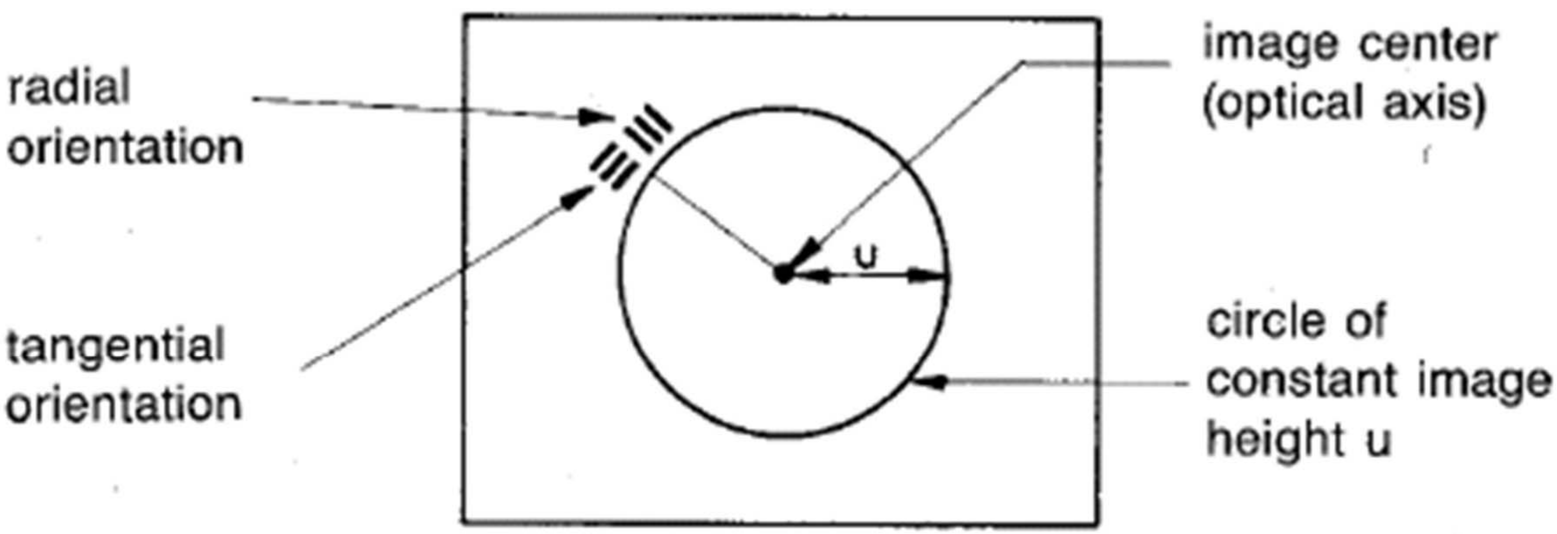
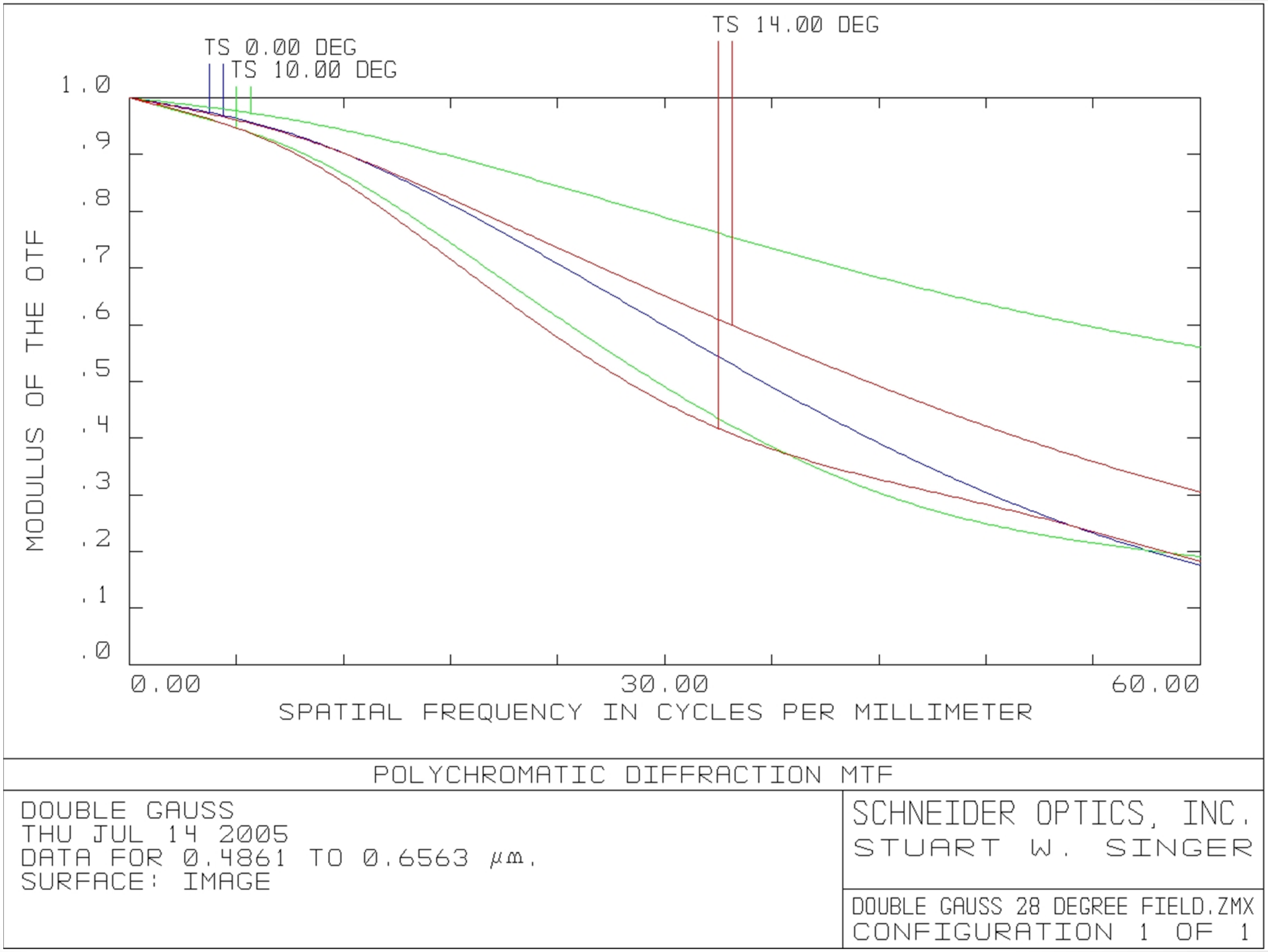
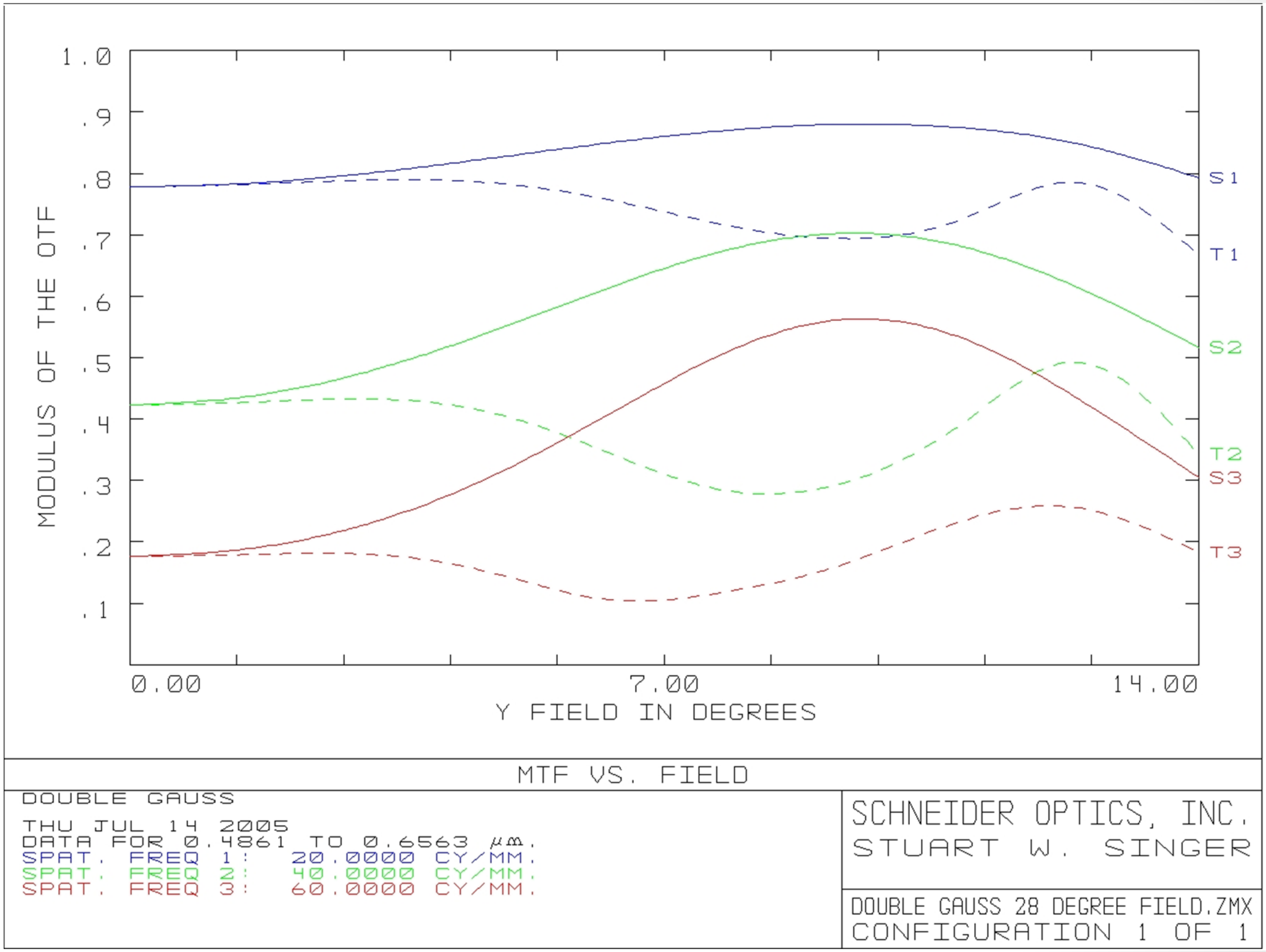



Figure 2
Radial and tangential orientation of object patterns.

# Classic MTF Plot



# MTF vs. Image Height (ISO/DIN)



# How Are Contrast and Resolution Linked

- Resolution and contrast are closely linked.
- Resolution is defined at a specific contrast.
- Contrast describes the separation in intensity between blacks and whites.
- For an image to appear well defined black details need to appear black, and the white details need to appear white.
- The greater the difference in intensity between a black and white line, the better the contrast.
- The typical limiting contrast of 10-20% is often used to define resolution of an CCD imaging system.
- For the human eye a contrast of 1-2% is often used to define resolution.

# Final MTF (Lens Quality)

- **Final Lens System MTF is comprised of numerous factors:**
  - Actual lens Design
  - f/number being used
  - Lens Performance with respect to actual Working Distance (Magnification)
  - Manufacturing Tolerances / errors
  - Focus position
  - Pixel Size………. To be Discussed
  - Object contrast
  - Lighting
  - Actual Blur Circle
  - Anti-Reflection Coatings / Veiling Glare

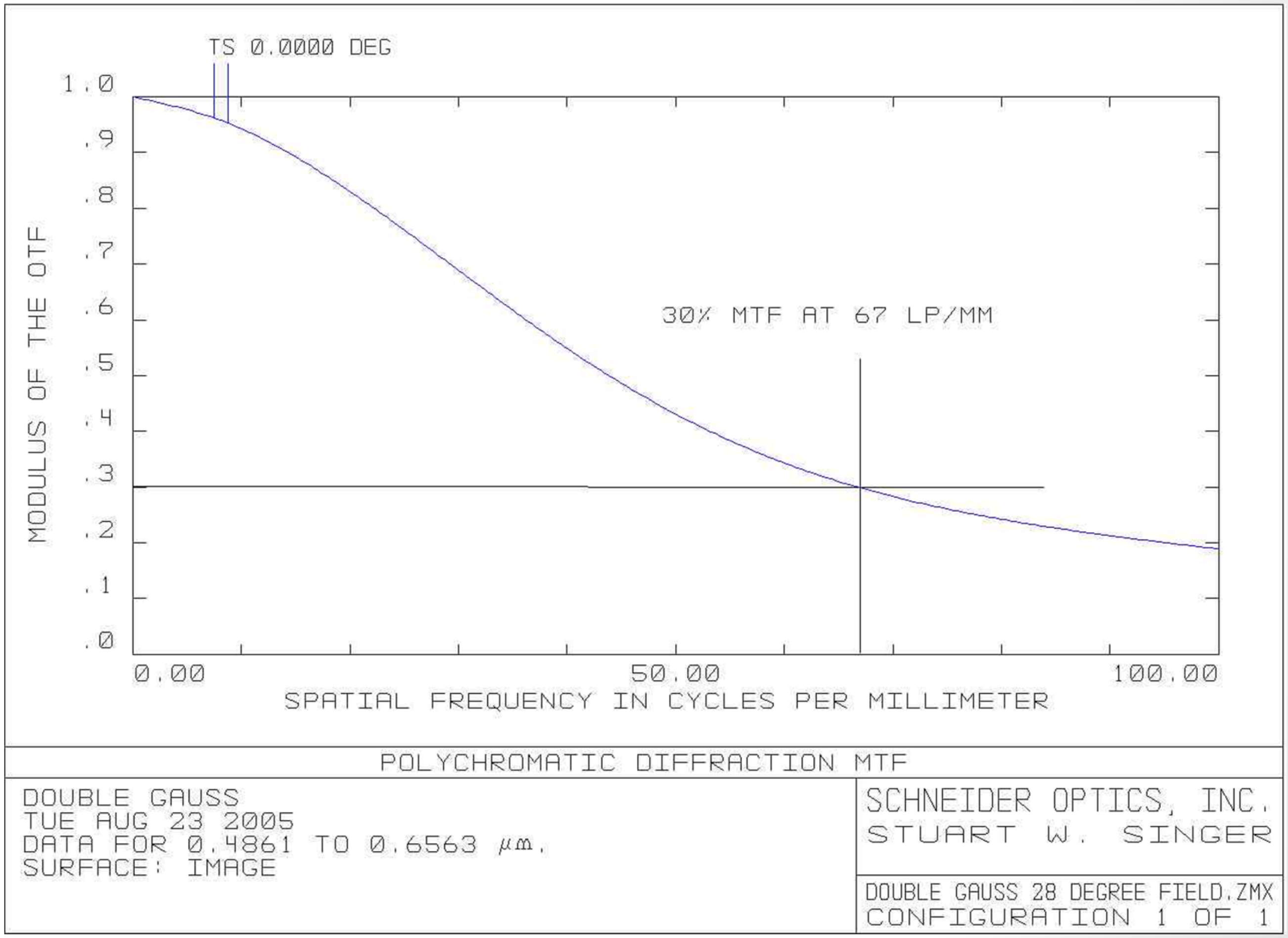
A reputable optical company should be able to provide you with MTF tolerances from Theoretical vs. what you actual purchase. Also other parameters (such as focal length tolerances, etc…..) should be provided.

# MTF (Ideal vs. Reality)

## What MTF do I need in my "Lens"?

**Typical criteria for a lens selection process:**
**30% contrast at 0.67*Nyquist frequency or**
**30% at Nyquist frequency**
**(but risk of Moiré-effects)**

**Note:**
**The total system's MTF is the product of the lens's MTF, filter's MTF, camera MTF and the MTF of the electronics.**



# Resolution Conversion

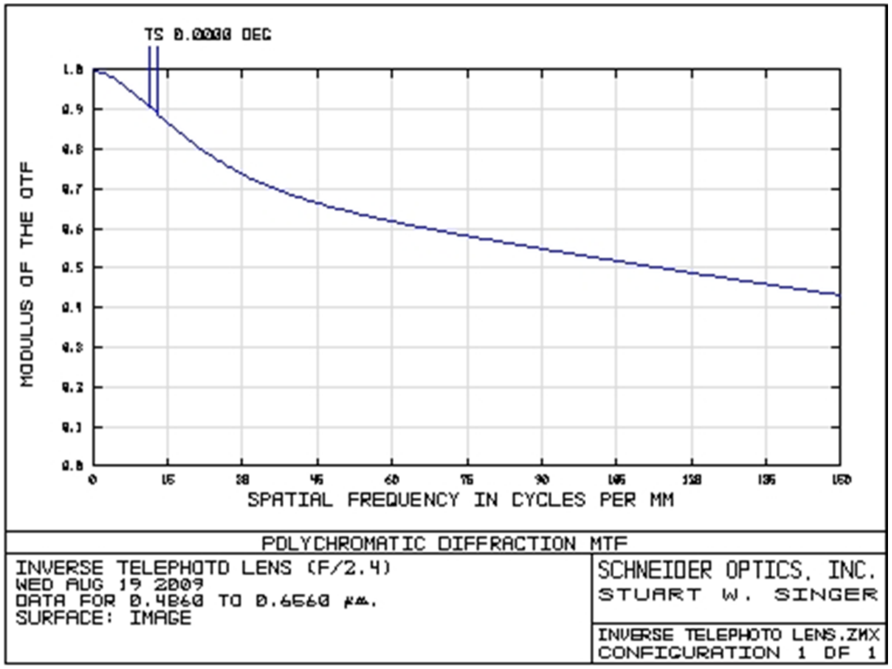
Lp/mm or Cy/mm $\longrightarrow$ Cy/mrad

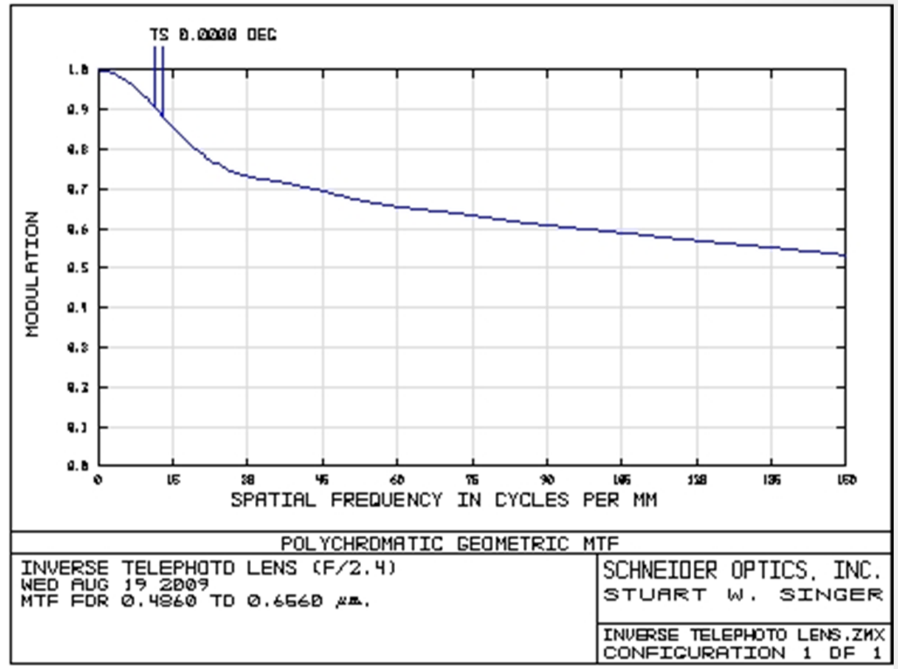
$$\text{Lp/mm} = \frac{1}{(f')\,\text{Tan}[(1000)(\text{Cy/mrad})]^{-1}}$$

$$\text{Cy/mrad} = \frac{1}{(1000)\,\text{Tan}^{-1}[(\text{Lp/mm})(f')]^{-1}}$$

**NOTE: Have Calculator in Radian Mode….!**

# Diffraction Vs. Geometrical MTF




**Diffraction MTF Polychromatic**

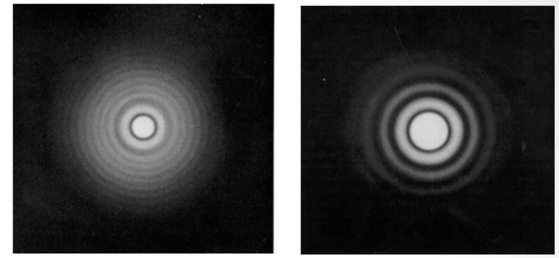
**Geometrical MTF Polychromatic**

**Note: Geometrical MTF is approx. 20% >**

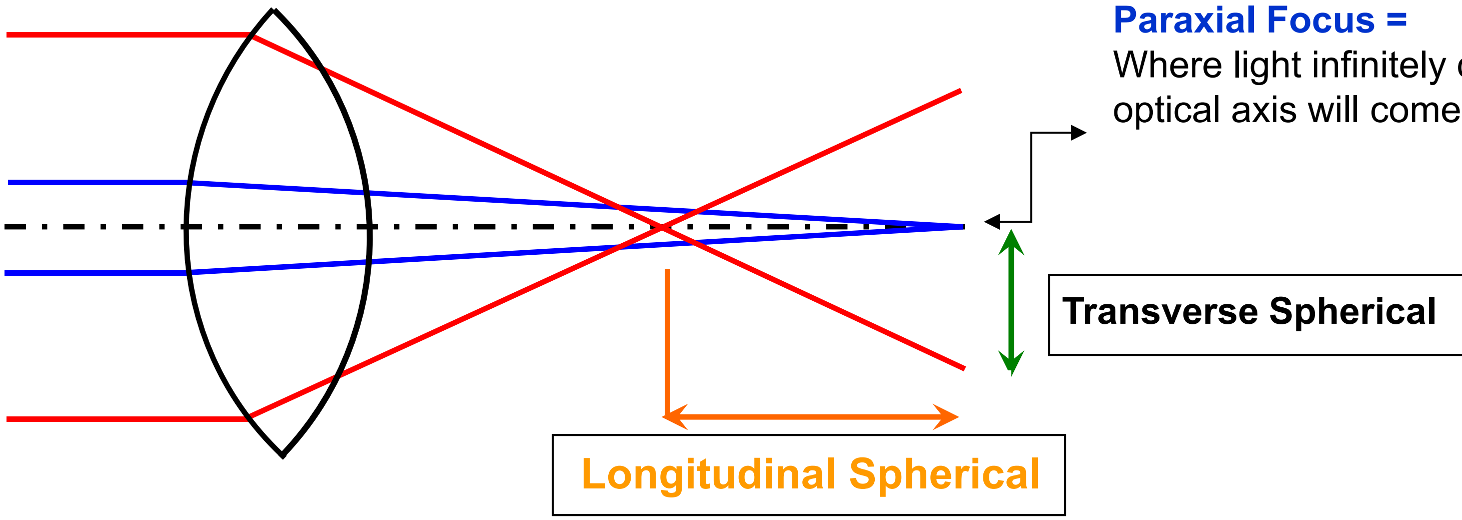
# Basics Optical Aberrations

## Basics Optical Aberrations

# Spherical Aberration



**Paraxial Focus =**
Where light infinitely close to the optical axis will come to focus




**Spherical Aberration** = can be defined as the variation of focus with aperture.

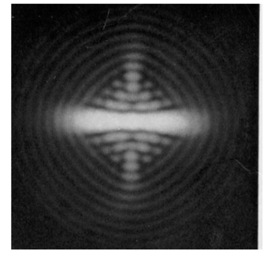
# Spherical Aberration

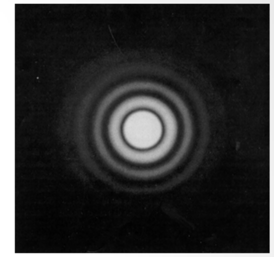
No Spherical Aberration

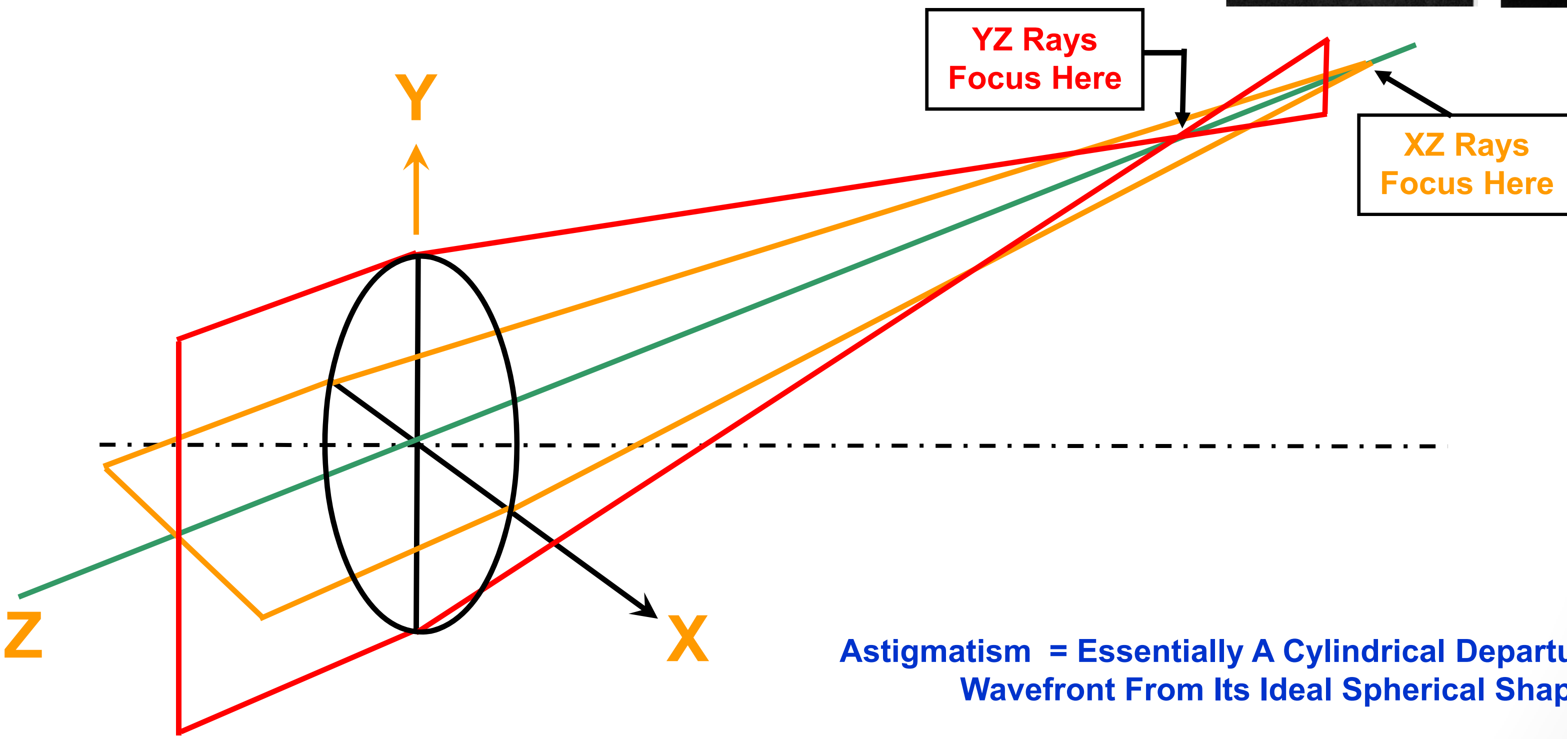
With Spherical Aberration

# Astigmatism

An Astigmatic Image Results When Light In One Plane (YZ) is Focused Differently From Light In Another Plane (XZ)

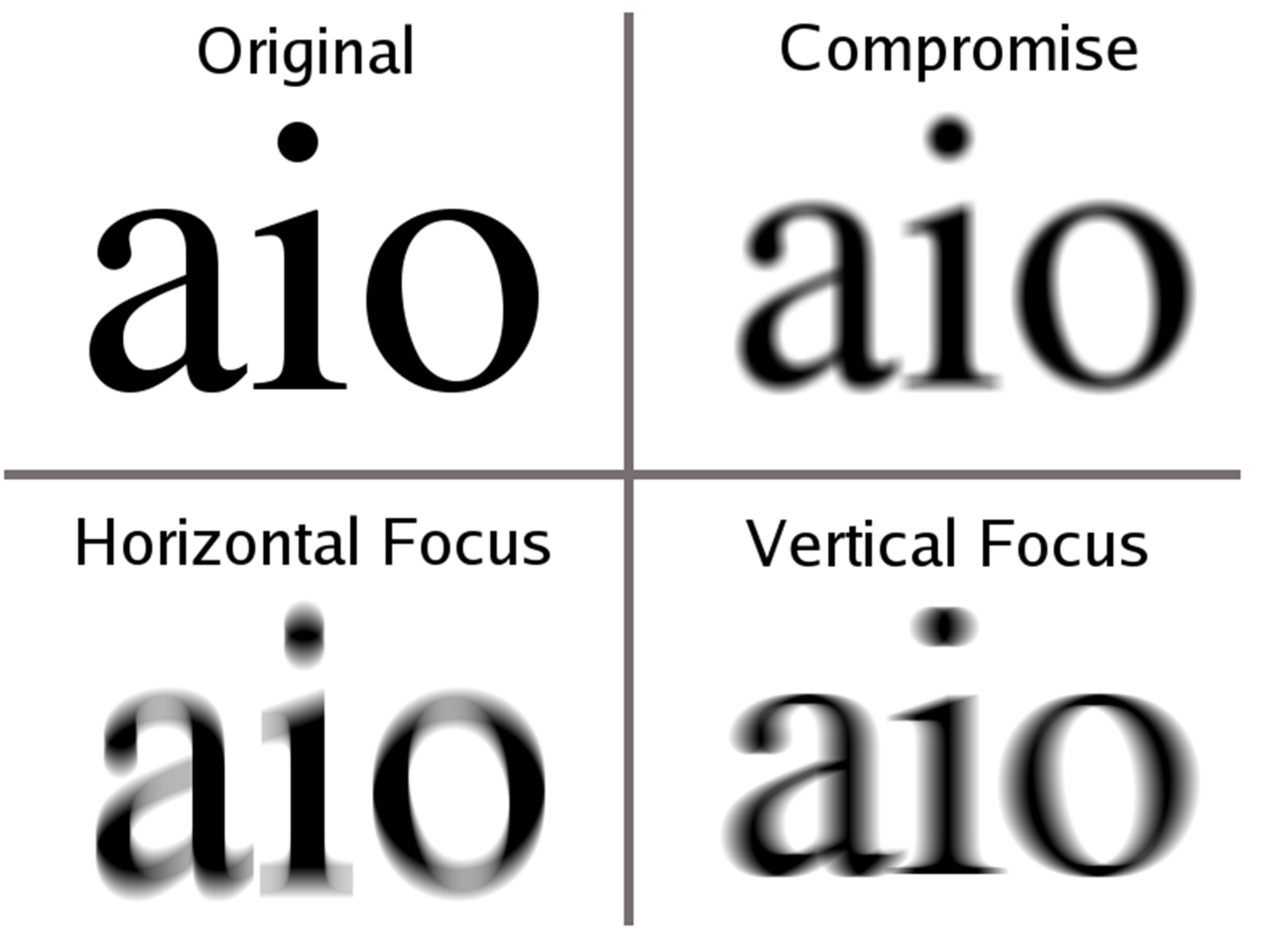






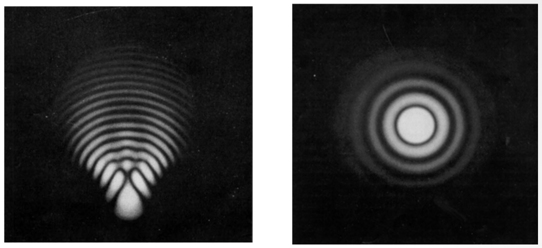

Astigmatism = Essentially A Cylindrical Departure of The Wavefront From Its Ideal Spherical Shape

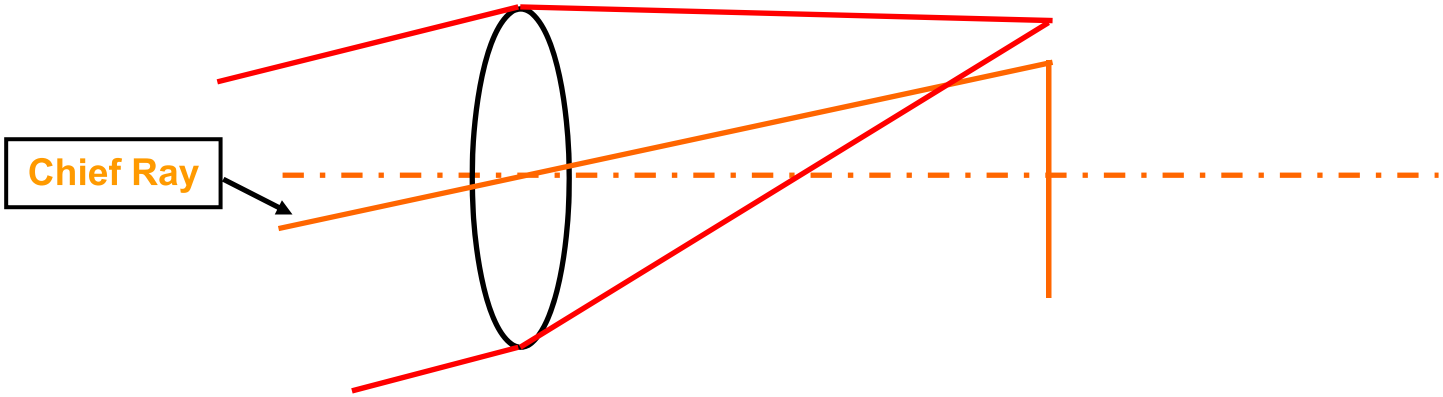
# Astigmatism



# Coma

**Coma:** can be defined as the variation of magnification with aperture.






- The Central or Chief Ray usually defines the image height
- A Comatic Image occurs when the outer periphery of the lens produces a higher or lower magnification than dictated by the Chief Ray
- Coma can be controlled by shifting the aperture stop and selectively adding elements

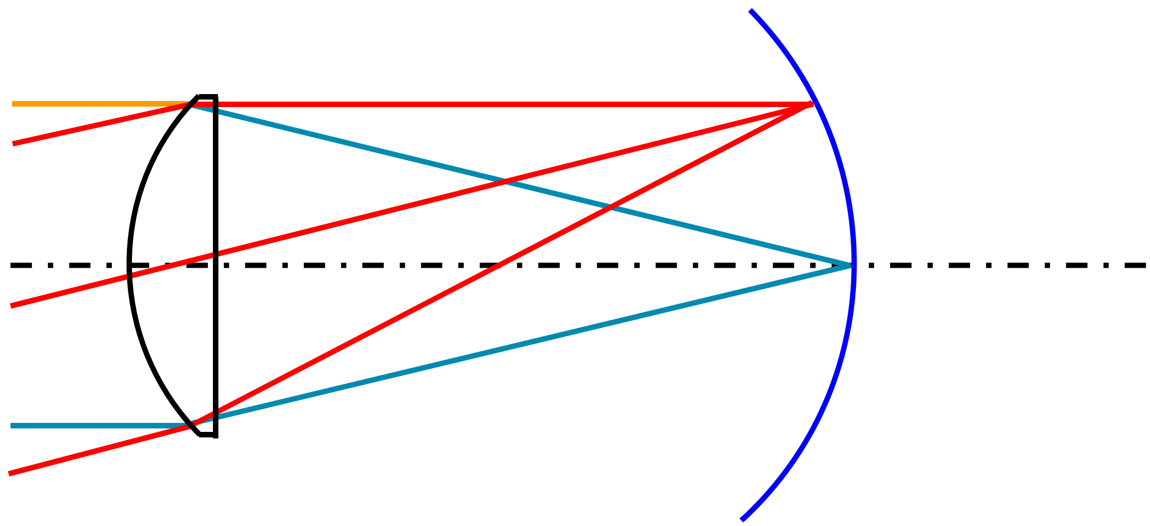
# Coma

No Coma

With Coma

# Field Curvature

In the absence of Astigmatism, the image is formed on a curved surface called the **"Petzval"** Surface



For a single element as shown above, the Petzval Radius is approximately 1.5 times the focal length

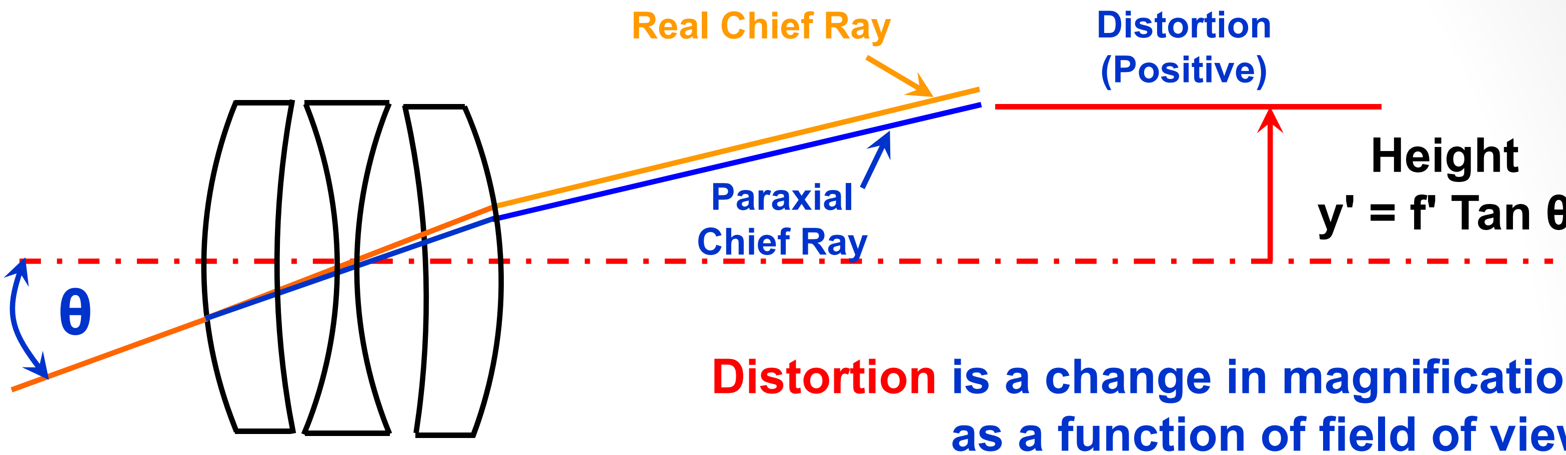
This is for glass of 1.5 refractive index

# Field Curvature

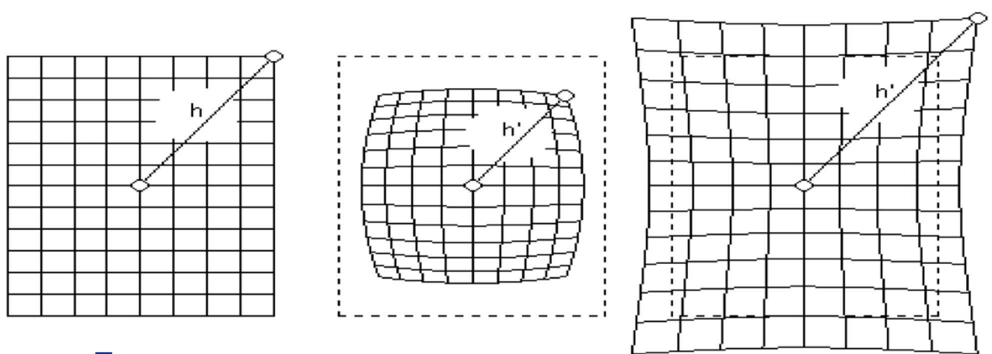
No Field Curvature

With Field Curvature

# Geometric Distortion




**Distortion is a change in magnification as a function of field of view**




**Zero Distortion** | **Negative or Barrel** | **Positive or Pincushion**

# Geometric Distortion

$$GD\% = \left(\frac{h' - h}{h}\right) x\ 100$$

* Note *  GD (Positive = Pin  & Negative = Barrel)
In projection note the effect = reversal

**EXAMPLE**

GD% = Percent Geometric Distortion

h' = Actual Image Height (includes distortion)

h = Image Height (without distortion effect)

GD% = 10
h = 4.5mm

h' = 4.95mm (actual Image Height)

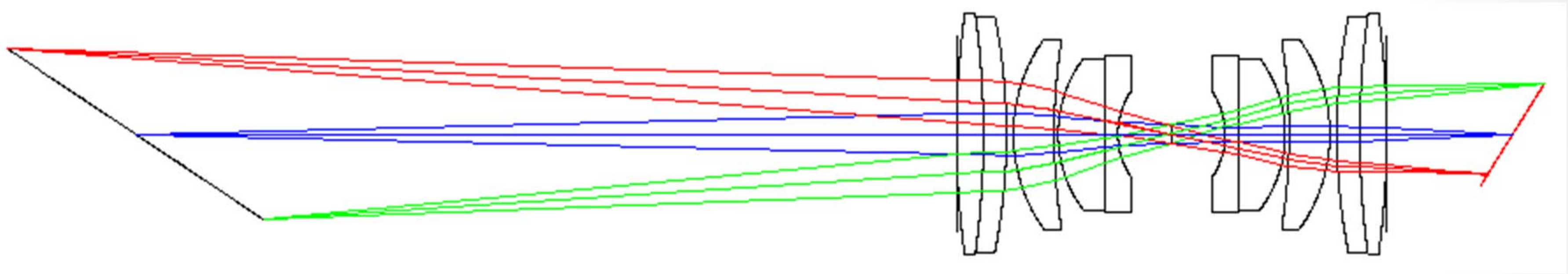
* Note *  Must Use Common Units

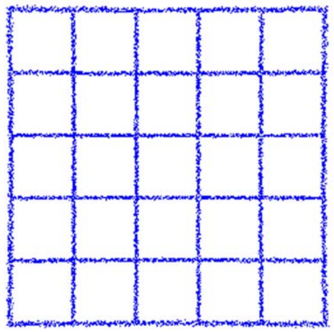
# Geometric Distortion Pictures

**No Geometric Distortion**

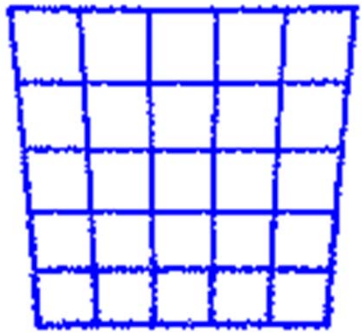
**- 40% Geometric Distortion**

# Keystone Distortion

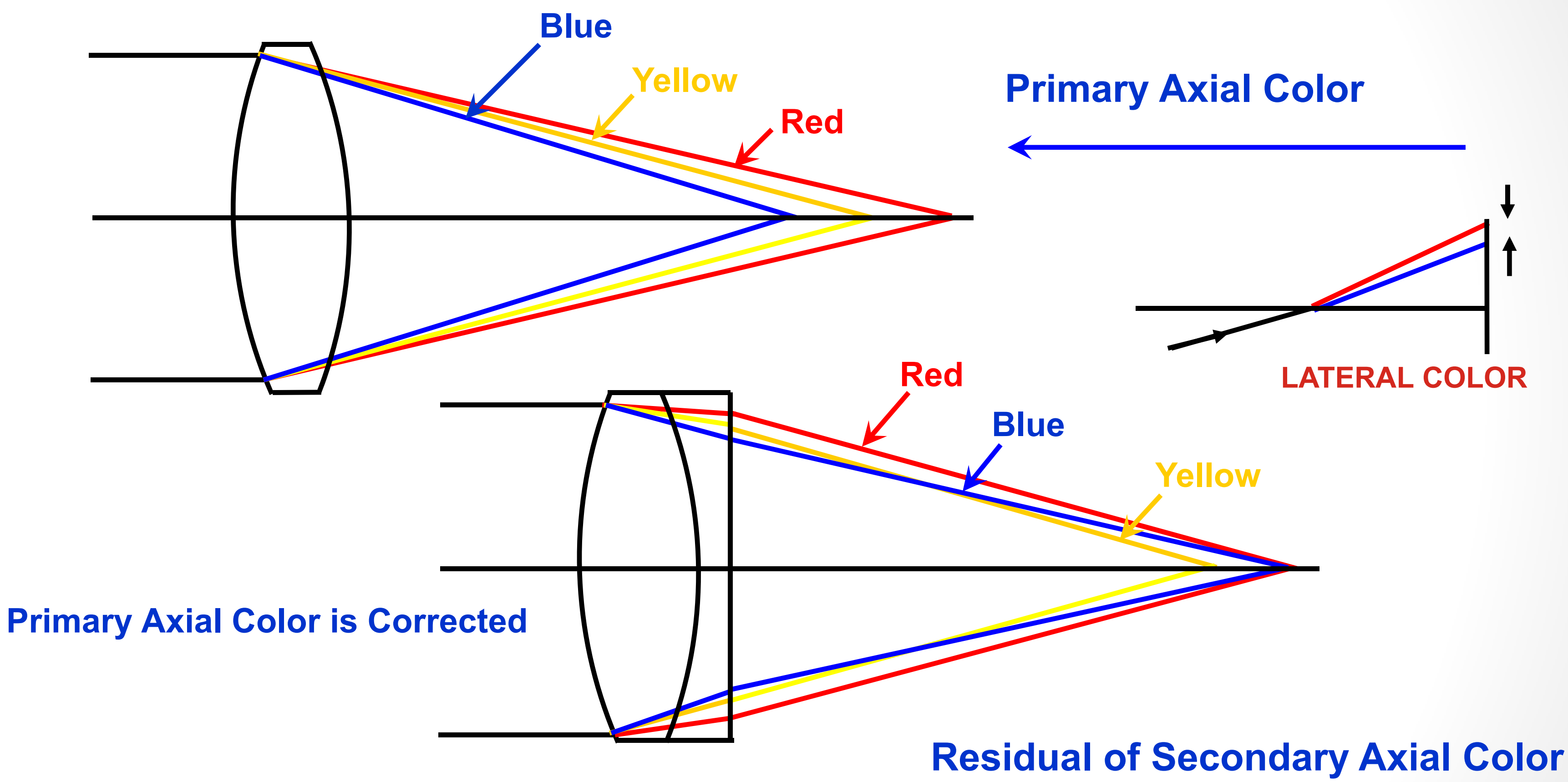




Introduced because of the geometry between the Image Plane and Object Plane.
Scheimpflug condition…great focus (longitudinal magnification), change in magnification with field…



# Axial Chromatic (Longitudinal)



# Chromatic Aberration

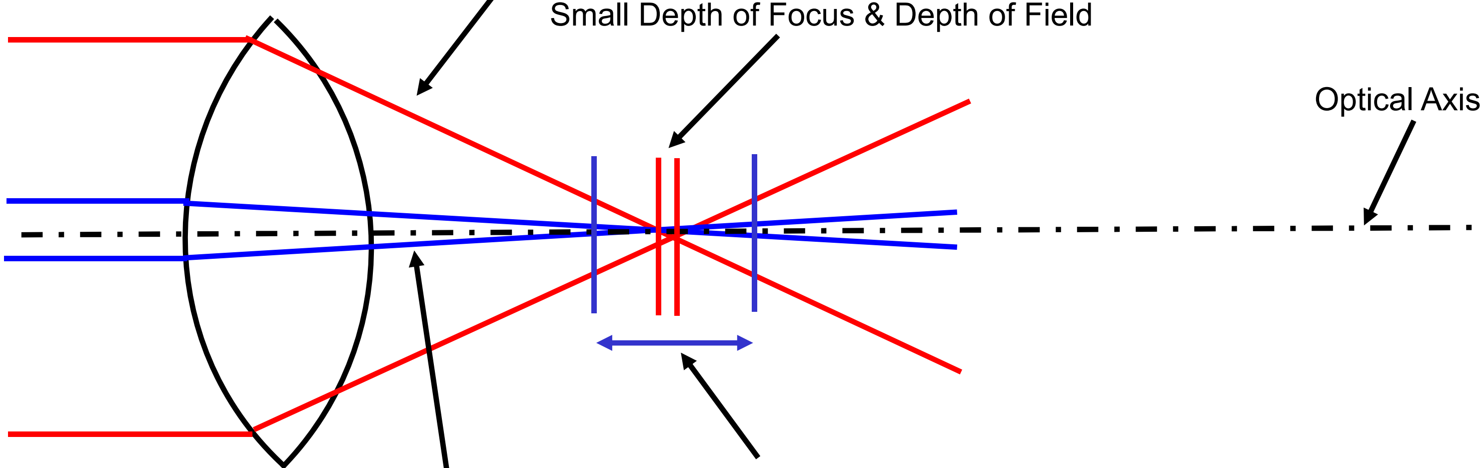
No Chromatic Aberration

With Lateral Color

# f-stops

## Aperture / f-stops

# f/number & Depth of Focus/Field




**f/# = Focal Length / Entrance Pupil Diameter**

**As your f/number is set lower = faster = larger aperture = more light = Smaller Depth of Focus & Smaller Depth of Field**

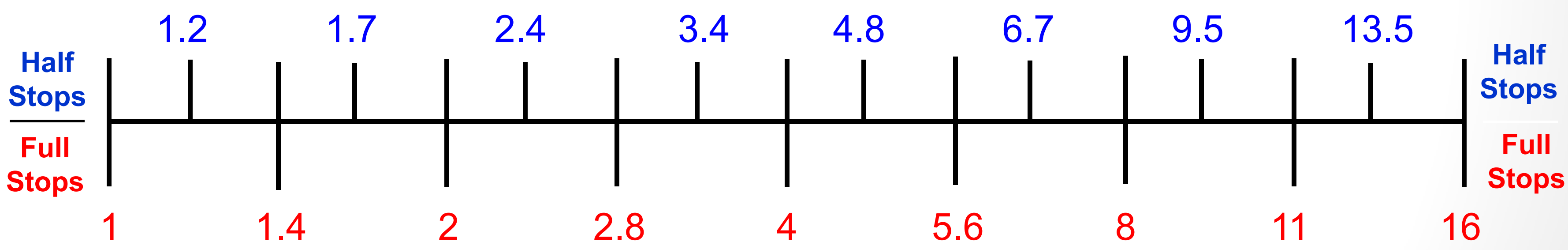
**As your f/number is set higher = slower = smaller aperture = less light = Larger Depth of Focus & Depth of Field**

# f-Numbers cont.

- Increasing the aperture one full stop doubles the amount of light transmitted by the lens
- Reducing the aperture one full stop halves the amount of light transmitted by the lens

**● Lowering the f/number = More Light**

**● Increasing the f/number = Less Light**



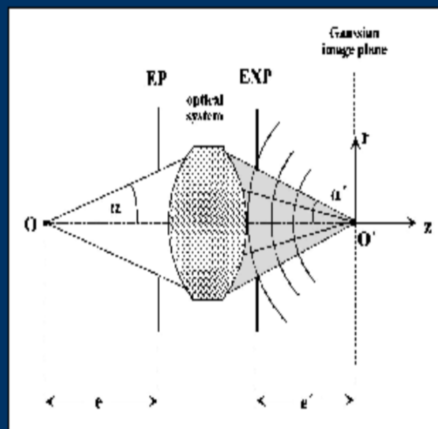

**Full Stops (cont.): 16, 22, 32, 45, 64, 90**

One Full Optical Stop = Factor 2x or 1/2x (Amount of Light)

# Optical Parameters

# Airy Disk

## Diffraction limited imaging: the Airy disc




For a point-like source the wave fronts on the object side are sphrical waves and limited in their extent by the EP. On the image side these wavefronts are limited by the EXP. For a diffraction limited system these wavefronts are again spherical with their center in the image point O'.

**Note**: a diffraction limited (or perfect) optical system is given if the wavefront in the EXP deviates less than $\lambda/4$ from a sphere (**Rayleigh-criterium**)

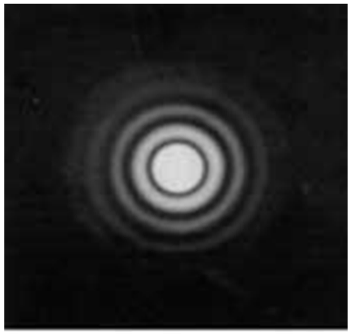
Because of the limitation of the spherical wavefronts the image point is no more a point without extension but a blurred disc, the diffraction disc.

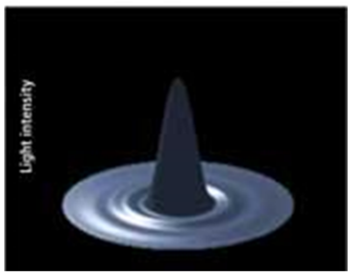
The extent of this disc depends (besides the wavelength $\lambda$) only on the form and extent of the limiting opening. For circular symmetric limitations (as usual in optics) the relative illumination distribution in the image plane is the so called **Airy disc**. For image points on optical axis this disc is rotationally symmetric.

$$\boxed{\Theta = 2.44\,\lambda\, f/\#}$$

**Θ ≈ 84% Total Energy**

# Airy Disk Diameter






The Airy disk is the smallest point a beam of light can be focused. The disk comprises rings of light decreasing in intensity and appears similar to the rings on a bulls-eye target. The center bright spot contains approximately 84% of the total spot image energy, 91% within the outside diameter of the first ring and 94% of the energy within the outside diameter of the second ring and so on

| | **Red = HeNe** | **0.0006328mm** |
|---|---|---|
| | **Diameter of Airy Disk** | **Diameter of Airy Disk** |
| f/1.0 | 0.00154mm | 1.54µm |
| f/1.4 | 0.00216mm | 2.16µm |
| f/2.0 | 0.00309mm | 3.09µm |
| f/2.8 | 0.00432mm | 4.32µm |
| f/4.0 | 0.00618mm | 6.18µm |
| f/5.6 | 0.00865mm | 8.65µm |
| f/8.0 | 0.01235mm | 12.35µm |
| f/11 | 0.01698mm | 16.98µm |
| f/16 | 0.02470mm | 24.70µm |

**ADD = (2.44)(f/#)(wavelength)**

# Optical Definitions

**Airy Disk =** The central peak (including everything interior to the first zero or dark ring) of the focal diffraction pattern of a uniformly irradiated, aberration-free circular optical system (Lens)

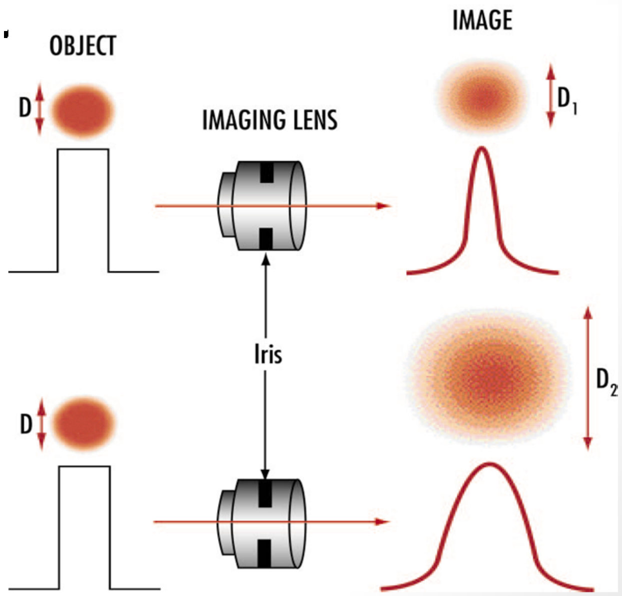
**Circle of Confusion =** The image of a point source that appears as a circle of finite diameter because of defocusing or the aberrations inherent in the lens design or manufacturing quality

**Blur Circle =** The image formed by a lens on its focal surface (image plane) of a point source object
The size of the blur circle will be dictated by the precision of the lens and the state of focus
The blur can be caused by aberrations in the lens, defocusing and manufacturing defects

**f/number (f/#) =** The expression denoting the ratio of the equivalent focal length of a lens to the diameter of is entrance pupil. Lower f/# on a well corrected lens = small spot size in the image plane – Larger f/# = larger spot size In the image plane

# How Does Diffraction Affect Performance?

- Not even a perfectly designed and manufactured lens can accurately reproduce an object's detail and contrast.
- Diffraction will limit the performance of an ideal lens.
- The size of the aperture will affect the diffraction limit of a lens.
- f/# describes the light gathering ability of an imaging lens (lower f/# lenses collect more light).
- As lens aperture decreases, f/# increases.



# MAGNIFICATION (β´)

$$\boxed{\beta' = y' / y}$$

* Note * Must Use Common Units

β' = Magnification

y' = ½ Image Height (CCD Length)

y = ½ Object Height (1/2 FOV)

**EXAMPLE**

y' = 4.4mm (1/2 CCD Length)
y = 50mm (1/2 FOV)
β' = 0.088
1/β' = 11.36x
Reduction of the Object

When β' < 1.0 = (Reduction of Object Size)

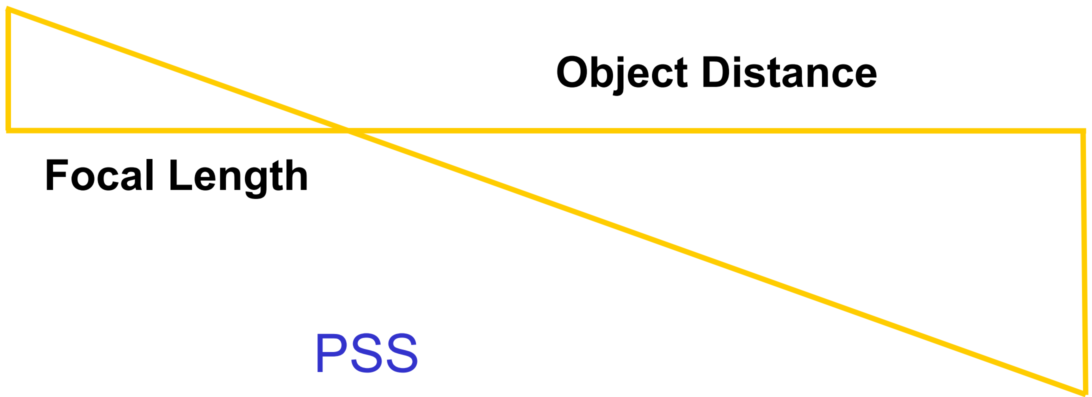
When β' > 1.0 = (Enlargement of Object Size)

# Magnification (PSS)

- **Pixel Sampled Size** **(PSS)** = Footprint of one Pixel in Object Space.

  **Pixel Size (PS)**

$$\text{Magnification} = \beta' = PS / PSS$$




$$\frac{\text{Pixel Size}}{\text{Focal Length}} = \frac{\text{PSS}}{\text{Object Distance}}$$

**Note: Can be use also for - CCD Size / Focal Length = FOV / Object Distance**

* Note * Must Use Common Units

# Magnification/Resolution DPI

## Typical Document Scanning Specification

**Dots Per Inch (dpi)**

1 inch

**256 dpi**

1(dpi) = 1/256 = 0.003906 inch = 1 dot

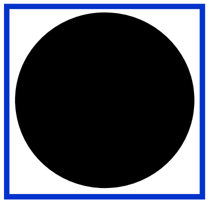
0.003906"/0.03937 = 0.099229

**1 dot = 0.09922mm**

Sensor (example)

Pixel Size (PS) = 13 microns

**PS = 0.013mm**



1 Pixel will Sample 1 Dot

Pixel Sampled Size (PSS) = 0.09922mm

Footprint of the pixel in Object Space

**Magnification**

ß' = PS / PSS

ß' = 0.013 / 0.09922

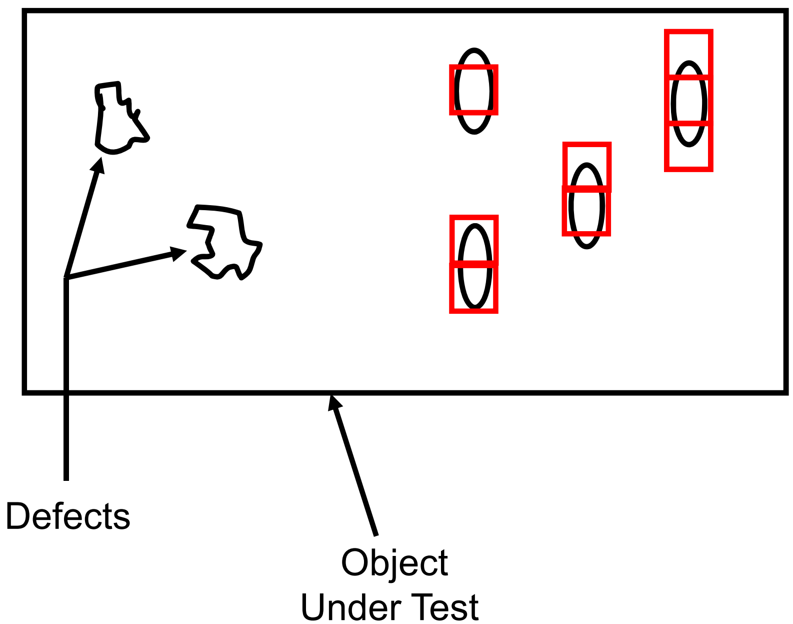
ß' = 0.13102

1/ß' = 7.63x reduction

# Resolution (Object / Image)

## Minimum Defect Size

**How Many Pixels do I need to Cover (sample) The Smallest Defect I am Trying to Resolve ?**




Sampled Size (in object space) = PSS

Object Resolved Distance (ORD) = 2(PSS)

**PSS = Pixel Sampled Size in Object Space (footprint)**

CONSIDER

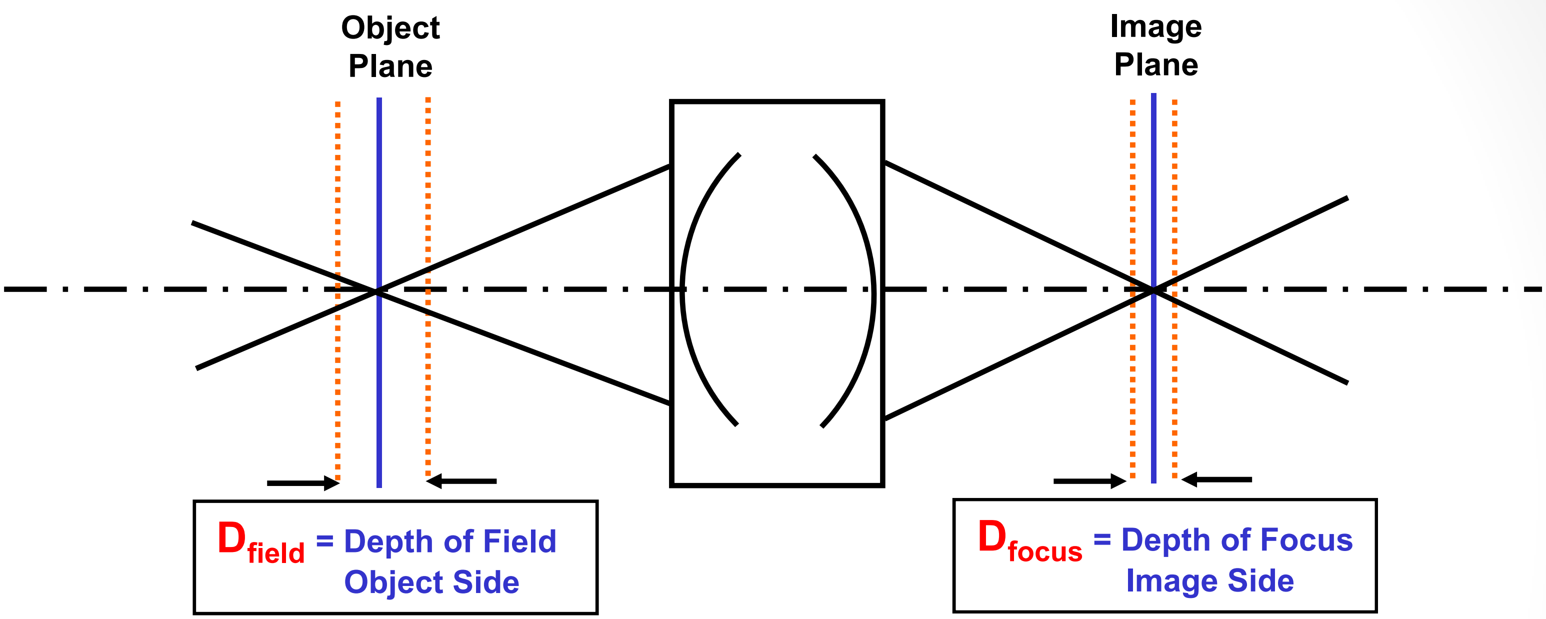
1) What is the size of the smallest defect/object I am trying to resolve?
2) What is the size of my Pixel?
3) How many pixels do I need to resolve my smallest defect?
4) Items 1,2,3 from above define my Optical Magnification !

Example: Why can't I count sheets of stacked paper?

Typical Minimum = 2 Pixels to sample
On/Off needed to find Edge

# Depth of Field & Depth of Focus

# Depth of Field / Focus Relationship




$$D_{focus} = (\beta')^2 \times D_{field}$$

A typical lens for Document Scanning:

Focal Length = 50mm
f/# = 2.8
Pixel Size = 0.013mm
Magnification = 0.14286
(7x reduction)

⇨ $D_{focus}$ = 0.08mm
$D_{field}$ = 4.04mm

# Hyperfocal Distance

**The object distance at which a camera must be focused so that the Far Depth of Field just extends to infinity.**

$$H = \frac{(f')^2}{(f/\#)(c)}$$

Using the Hyperfocal Distance "method" is best when you only know the closest distance that your object will be from your lens/camera; the farthest distance could be anywhere from there to infinity

**EXAMPLE**

**Focal Length (f') = 50mm**
**F-Number (f/#) = 5.9**
**Circle of Confusion (c) = 0.010mm**
**i.e. Pixel Size or any Value**

**H = 42,373mm**

* Note * Must Use Common Units

# DEPTH OF FIELD (Far)

Depth of Field = The amount by which the object may be shifted before the acceptable blur is produced.

H = Hyperfocal Distance
f' = Focal Length
a = Focus Distance
(distance from lens front nodal point to the principal plane of focus at the object)

$$\text{Depth of Field (Far)} = \frac{(H) \times (a)}{H - (a - f')}$$

**EXAMPLE**

f' = 50mm
a = 1000mm
H = 42,373mm

FAR = 1,023mm

FYI Depth-of-Field (Far & Near) Equations should be used for objects that lie between (300mm to 2,500mm) from the lens/camera

* Note * Must Use Common Units

# DEPTH OF FIELD (Near)

Depth of Field = The amount by which the object may be shifted before the acceptable blur is produced.

$$\text{Depth of Field (Near)} = \frac{(H) \times (a)}{H + (a - f')}$$

H = Hyperfocal Distance
f' = Focal Length
a = Focus Distance
(distance from lens front nodal point to the principal plane of focus at the object)

**EXAMPLE**

f' = 50mm
a = 1000mm
H = 42,373mm

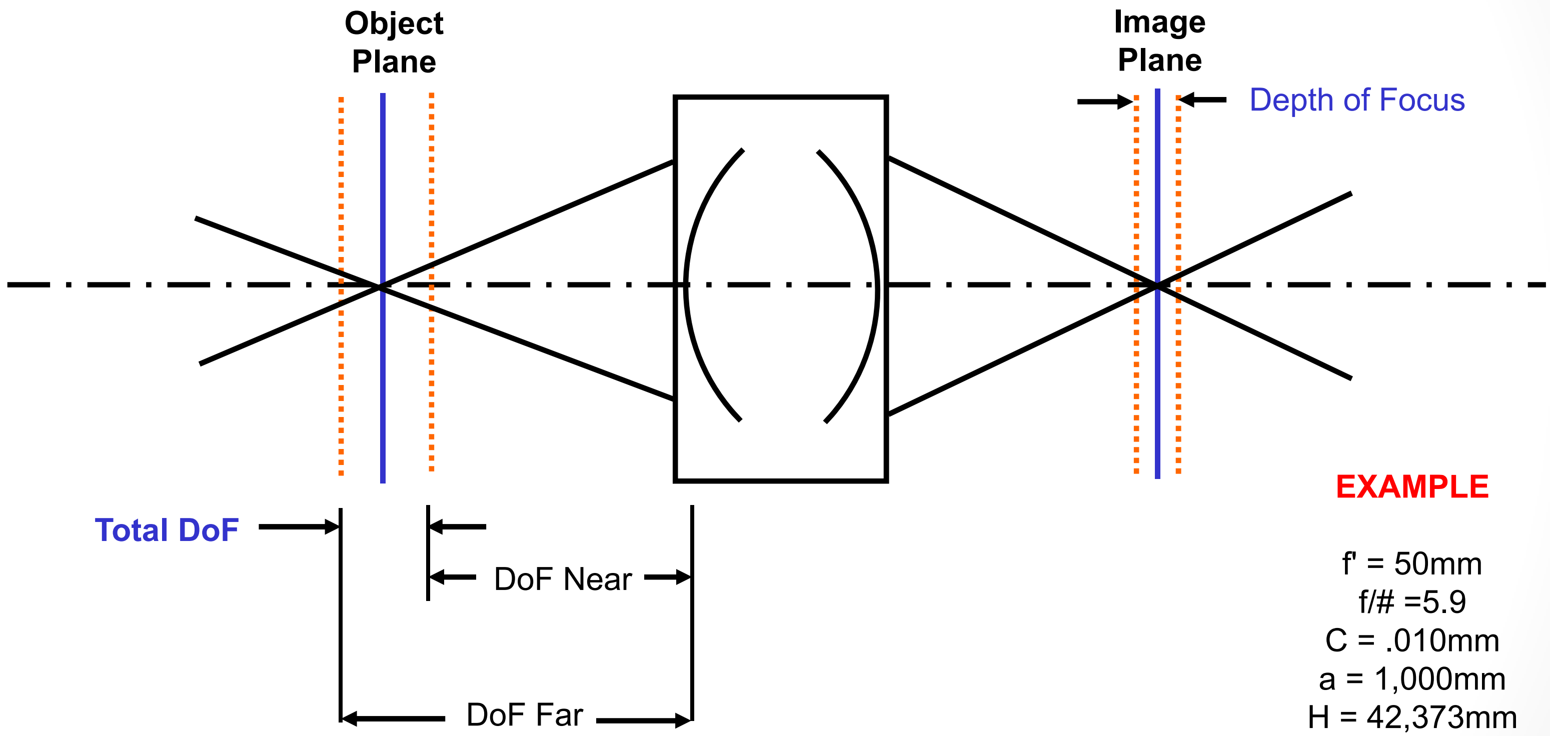
NEAR = 977mm

FYI Depth-of-Field (Far & Near) Equations should be used for objects that lie between (300mm to 2,500mm) from the lens/camera

* Note * Must Use Common Units

# Depth of Field Cont…

**Total Depth of Field = FAR - NEAR**




**EXAMPLE**

f' = 50mm
f/# =5.9
C = .010mm
a = 1,000mm
H = 42,373mm
NEAR = 977mm
FAR = 1,023mm
TOTAL = 46mm

# DEPTH OF FIELD (cont.)

To be used for close-up object distances & when your magnification is known.

$$\text{Depth of Field (Total)} = \frac{2C(EF)}{(\beta')^2}$$

EA = Effective f/number

β' = Magnification

C = Circle of Confusion (diameter)
i.e., Pixel Size or any Value

**EXAMPLE**

EF = 8.0
β' = 0.5
C = 0.010mm
Depth of Field= 0.64mm

* Note *   Must Use Common Units

# How Can Apertures Be Used To Improve Depth Of Field?

- If we express our resolution as an angularly allowable blur ($\omega$) we can define depth of field geometrically.
- Below we see how two lenses with different f/#s have very different DOF values.

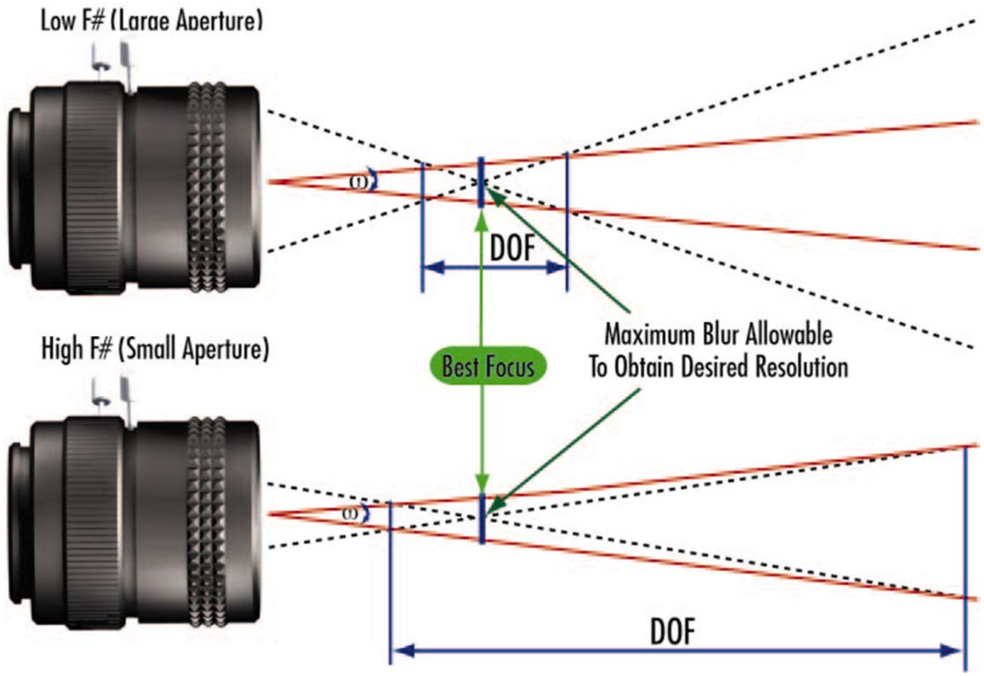



Illustration adapted from Smith, Modern Optical Engineering: The Design Of Optical Systems, New York, McGraw-Hill, 1990

# More Points To Remember

- DOF is often calculated using diffraction limit, however this is often flawed if the lens is not working at the diffraction limit.
- Increasing the f/# to increase the depth of field may limit the overall resolution of the imaging system. Therefore, the application constraints must be considered.
- An alternative to calculating DOF is to test it for the specific resolution and contrast for an application.
- Changing the f/# can also have effects on the relative illumination and overall system resolution illumination of the image obtained.

# Depth of Focus

Depth of Focus = is the amount by which the image may be shifted longitudinally with respect to some reference plane and introduce no more than the acceptable blur.

$$\text{Depth of Focus } (1/4\lambda \text{ OPD}) = \pm \frac{\lambda}{2N \sin^2 U_m}$$

* Note * Must Use Common Units

$\lambda$ = Wavelength of Light

N = Index of Final Medium
Air = 1.0

$U_m$ = Final Slope of Marginal Ray

U = arcsine (NA)

OPD = Optical Path Difference

**Depth of Focus = ± (f/#) (Pixel Size)**

IFF $\lambda$ = Visible Light

# Depth of Focus Cont…

## Effective f/number (Finite Systems)

**Finite Systems - Employ Your EF Value For The f/#**

$$\boxed{EF = (f/\#)\,(\beta' + 1)}$$

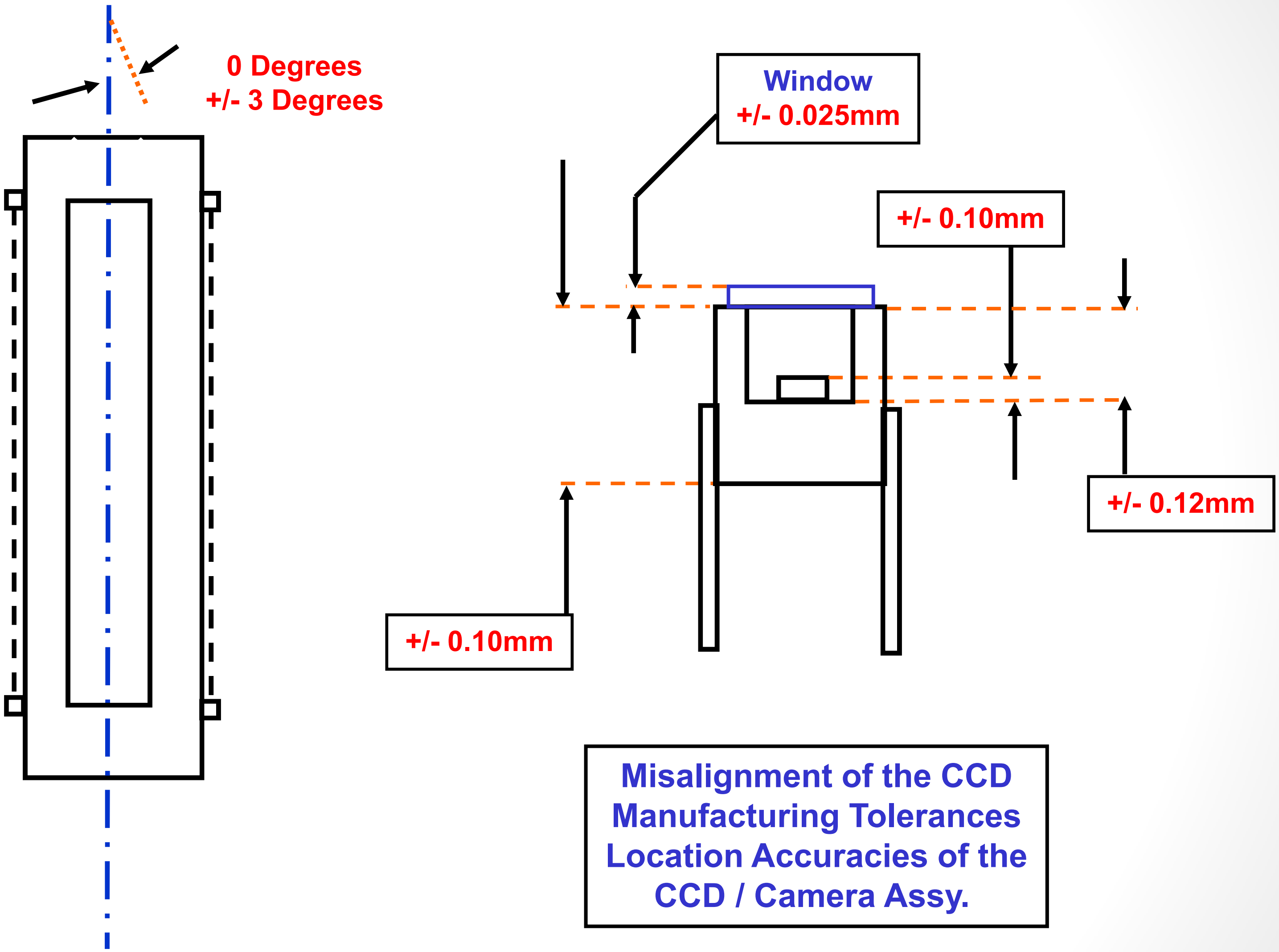
$$\boxed{EF^{*} = f/\#\,[(\beta'/\beta'p) + 1]}$$

EXAMPLE
f/4.0
$\beta' = 1$
EF = 8.0

**Effective f/number should be used when calculating Depth of Field & Depth of Focus when imaging "Close–up" Objects and/or low magnifications (1:4 to 4:1)**

* = Use when the pupil magnification of the lens is known

# Sensor / Camera Alignment Tolerances




Misalignment of the CCD
Manufacturing Tolerances
Location Accuracies of the
CCD / Camera Assy.

# Sensor / Camera Alignment Tolerances

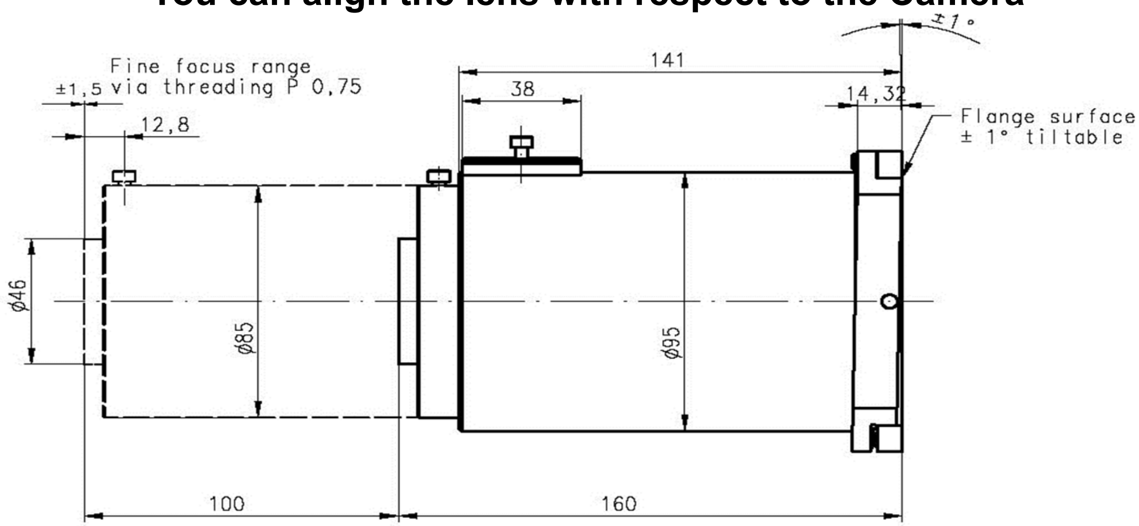
**Typical Active Length (2y') of Linear & TDI Sensors:**

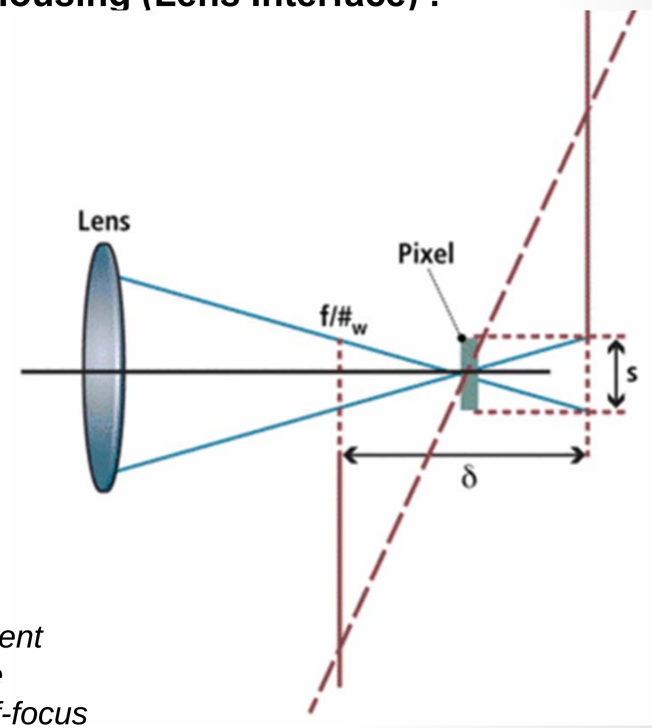
2k = 20.48mm
4k = 40.96mm
6k = 43.01mm
8k = 57.34mm
12k = 86.02mm

**Attention must be made to the critical alignment required between the Lens to CCD/Camera Assy.**

**Can not change the alignment of the CCD to the Camera Housing (Lens Interface) !**

**You can align the lens with respect to the Camera**



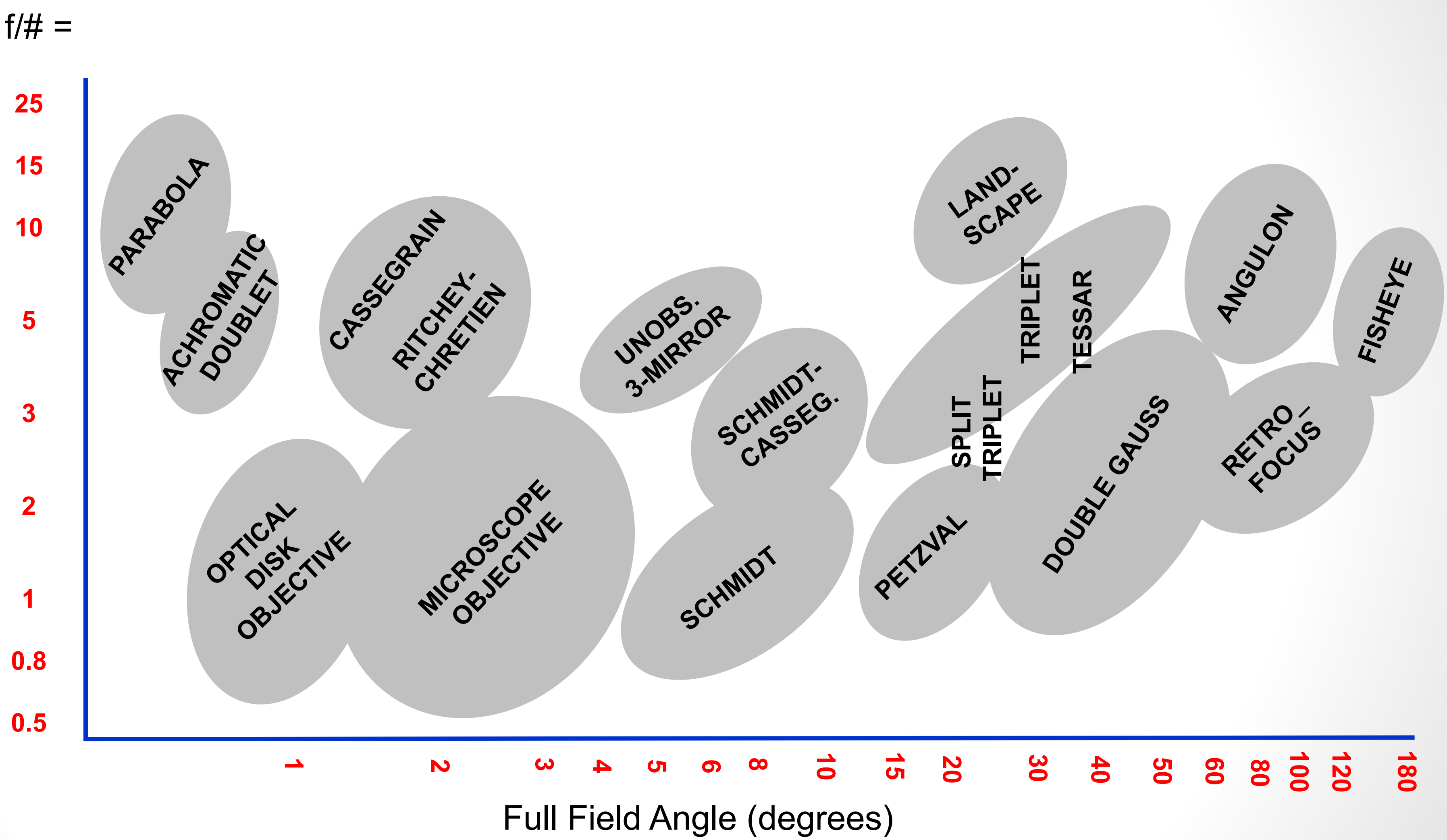

*A sensor (red) may be tipped in relation to the lens system. Red dashes represent individual pixels; solid red line indicates the point at which the defocusing of the cones of light produced by the lens grows larger than the pixels, creating out-of-focus imaging beyond those points. If enough pixels are added and the alignment is not perfect, the system will become defocused.*

# Lens Design Types

## Lens Design Types and Form Selection

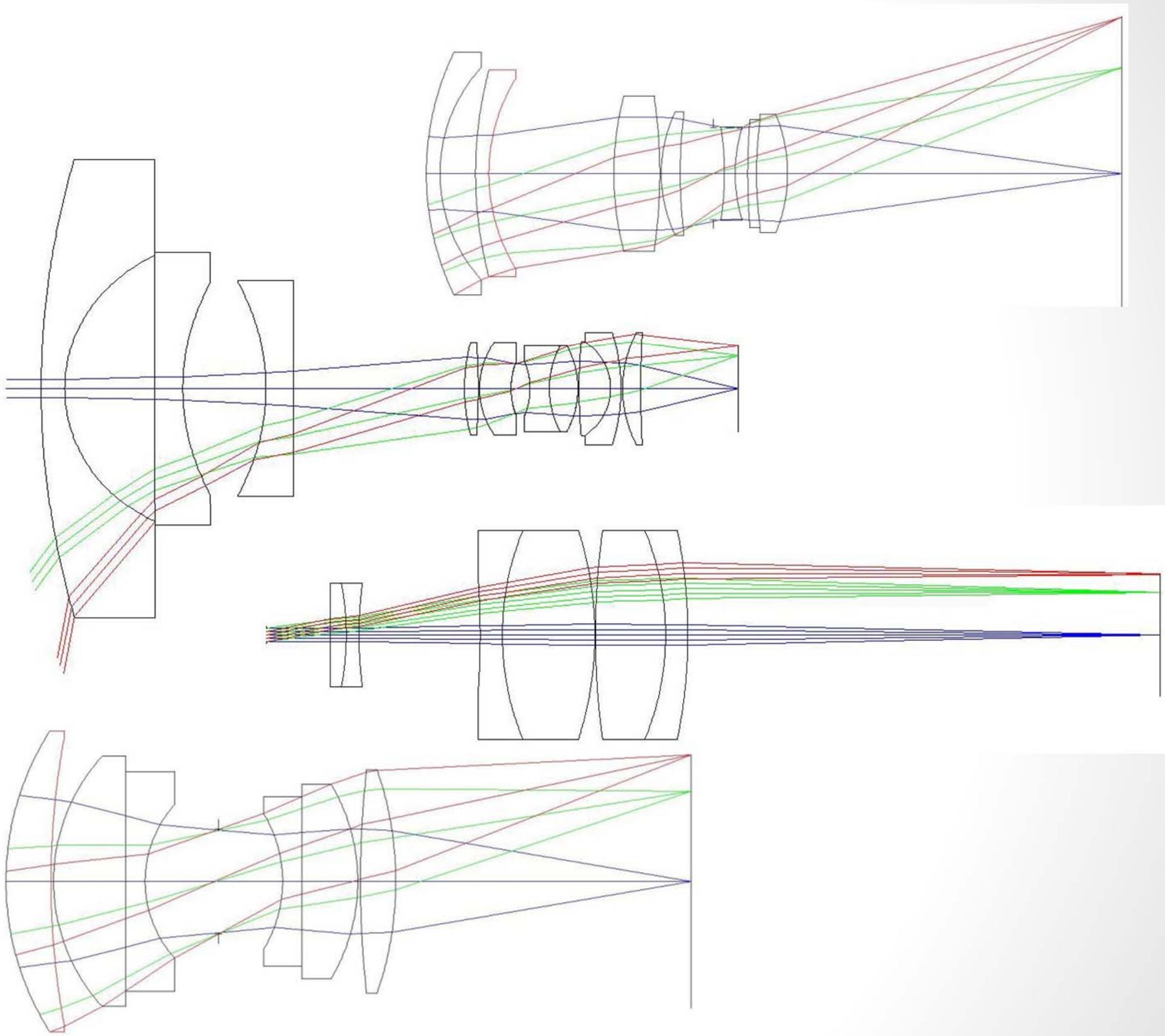
How Lens Forms change with Working Distance & Magnification

# LENS DESIGN TYPES

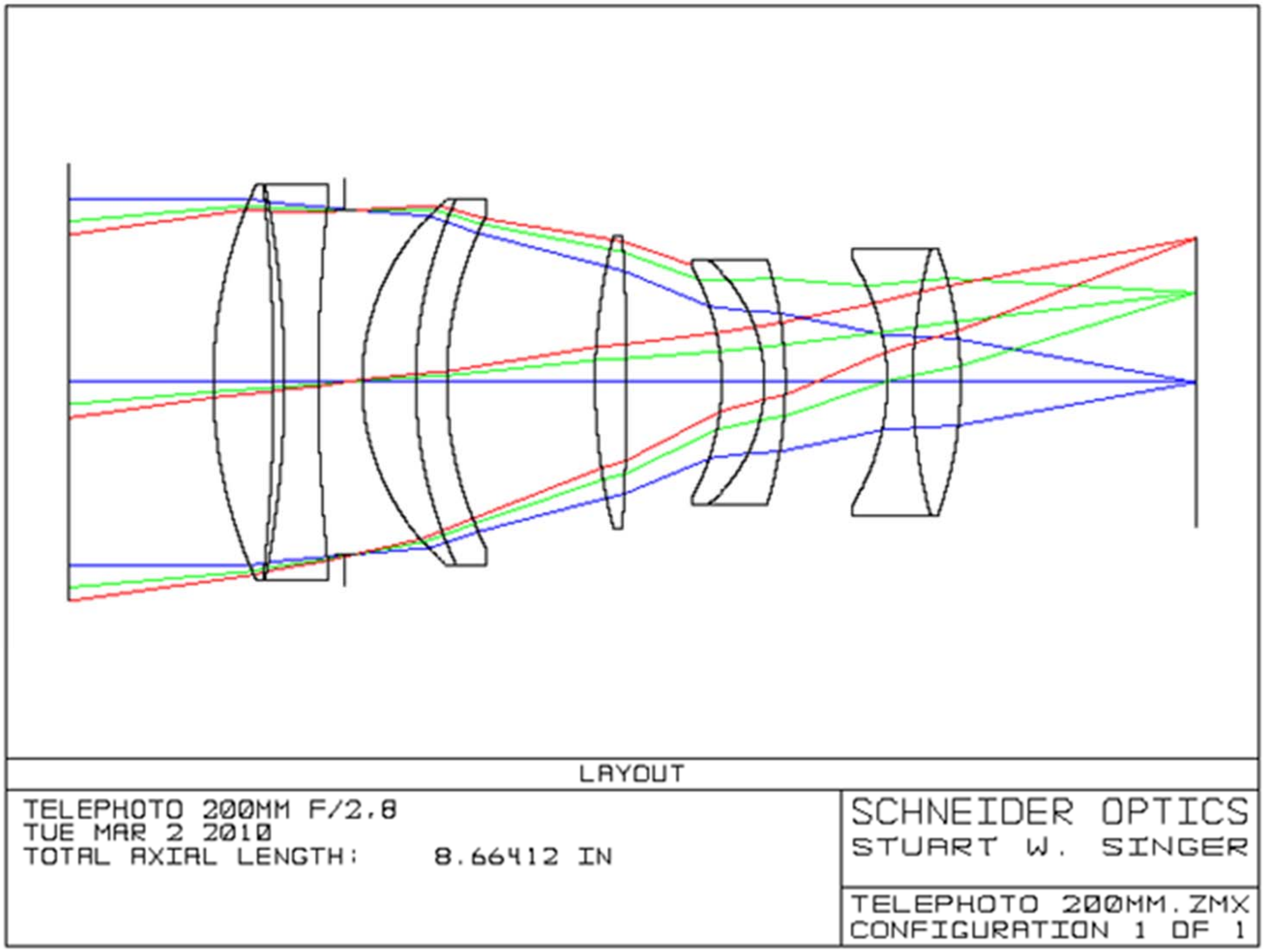


# Machine Vision (Possible) Lens Types

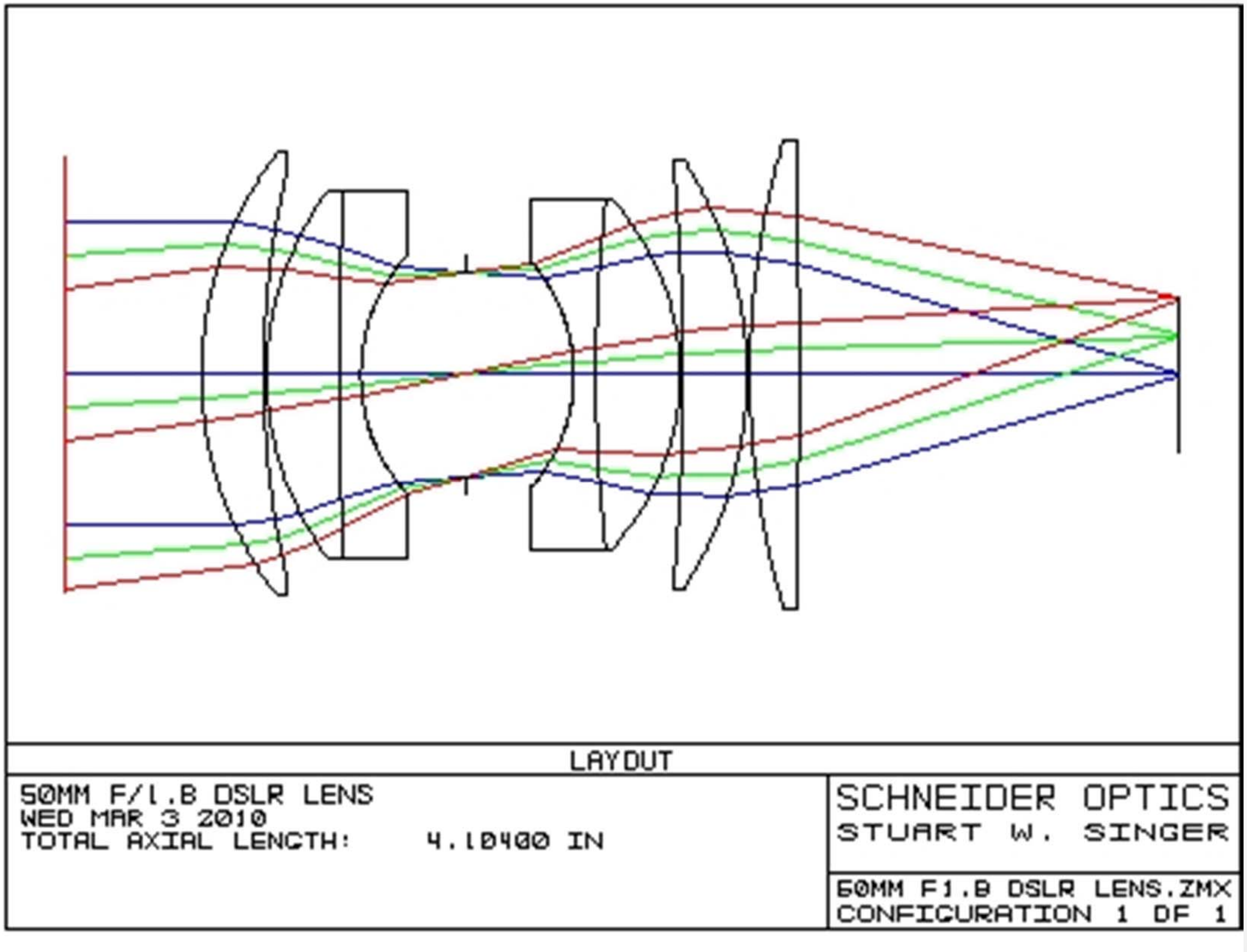
- Telecentric
- Macro
- Macro Zooms
- Zooms
- Large Format Taking
- Fish-eye
- Telephoto
- Inverse Telephoto
- Retrofocus
- Mirror / Catadioptric
- Micro
- Afocal
- Very Wide Angle
- Relay
- Double Gauss
- Petzval
- F-Theta
- Projection
- Enlarging
- Cylinder Anamorphic
- Doublets
- Triplets
- ETC……..



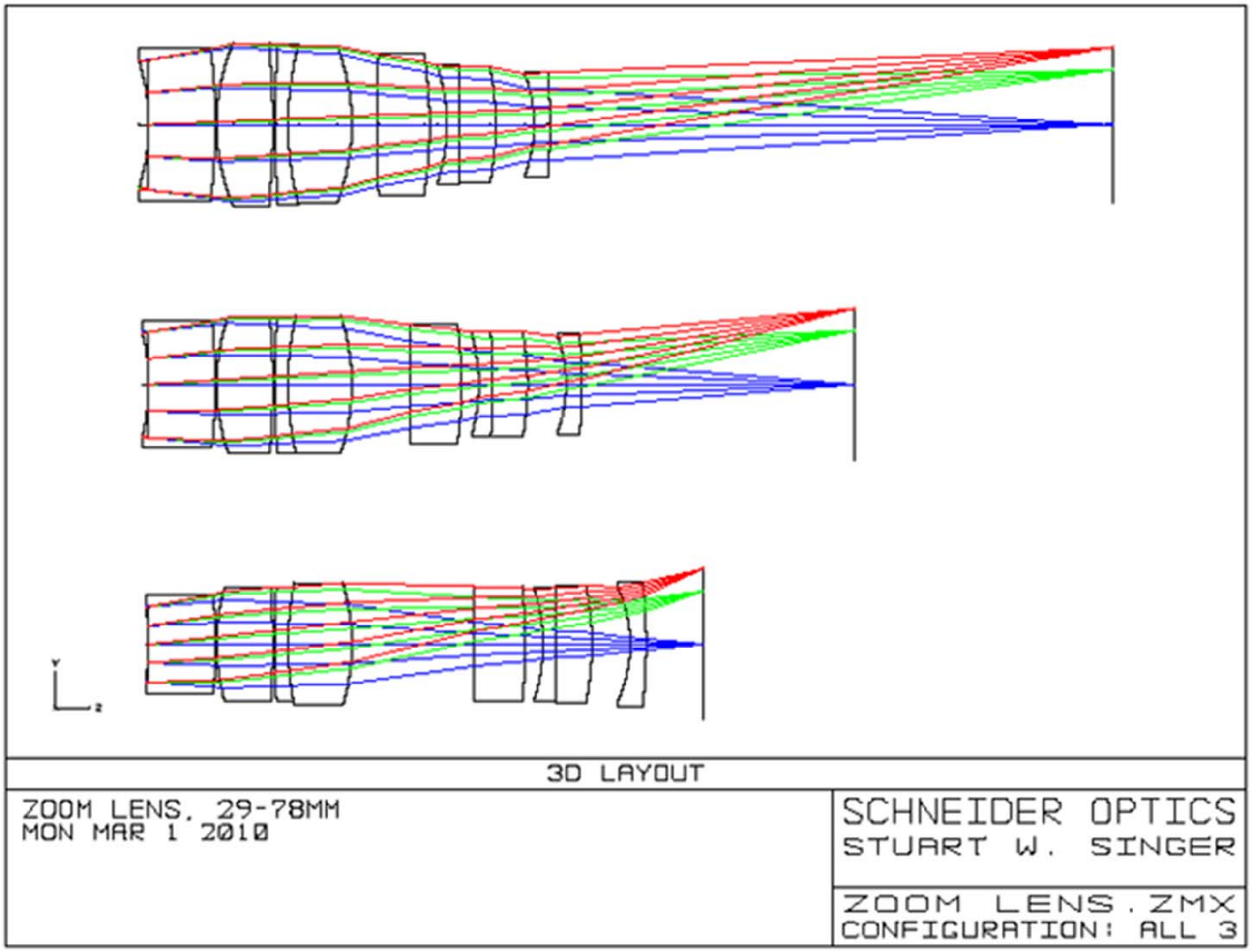
# Telephoto Lens



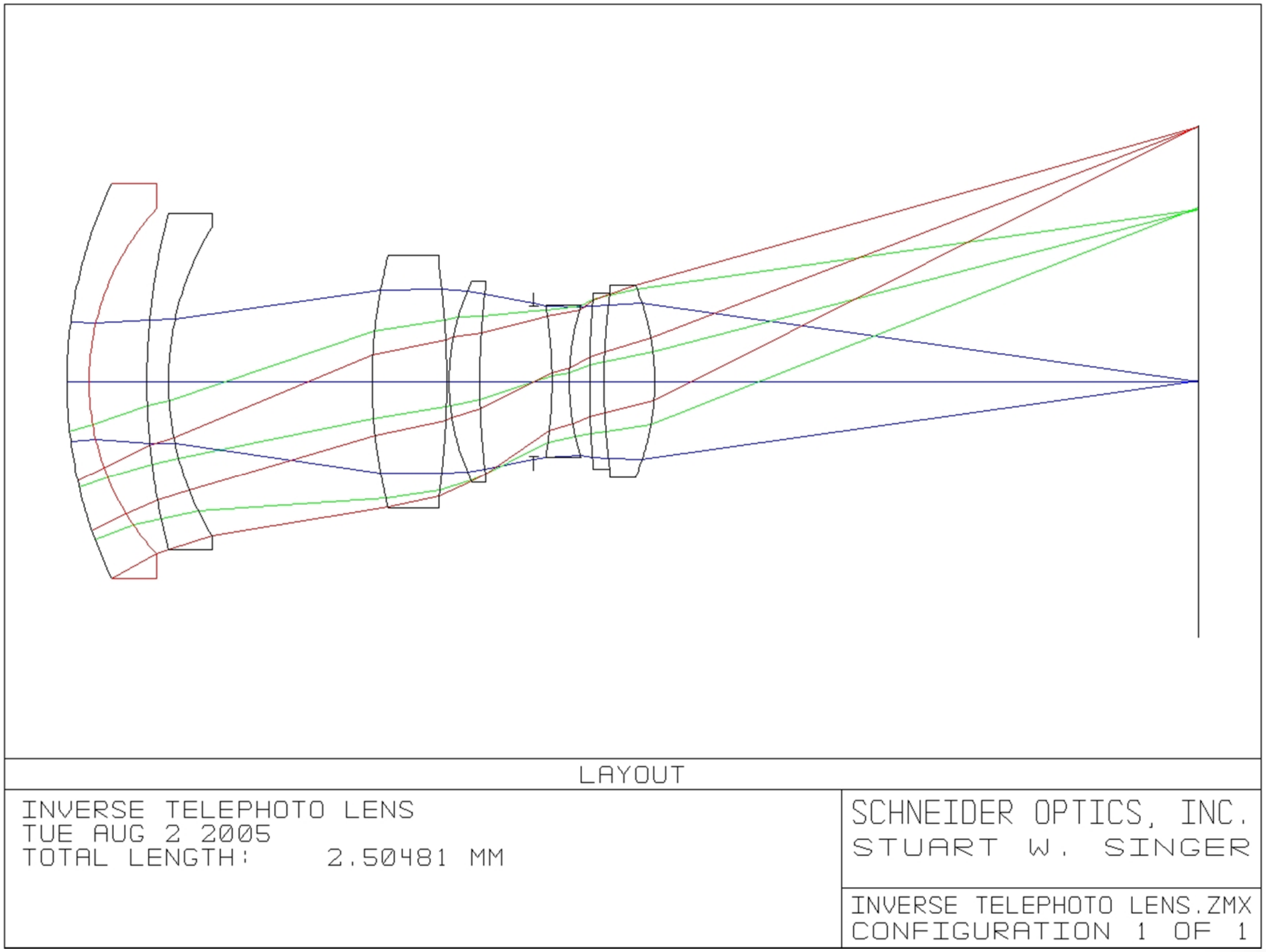
# Double Gauss 50mm f/1.8 (Typical SLR/DSLR Lens)



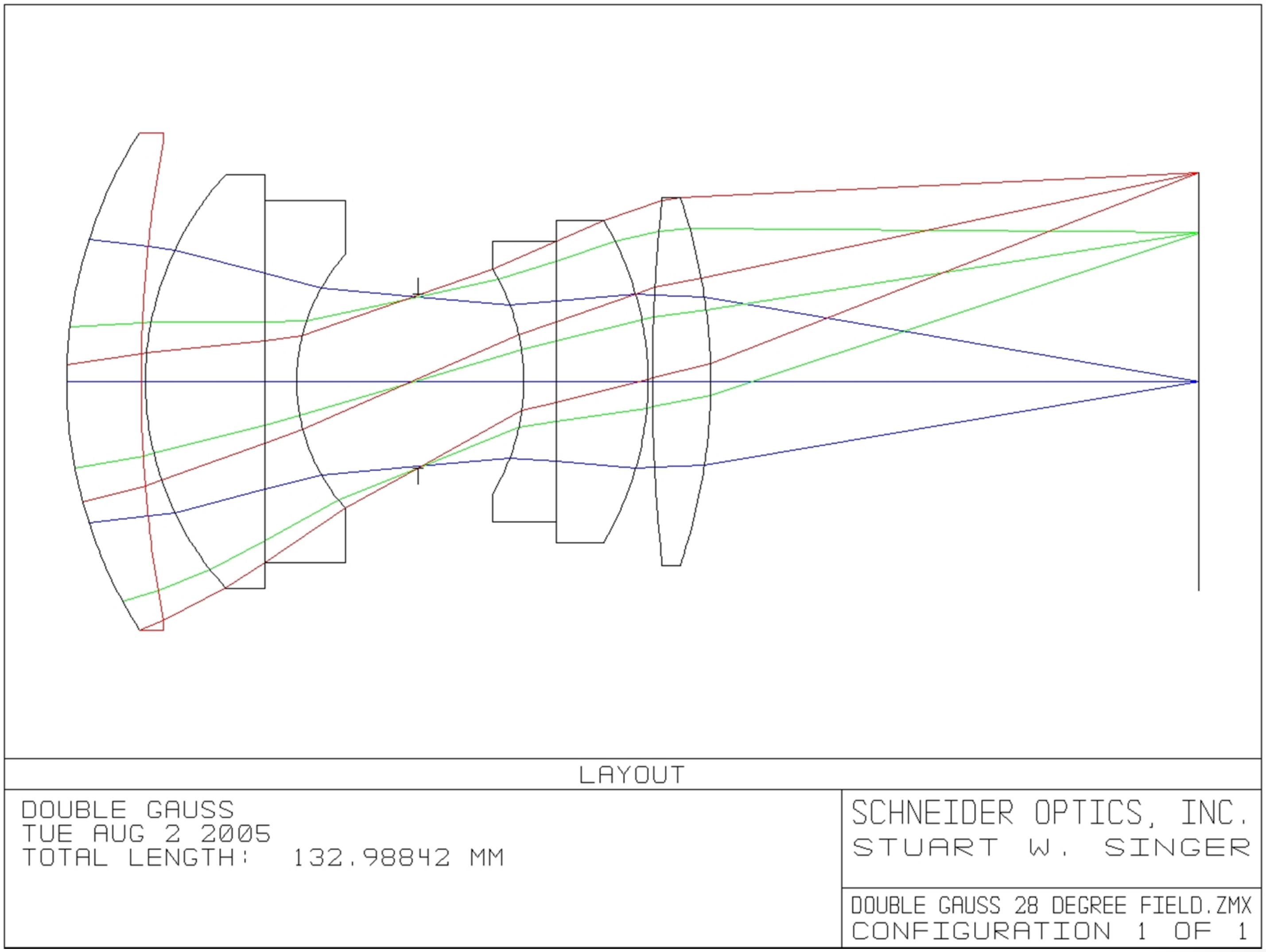
# Zoom Lens


3D LAYOUT
ZOOM LENS, 29-78MM
MON MAR 1 2010
SCHNEIDER OPTICS
STUART W. SINGER
ZOOM LENS.ZMX
CONFIGURATION: ALL 3

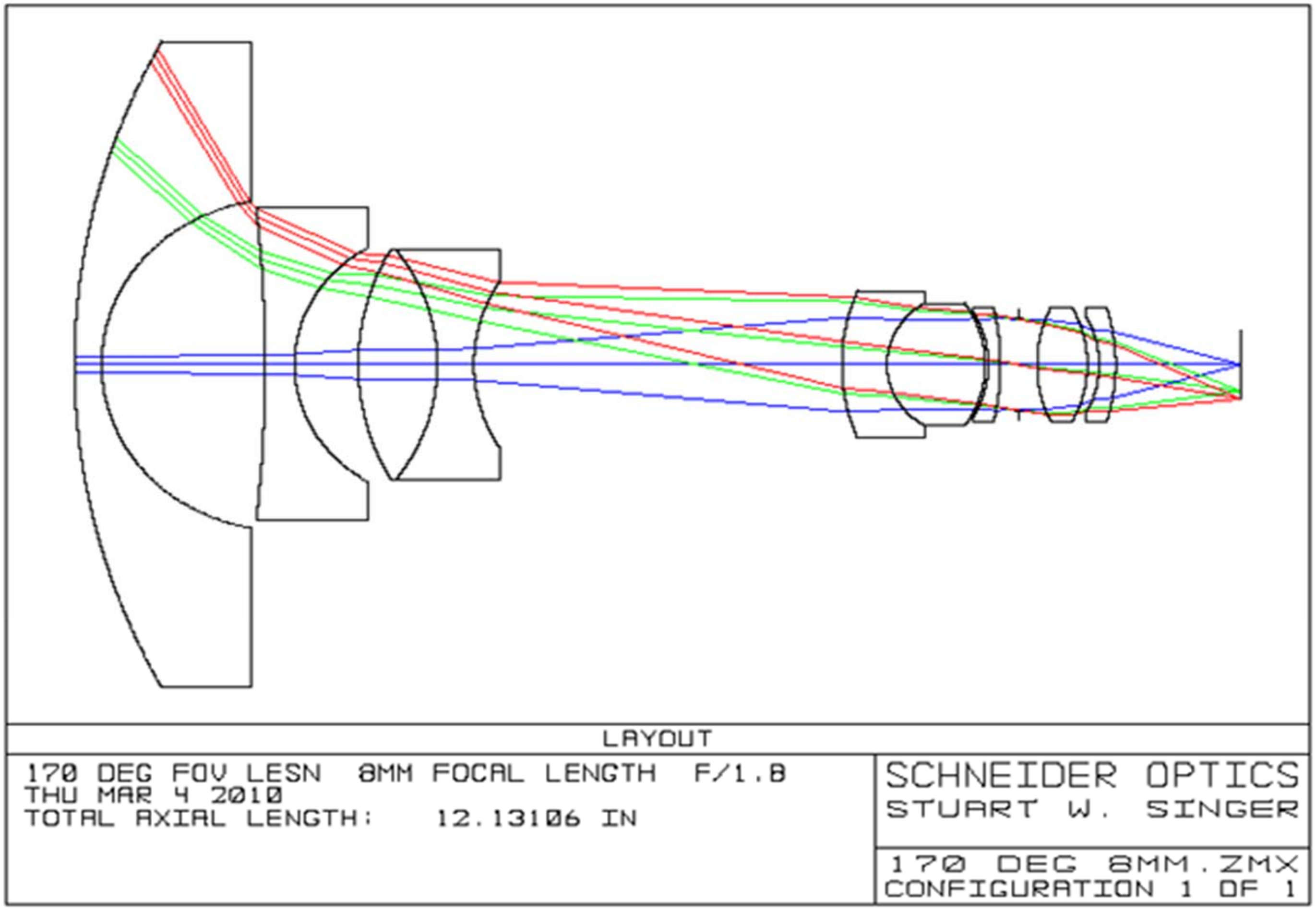
# Design Sample (Inverse Telephoto)



# Design Sample (Double Gauss – Macro Lenses)



# Design Sample (Wide Angle Fisheye)



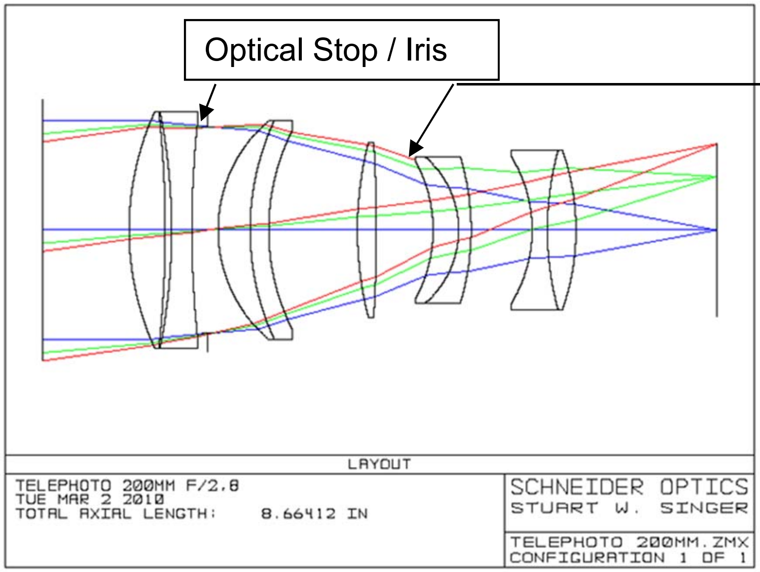
# Lens Performance Issues

Issues That Factor Into A
Lens Design / Performance

# Vignetting

**Vignetting** = In an optical system, the gradual reduction of illumination as the off-axis angle increases, resulting from limitations of the clear aperture of the elements (or mechanical constraints) within the lens system.

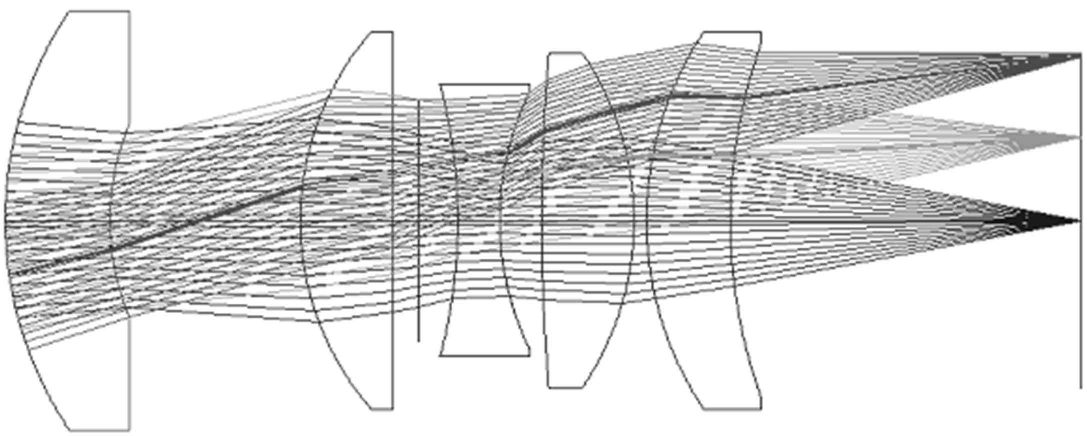
**Lens Design Tool or Trick** = Sometimes a lens designer induces Vignetting to intentionally block some of the off-axis rays in order to produce greater off-axis performance. This does not effect ray near the optical axis. Less light falls on the off-axis spot/image area creating a large spot size (higher f/#) but creating a better image at the penalty of loosing light.

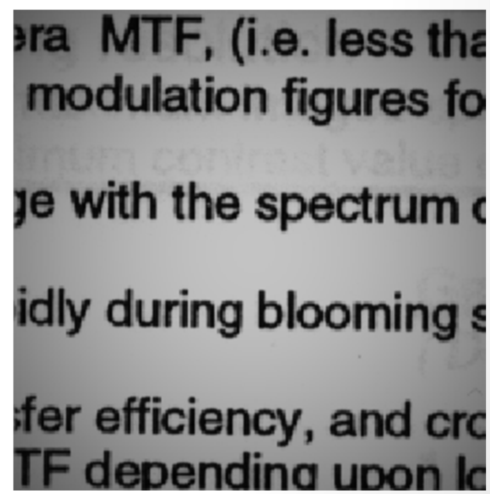



Vignetting taking place when the Optical Element is reduced in diameter to block unwanted light

# Vignetting Cont...

**Not really an aberration – still important**
**Used to control aberration (cheating?)**
**Commercial lenses 35-50% vignetting**

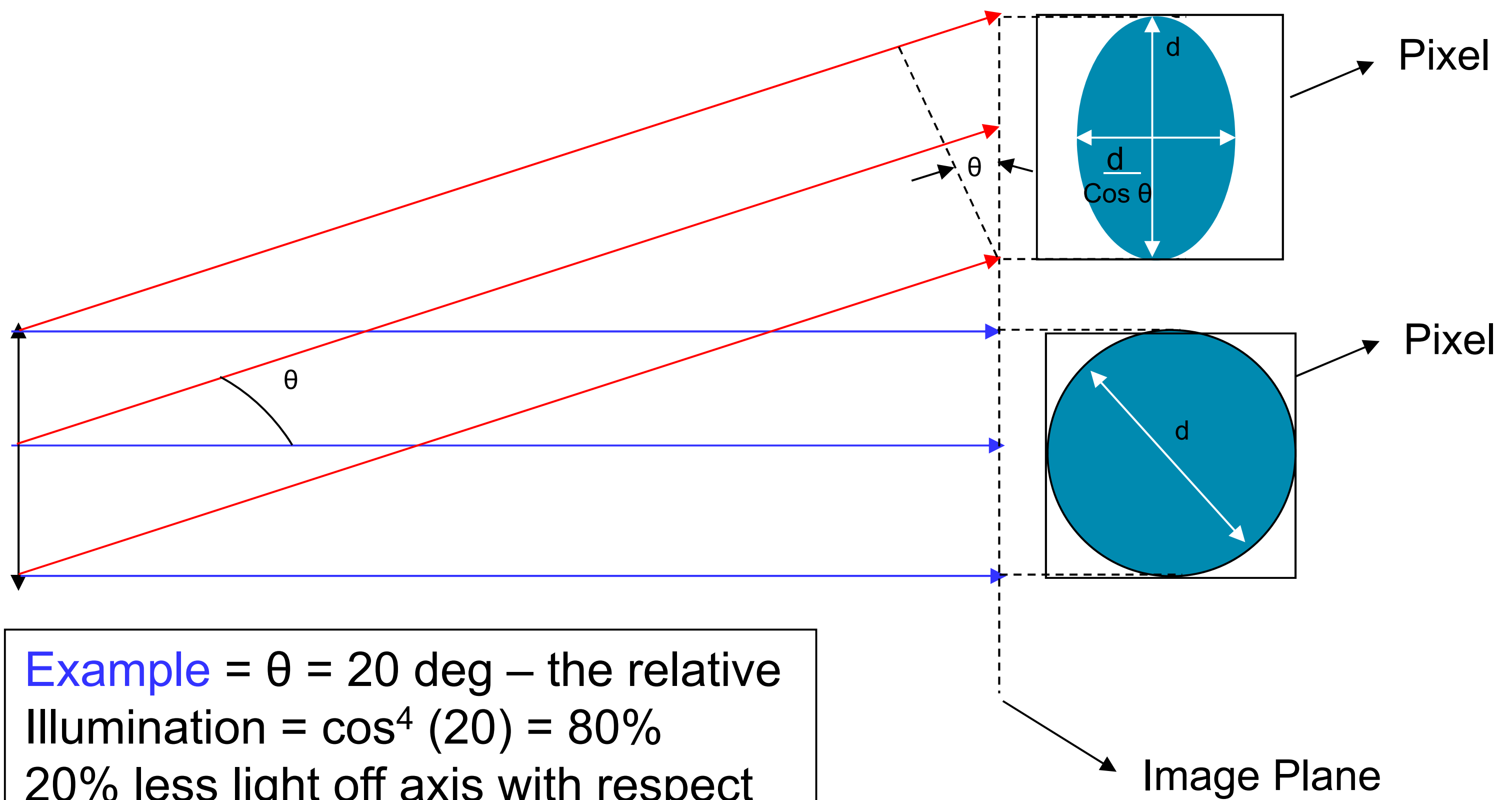





**Vignetting**

# $Cos^4$ Fall-Off

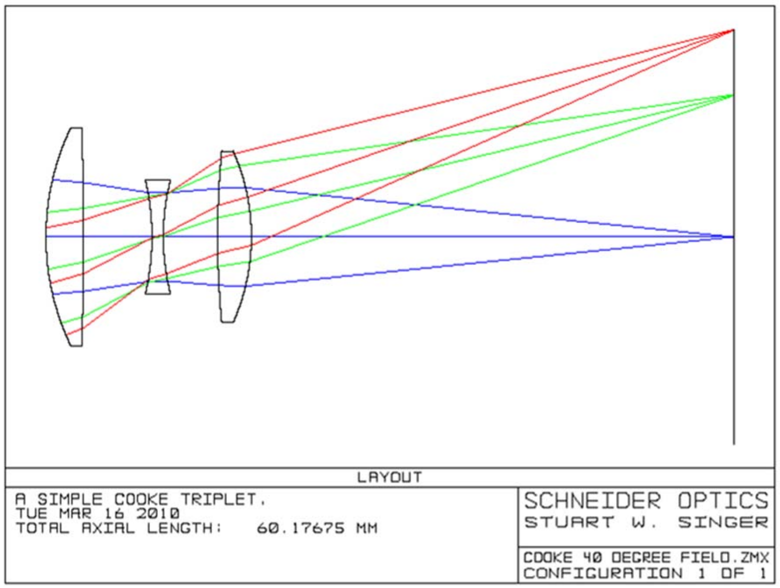
**Cosine Fourth Law** = A formula indicating that, for an imaging lens system, the image brightness for off axis points will fall off at a rate proportional to the $COS^4$ of the off axis angle.

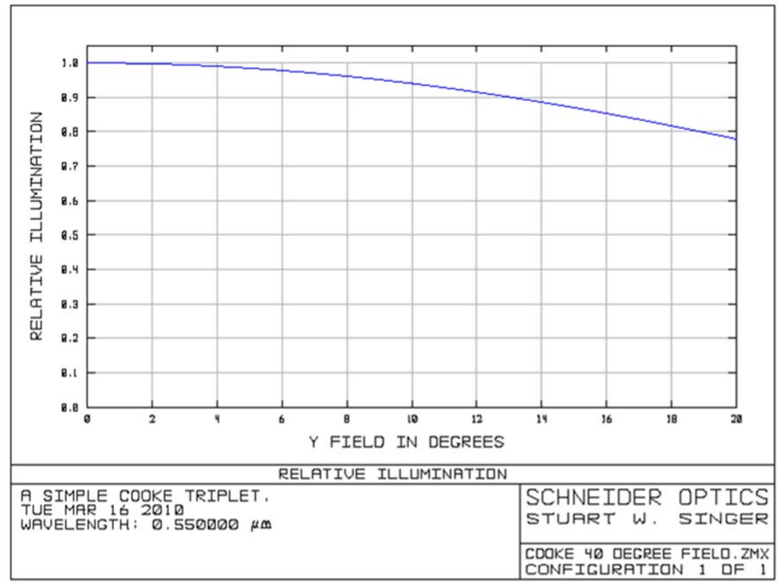



Example = θ = 20 deg – the relative Illumination = $\cos^4(20) = 80\%$
20% less light off axis with respect to on axis

# Relative illumination

**Relative illumination** = takes into account $\cos^4$ loss and vignetting and is typically plotted and part of your lens performance package/data




TFOV = 40 deg = +/- 20 deg.

Relative Illumination slightly below 80% due to small vignetting factors in the lens design

# Relative Illumination Cont….

Fall-off of illumination in % from the optical axis to the maximum image height - also called vignetting. One differentiates the natural vignetting, which depends on the $Cos^4$ of the angle of field (can not be prevented) and those, which is intentionally implemented by the optics designer, in particular for lenses with high relative apertures.

**ORIGINAL**

**25% Fall-Off**

**50% Fall-Off**

**75% Fall-Off**

# Stray Light

**Stray Light:**

Also known as the expression scattered light.
Stray Light is caused by reflections within the optical system.

By thorough matting (Blacking) the lens edges and grooving or matting of the internal mechanical parts, the stray light can be further reduced.

Good lens systems have a stray light ratio of less than 3%.

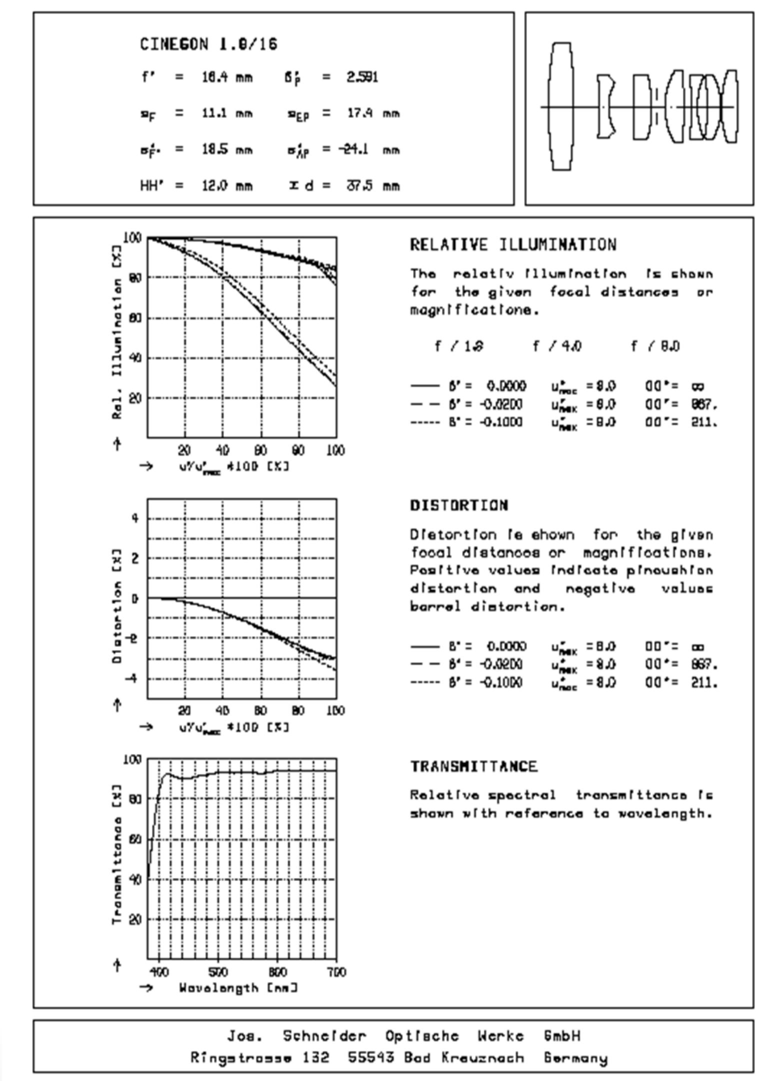
Original

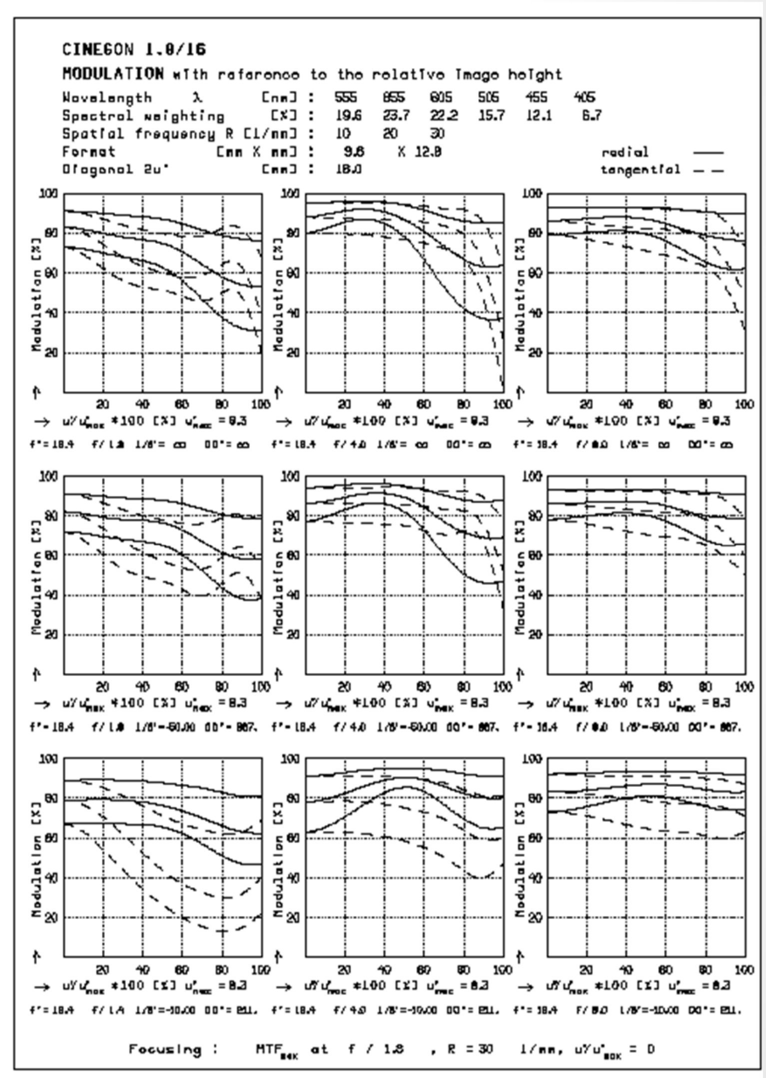
6%

12%

24%

# Lens Performance Changes with (Working Distance / Magnification)

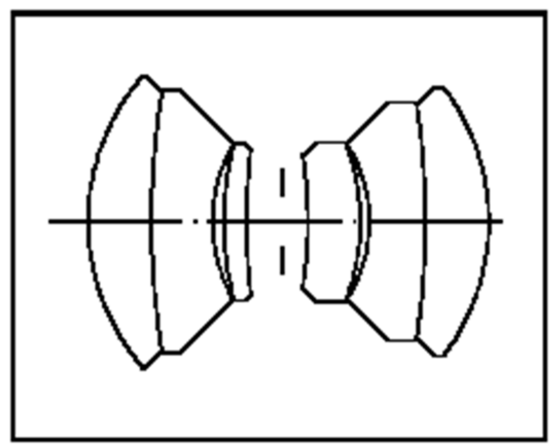


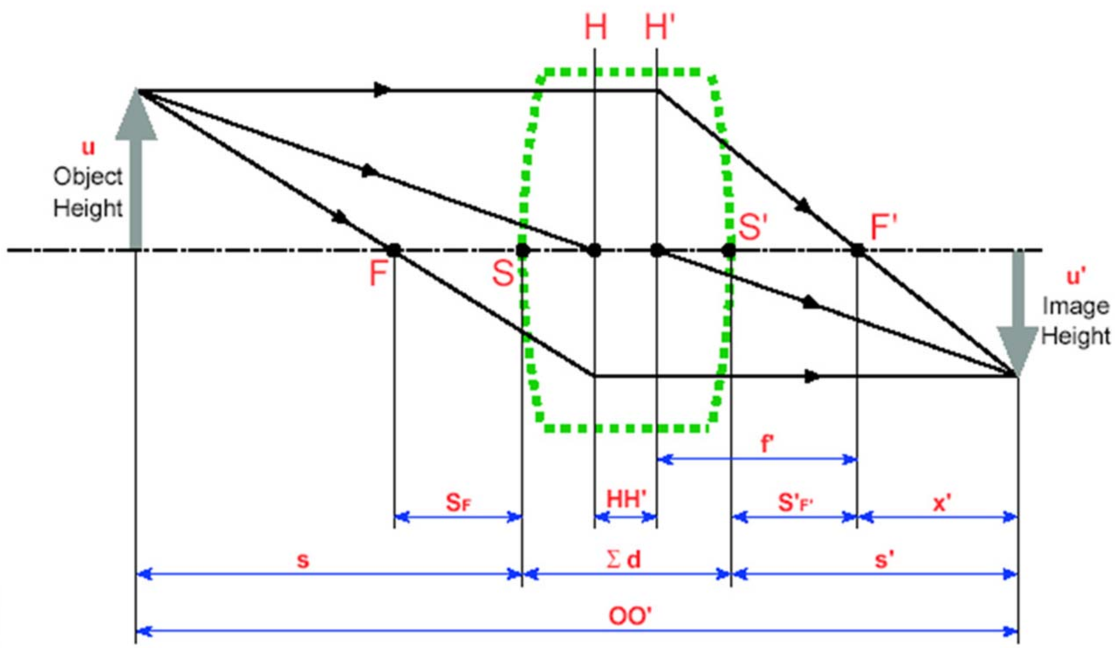



# Basic Lens Data

APO-COMPONON 2.8/40

| | | | | | |
|---|---|---|---|---|---|
| $f'$ | = | 41.5 mm | $\beta'_P$ | = | 1.049 |
| $s_F$ | = | -24.5 mm | $s_{EP}$ | = | 15.0 mm |
| $s'_{F'}$ | = | 27.8 mm | $s'_{AP}$ | = | -15.7 mm |
| $HH'$ | = | -2.2 mm | $\Sigma d$ | = | 28.5 mm |






f' = focal length
u = . total object size
u' = . total image size
s' = image/object size ( = u'/u )
s = object/image size ( = u/u' )
OO' = object-to-image distance
s'F' = back focal distance for infinity
x' = shift from infinity
sEP = entrance pupil position
s'AP = exit pupil position
β'P = exit/entrance pupil diameter
(entr.p.d. = f'/f# = 41.5/2.8 = 14.8mm)

# DIN MTF Data Sheet

APO-COMPONON 2.8/40

MODULATION with reference to the relative image height

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Wavelength λ [nm] : | 546 | 706 | 644 | 480 | 436 | 405 | |
| Spectral weighting [%] : | 27.4 | 12.4 | 24.1 | 18.3 | 12.6 | 5.2 | |
| Spatial frequency R [l/mm] : | 10 | 20 | 40 | | | | |
| Format [mm X mm] : | 24.0 | X 36.0 | | | | | radial ——— |
| Diagonal 2u' [mm] : | 43.2 | | | | | | tangential — — |

Wavelength Used for 1st Order Data

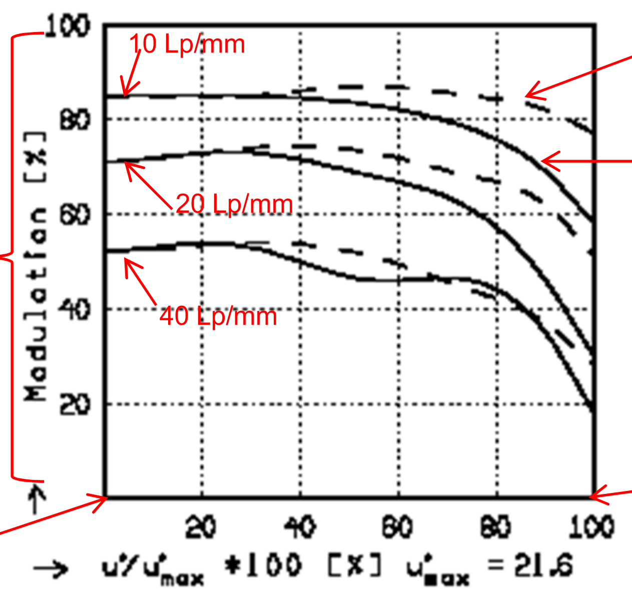
Wavelenths in Nanometers
Note: Visible light

Weighting Factors / Values
CCD / CMOS Factors

Up to 40 Lp/mm data at Image Plane is Graphed

Image Circle = +/- 21.6mm

Our common presentation of three line pair values for tangential and radial test grid orientation over the image height (from the image center to the image corner).




f'= 41.5 f/ 2.8 1/β'= -25.00 OO'= 1121

Lens Focal Length = f'

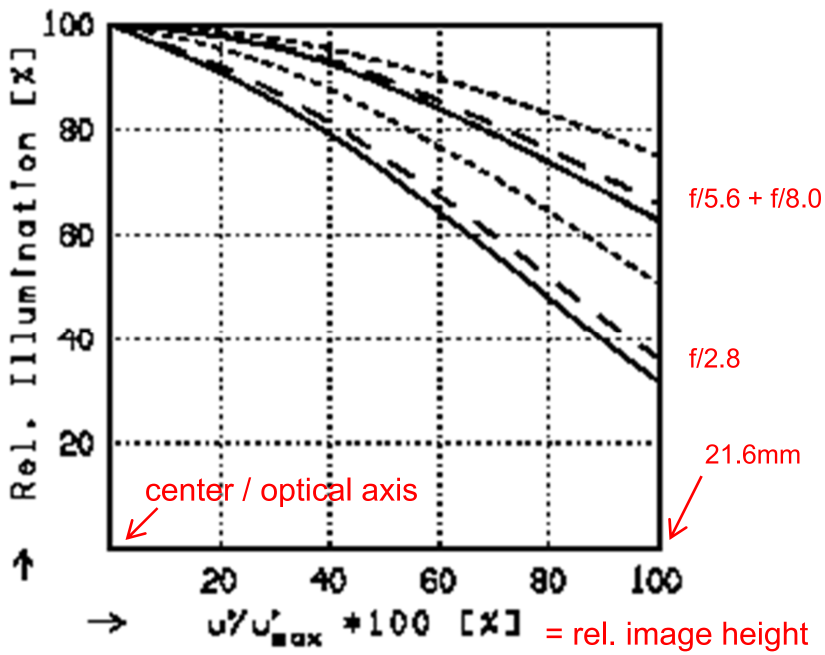
Lens f/number

1/magnification
B' = 0.040

Object to Image Distance

# Relative Illumination

Fall-off of illumination in % from the optical axis to the maximum image height - also called vignetting. One differentiates the natural vignetting, which depends on the Cos⁴ of the angle of field (can not be prevented) and those, which is intentionally implemented by the optics designer, in particular for lenses with high relative apertures.




RELATIVE ILLUMINATION

The relativ illumination is shown for the given focal distances or magnifications,

f / 2.8     f / 5.6     f / 8.0

image circle radius

| | | | |
|---|---|---|---|
| —— | $\beta' = -0.0400$ | $u'_{max} = 21.6$ | $OO' = 1121.$ |
| — — | $\beta' = -0.1000$ | $u'_{max} = 21.6$ | $OO' = 500.$ |
| ----- | $\beta' = -0.3333$ | $u'_{max} = 21.6$ | $OO' = 219.$ |

magnification

object to image distance

# Mega Pixels

## Mega Pixels – Sensors & Lenses

# MegaPixel Craze

**A possible definition:**

***A lens which is able to image an object onto a sensor with about a million pixels in a quality where the image quality is not limited by the performance of the lens.***

**... and more general:**

***A"X"megapixel lens is a lens which is able to image an object onto a sensor with about "X" million pixels in a quality where the image quality is not limited by the performance of the lens."***

**A simple conclusion might be:**

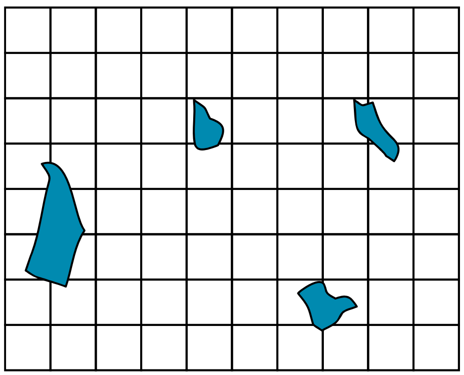
***I have a "X" megapixel sensor. I can choose any "X" megapixel lens and I will get a good match of sensor and lens for my application.***

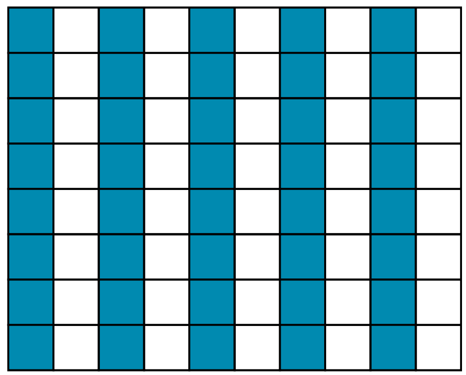
***... but is this the truth?***

# The Key Sensor Characteristics for a Lens

**Pixel size:** Defines the required resolution of the lens.

The lens resolution must be high enough to image structures onto the sensor as small as the pixels are.



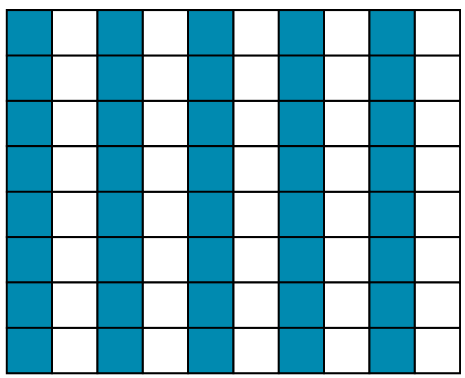


Irregular structures are not well suited to describe resolution. Therefore line pairs (a dark and a bright line) are used as description. The sensor‘s maximum resolution is reached when a line pair is imaged on two rows of pixels

# Limiting Sensor Resolution (Nyquist Frequency)

The limit is reached when a dark and a bright line fill 2 rows of pixels.

**Nyquist Frequency (line pairs/mm)** = 1000 / (2 x pixel size (µm)

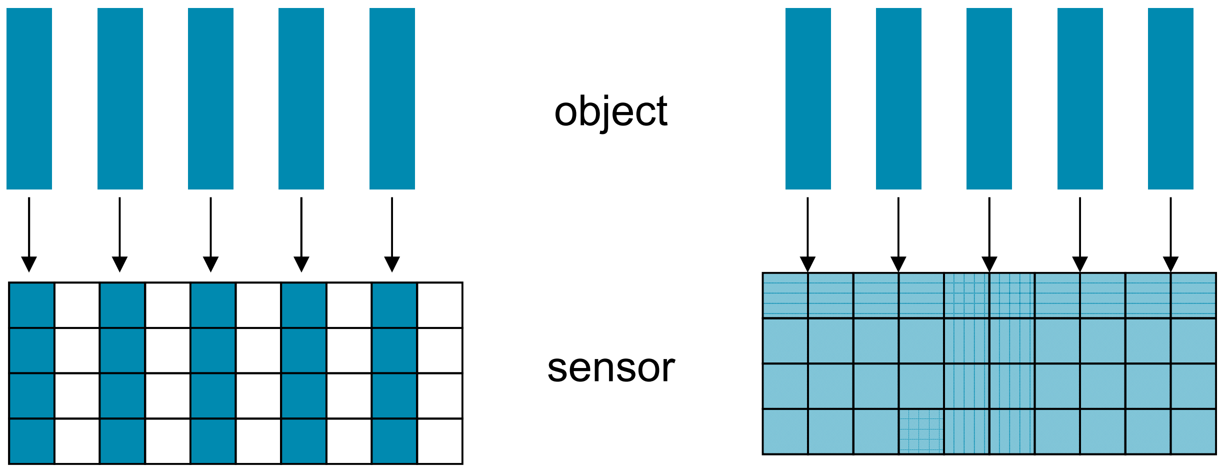


Example:

Pixel size = 3.4µm
Nyquist Frequency = 1000 / (2 x 3.4) = **147 lp/mm**

# Is the Limit the Limit?

When object structures close to the Nyquist frequency are imaged, the sensor information might not properly reprsent the object:




The same object can cause totally different information on the sensor when structures close or over the Nyquist frequency are resolved (e.g., **Moiré-effects**).

# Examples of MegaPixel Sensors

**Kodak KAI 16000 (16 Mpix)**

| | |
|---|---|
| Pixels: | 4872 x 3248 |
| Pixel Size: | 7.4µ x 7.4µ |
| Sensor Diagonal: | **43.2mm** |
| Nyquist Frequency: | 68lp/mm |
| 2/3 of Nyquist: | **45lp/mm** |

**Kodak KAI 8050 (8 Mpix)**

| | |
|---|---|
| Pixels: | 3296 x 2472 |
| Pixel Size: | 5.5µ x 5.5µ |
| Sensor Diagonal: | **22,7mm** |
| Nyquist Frequency: | 91lp/mm |
| 2/3 of Nyquist: | **61lp/mm** |

**Sony ICX 625 (5 Mpix)**

| | |
|---|---|
| Pixels: | 2456 * 2058 |
| Pixel Size: | 3.45µ x 3.45µ |
| Sensor Diagonal: | **11,0mm** |
| Nyquist Frequency: | 145lp/mm |
| 2/3 of Nyquist: | **97lp/mm** |

**Aptina MT9J003 (10 Mpix)**

| | |
|---|---|
| Pixels: | 3856 x 2764 |
| Pixel Size: | 1,67µ x 1,67µ |
| Sensor Diagonal: | **7,9mm** |
| Nyquist Frequency: | 299 lp/mm |
| 2/3 of Nyquist: | **200lp/mm** |

**Megapixel sensors are very different => There is not "The Megapixel Lens"**

## Example: Lens for 5 Mpix Sensor

**Sony ICX 625  (5 Mpix)**
Pixels: 2456 * 2058
Pixel Size: 3.45µ x 3.45µ
Sensor Diagonal: **11,0mm**
Nyquist Frequency: 145 lp/mm
2/3 of Nyquist: **97 lp/mm**


This sensor requires a lens with an image circle of **11mm** and 30% MTF at **97 lp/mm**. Is there a lens available that fulfills this specification under all circumstances (i.e., magnification, object contrast, etc.....?

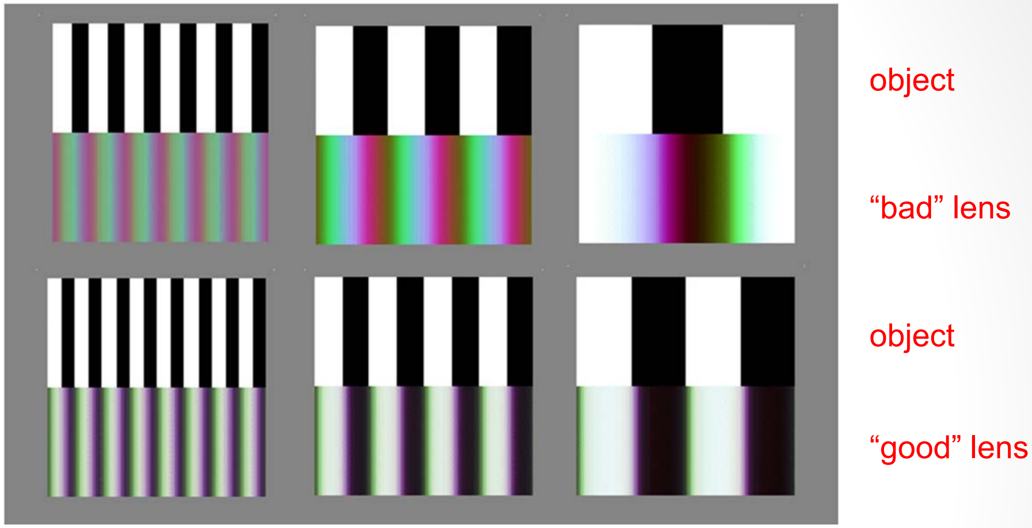
# Example: Lens for 10 Mpix Sensor

| | |
|---|---|
| **Aptina MT9J003 (10 Mpix)** | |
| Pixels: | 3856 x 2764 |
| Pixel Size: | 1,67µ x 1,67µ |
| Sensor Diagonal: | **7,9mm** |
| Nyquist Frequency: | 299 lp/mm |
| 2/3 of Nyquist: | **200lp/mm** |

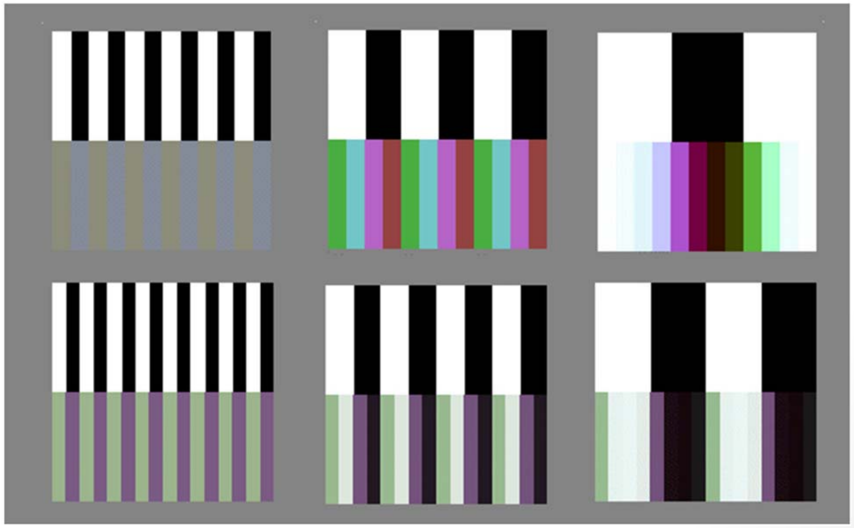
It is extremely difficult to design and produce a lens which resolves 200 lp/mm for a practical range of working distances and iris settings. Moving towards a custom design solution.

# Color Fringes

Color fringes are also affecting the MTF. They occur at dark/bright and bright/dark transitions. Not only the width, but also the color saturation plays an important part for the effects of these color fringes.



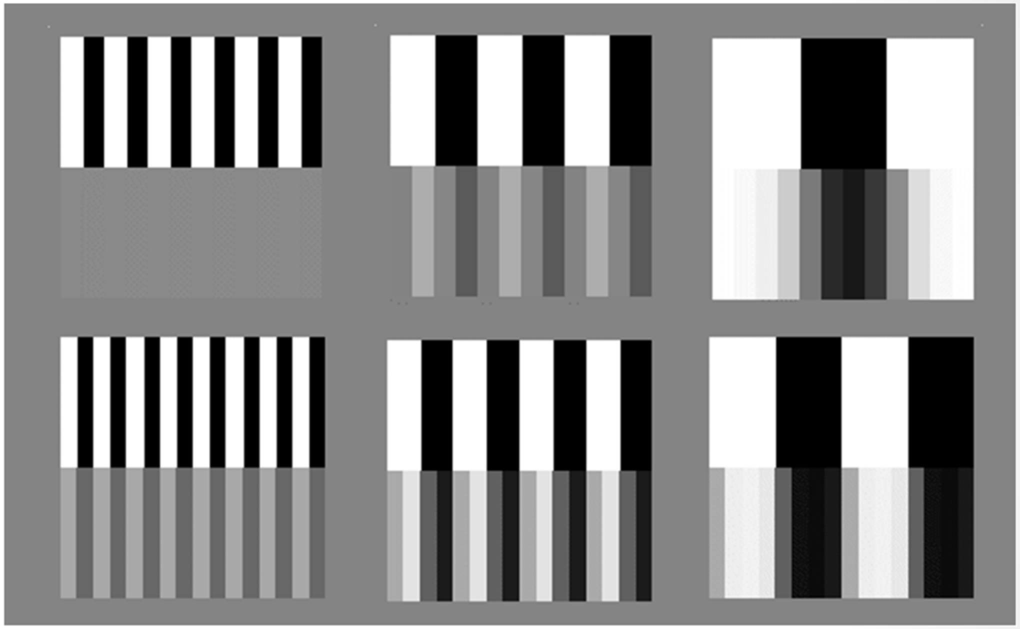

The above color fringes, caused by the lens, are “seen” by the sensor as shown at this figure.



# Color Fringes in Black & White

For black & white applications the color fringes have the same effect.

Due to the decreasing pixel sizes, the lenses have to be designed for smaller color fringes. This is only possible by using very special glass types, which are not only expensive, but also difficult to be produced.



# Mega Pixel Summary

*A X-Megapixel lens can not be combined with every X-Megapixel sensor.*

*Even if the correct lens for the sensor is choosen, a X-Megapixel lens does typically not fulfill the requirements for a X-Megapixel sensor under all circumstances.*

*A lens not intended for a certain sensor resolution can also be well suited for specific applications.*

*The smaller the pixel size, the more difficult it is to design and manufacture a suitable lens.*

# Mega Pixel Conclusion

*You should never choose a lens only because of its description.*

*You should know from your application, which image size, resolution, working distance and iris setting is required.*

*You should verify at least by the data sheets, if the choosen lens fulfills these requirements. (Data sheets need to be available!)*

*You should not choose too small pixels, otherwise it will be hard (or impossible) to find a suitable lens.*

*Knowing the requirements and lens data, you may choose also a lens from a lower level series for your application.*

*Remember to take into consideration the airy disk / circle of confusion of a lens at a particular f/stop and realize that you are not availing yourself of all the pixels on a megapixel sensors.*

# Lens Choice

- Choosing the correct lens / Type for your Application

THE ala Vision SHOW

# Best Type/Form Machine Vision Lens

**Magnification (β′) Calculation**

↓

**Define Working Distance (max/min) WD**

↓

**Focal Length (f′) Calculation**

↓

**Determine which lenses (Required f′) can properly image (Required β′)**

↓

**Which lens/lenses can cover Required 2y′**

Maximum Sensor Dimension with respect To Maximum lens Image Circle

↓

**Is the Lens Performance (MTF / Resolution) Commensurate with Sensor Pixel Size (Image resolution) or Object Space Require Resolution**

↓

**Which lens/lenses can interface/mount to the (Require Camera Mount) (i.e., F-Mount, C-Mount, M72, etc…**

↓

**Final Lens Selection & Associated Hardware**

# Best Type/Form Machine Vision Lens

**MAGNIFICATION**
**β'**

**$1/\beta' \rightarrow \infty$**
Infinity Corrected
Lenses

**$\beta' \geq 6x$**
Microscope Objectives
2y‘ Limitations

**$\beta' \approx 0.04$ to $0.33$**
25x to 3x
Reduction of
The Object

**$\beta' \approx 0.5$ to $2.0$**
2x Reduction
To
2x Enlargement
of The Object

**$\beta' \approx 3.0$ to $5.0$**
3x to 5x
Enlargement of
The Object

**•Does Not Include Telecentric Lenses**

THE ala Vision SHOW

# Best Type/Form Machine Vision Lens

**β' ≈ 0.04 to 0.33**

25x to 3x
Reduction of
The Object

Double Gauss
Telephoto
Inverse Telephoto
Large Format
Zoom…..

## 2y' > 22mm

- 12k/16k
- 8k
- 6k
- 4k
- 2k
- Linear
- TDI
- Area

Common Mounts:
F-Mount (2y'<42mm)
Threaded (M95,M72, M58,M42, Etc..)

## 2y' ≈ 22mm

- 1.3" (=22mm)
- 1k
- 2k
- Linear
- Area

Common Mounts:
C-Mount
F-Mount
Threaded (T2, etc..)

## 2y' < 22mm

- 1" (=16mm)
- 2/3" (=11mm)
- 1/2" (/= 8mm)

Common Mounts:
C-Mount
CS Mount

2y' = Maximum Image Plane Length

# Best Type/Form Machine Vision Lens

**β' ≈ 0.5 to 2.0**

2x Reduction
To
2x Enlargement
of The Object

Macro
Double Gauss (2y'<16mm)
(β'<1.0)
Reverse Double Gauss
(β'≥ 1.0)

**2y' > 16mm**

- 12k/16k
- 8k
- 6k
- 4k
- 2k
- 1.3"(= 22mm)
- Linear
- TDI
- Area

Common Mounts:
(2y'≤22mm)
C-Mount
CS-Mount
(2y"≥24mm
F-Mount
Threaded Mounts (M95,M72, M58, Etc..)

**2y' < 16mm**

- 1" (=16mm)
- 2/3" (=11mm)
- 1/2" (= 8mm)

Common Mounts:
C-Mount
CS Mount

2y' = Maximum Image Plane Length

# Best Type/Form Machine Vision Lens

**β' ≈ 3.3 to 5.0**

3x to 5x
Enlargement of
The Object

Macro
Reverse Double Gauss
(β'≥ 1.0)
Long WD Objectives
(2y''< 11mm)

**2y' < 86mm**

- 12k/16k
- 8k
- 6k
- 4k
- 2k
- 1.3"(= 22mm)
- 1" (= 16mm)
- 2/3" (= 11mm)
- 1/2" (= 8mm)
- Linear
- TDI
- Area

Common Mounts:
(2y' ≤ 22mm)
C-Mount
CS-Mount
(2y''≥ 24mm
F-Mount
Threaded Mounts (M95, M72, M58, Etc..)

2y' = Maximum Image Plane Length

# Basic Optical Calculations

# FOCAL LENGTH (f')

$$f' = \frac{a}{1 + (1/\beta')} \quad \Rightarrow \quad f' = \frac{a}{1 + (y/y')}$$

* Note * Must Use Common Units

f' = Focal Length

a = Object Distance

β' = Magnification

y = ½ Object Height

y' = ½ Image Height

**EXAMPLE**

a = 1000mm
β' = 0.1 (10x reduction)
f' = 91mm

# TOTAL TRACK (OO')

* Note * Sign Condition of HH'

$$\boxed{OO' = f'(2 + \beta' + 1/\beta') + HH'}$$

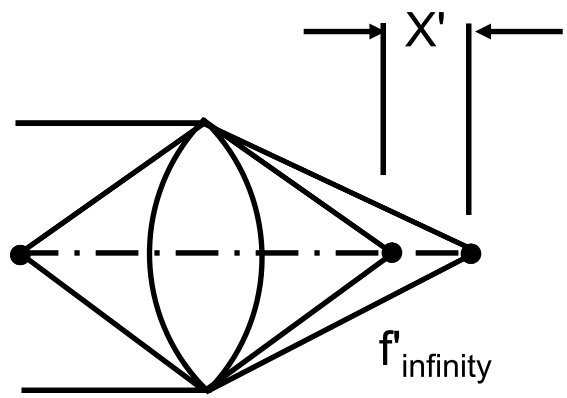
* Note * Must Use Common Units

OO' = Total Track (Object to Image)
f' = Focal Length
β' = Magnification
HH' = Nodal Point Separation

**EXAMPLE**

$\beta' = 0.10$
$f' = 100mm$
$HH' = 5mm$
Object to Image (OO') = 1215mm

# INFINITY FOCUS SHIFT (X')




$$X' = \frac{(f')^2}{a - f'}$$

* Note * Must Use Common Units

X' = Shift From Infinity Focus

a = Object Distance

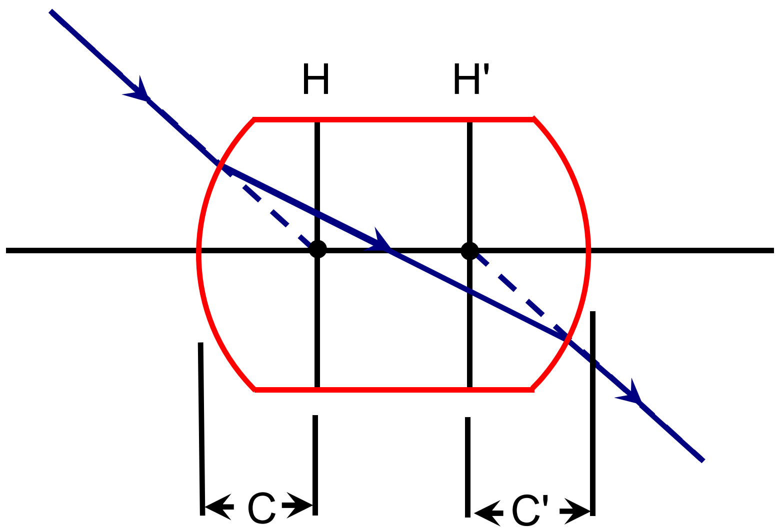
f' =Focal Length

**EXAMPLE**

f' = 50mm
a =250mm
X' = 12.5mm

As an object comes closer to a lens the image moves away (increases) from the lens

# NODAL POINT Locations




$$\boxed{C = S_f + f'}$$

$$\boxed{C' = f' - S'_{f'}}$$

C = Front Lens Vertex to Front Nodal Point

C' = Rear Lens Vertex to Rear Nodal Point

f' = Focal Length

$S_f$ = Front Focal length

$S'_f$' = Back Focal Length

Typically provided by the Lens manufacturer

**EXAMPLE**

**f' = 102.3mm**
**$S_f$ = -61.8mm**

**C = 40.5mm**
**Distance from EL#1 R1 Vertex into the lens (40.5mm) is the location of the front Nodal Point**

# ANGULAR FOV

$$\boxed{\alpha = \arctan(y'/f')}$$

$$\boxed{2\alpha = \text{Total Angular FOV}}$$

$\alpha$ = ½ Angular FOV

$y'$ = ½ Image Height

$f'$ =Focal Length

**EXAMPLE**

CCD Length = 11mm
$y' = 11/2 = 5.5$mm
$f' = 50$mm
$\alpha = 6.28$ degrees
Total Angular FOV = $2\alpha$ = 12.56 deg.

* Note * Must Use Common Units

# Angular Resolution

$$\text{Ang. Res.} = \frac{\text{Pixel Size}}{\text{Focal Length}}$$

**EXAMPLE**

Focal Length = 100mm
Pixel Size = 0.007mm

Ang. Res. = 0.00007 radians
= 0.00401 degrees
= 14.438 arc seconds

FYI – Human Eye
Normal visual acuity is one minute and this is the value for the resolution of the eye under what may be termed "Normal Conditions"

* Note * Must Use Common Units

# NEUTRAL DENSITY

Two Basic Types:

"Grey" Glass = typical range 400 to 700nm
Reflective = typical range (Visible to Near IR) (Invariant to wavelength)

$$\text{Density} = \log \frac{1}{\text{Transmission}}$$

$$\text{\# of Stops} = \frac{\text{Density}}{0.3}$$

$$\text{\% Trans.} = \frac{1}{\text{antilog (Density)}}$$

EXAMPLE

Neutral Density = 0.9
%Transmission = 12

EXAMPLE

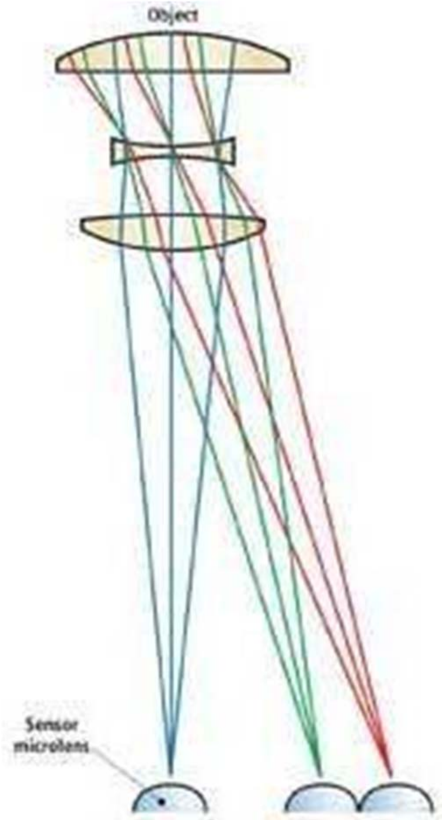
Neutral Density = 0.9
# of Stops = 3

# Micro Lenses

## Micro Lenses / Lenslets

# Micro Lenses (lenslets)

**Conventional Lens**



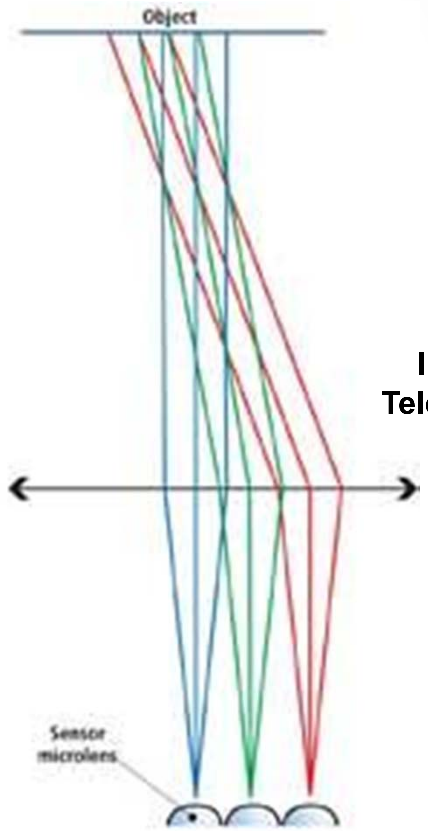
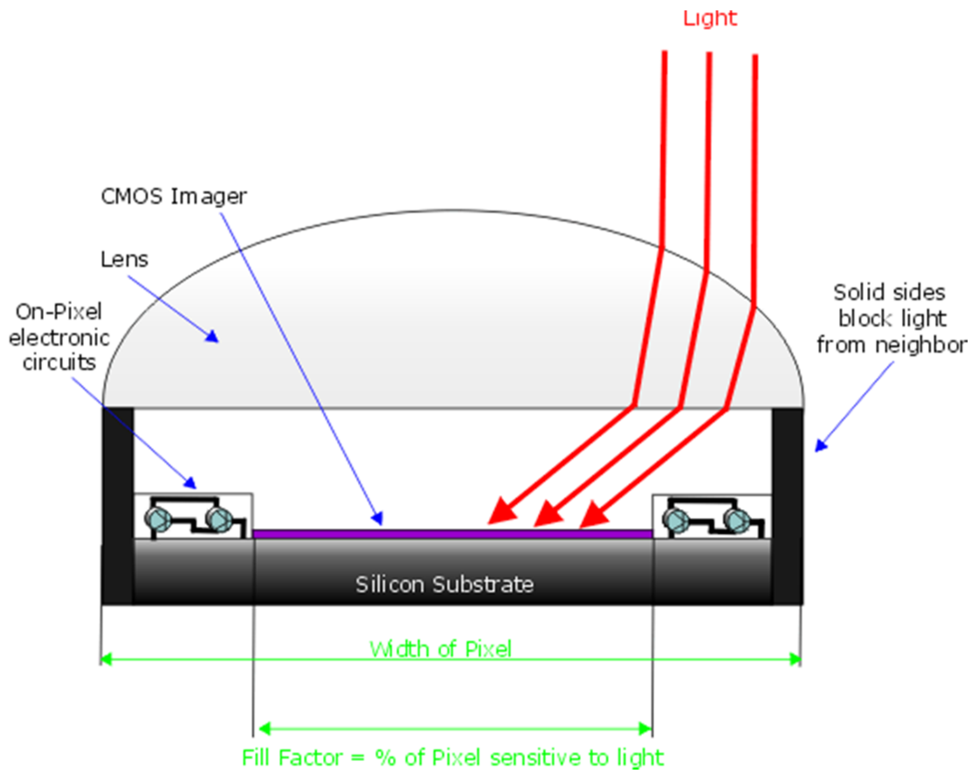




**Image Sided Telecentric Lens**

***If the external lens used in a design exceeds the acceptance angle of the microlens used with the sensor, light from objects farther from the center field of view of the lens (green and red) may not reach the sensor.***

***To overcome the problem associated with microlens-based sensors, lens manufacturers will offer external lenses that are near telecentric in image space. The angle from light farther and farther from the center will remain on-axis and no angular roll-off will occur.***

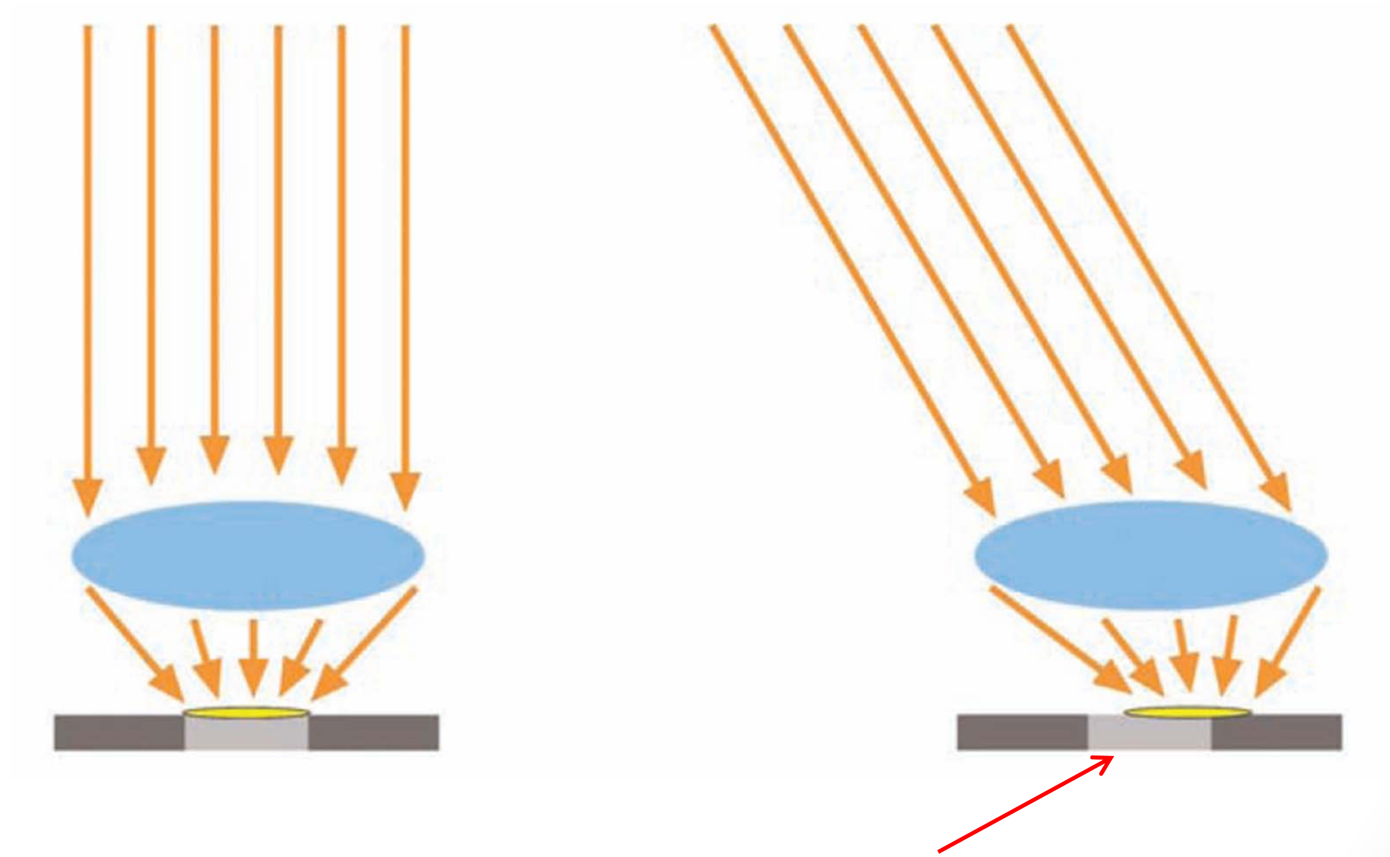
# Micro Lenses Cont….




*Microlenses increase the fill factor of the sensor by capturing as much light as possible. However, they have an acceptance angle at which they will effectively collect light and focus it onto the active portion of the pixel.*

# Why Anti-shading Lenses

**Sensors are using often micro lenses to improve the sensitivity**



Schematic view of the micro lenses on a single pixel (grey = active pixel surface)
(yellow = focused light area)

# Modification or Development

## COTS - Modification – Development

COTS = Commercial Off-The-Shelf)

- **Modifying Existing Designs and Creating New Ones**
  - What it takes
  - What Information needs to be taken into account
  - How to get what you need
  - General time lines
  - Volume requirements across industry

# Designs/Lenses (How to get what you Need)

## Modifying Existing Designs and Creating New Ones

If a standard design/lens "off-the-shelf" cannot satisfy your requirements then your first approach should be to see if the Lens Manufacturer can make a modification to an existing design

This will save time and "$'s" and gets you a finished / working lens ASAP. Depending on the amount of "Modifications" that might have to be made to a lens (change out an element, air-space, etc…..) this could take ≈ 4 to 8 weeks for a prototype lens and after approval serial production could start to deliver lenses ≈ 6 to 10 weeks from prototype approval. Depends upon the Optical Company….! Do not be afraid to ask…..!

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If a new lens design is deemed necessary – you must be prepared for the following:

Quote Lead Time ≈ 4 to 6 weeks.

Quote would include (All Optical & Mechanical NRE), small prototype quantity approx 2 to 6 lenses. Delivery of Prototypes ≈ 12 – 16 weeks ARO.

Once prototypes are tested /evaluated and approved by you – serial production can first start. Delivery of first production lenses ≈ 12 – 16 weeks ARO.

Minimum time starting including quote ≈ 6 months to production lenses.

In order for a custom lens to be made in production – quantities should be > 100 lenses to be somewhat cost effective.

# Lens Selection “Up-Front” ?’s

1) Object Size (L W H) {sometimes called “FOV”}?
2) Image (Area or Linear, L W H, # of Pixels)?
3) Magnification?
4) CCD (Color, BW, Pixel Size, IR Block Filter)?
5) Wavelength Region (mono, visible, Near IR)?
6) Relative Aperture (f/#, How much light)?
7) Camera Mount (C-Mount, F-Mount, .....)?
8) Camera Flange Focus Depth?
9) Object Distance (Working Distance)?
10) Black Box Size (Lens: Max Diameter, Length)?
11) Black Box Size (system, OO)?
12) System Resolution (Object Space)?
13) Object Contrast?
14) Environmental (Temp Range, Vibration, Dust)?
15) Geometric Distortion?
16) Optical Filtering ?
17) Focal Plane (Sensor) Micro Lenslets?
18) Single sensor or “3 CCD” prism assembly?

# Is it Too Late?

- Do Not treat the lens/optics as an "After Thought" !

- It is somewhat common to 1st look into your lens selection AFTER:

- Camera is Chosen (Mount type, Sensor Format/Size, Lighting, Etc…)
- This can greatly limit your "off-the-shelf" lens choices
- As well as possibly driving you towards a "Custom lens Design/Development"
- Lens parameters needs to be defined concurrently during your initial system layout – specifications!

Classic Case: I have a CCD camera that contains a 60mm CCD length
I want a working Distance of about 1 foot
My magnification needs to be 10x Enlargement
I want to resolve 1 micron defect in object space
My total "Black Box" length = 18 inches

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