



Imaging Optics Fundamentals

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Topics for Discussion

Fundamental Parameters of your system

- Field of View

- Working Distance

- Sensor Sizes

Understanding Resolution and Contrast

- Basics

- MTF

Depth of Field and Effects of F#

Measurement Accuracy

- Distortion

- Telecentricity

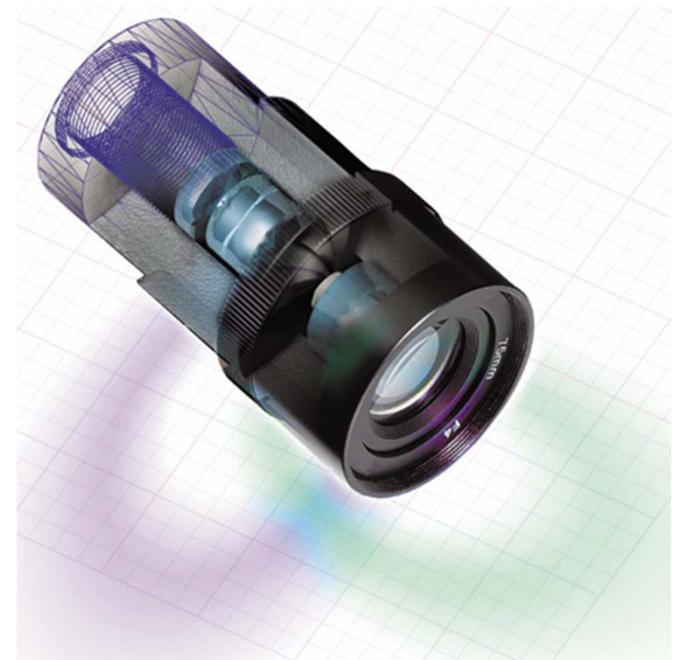
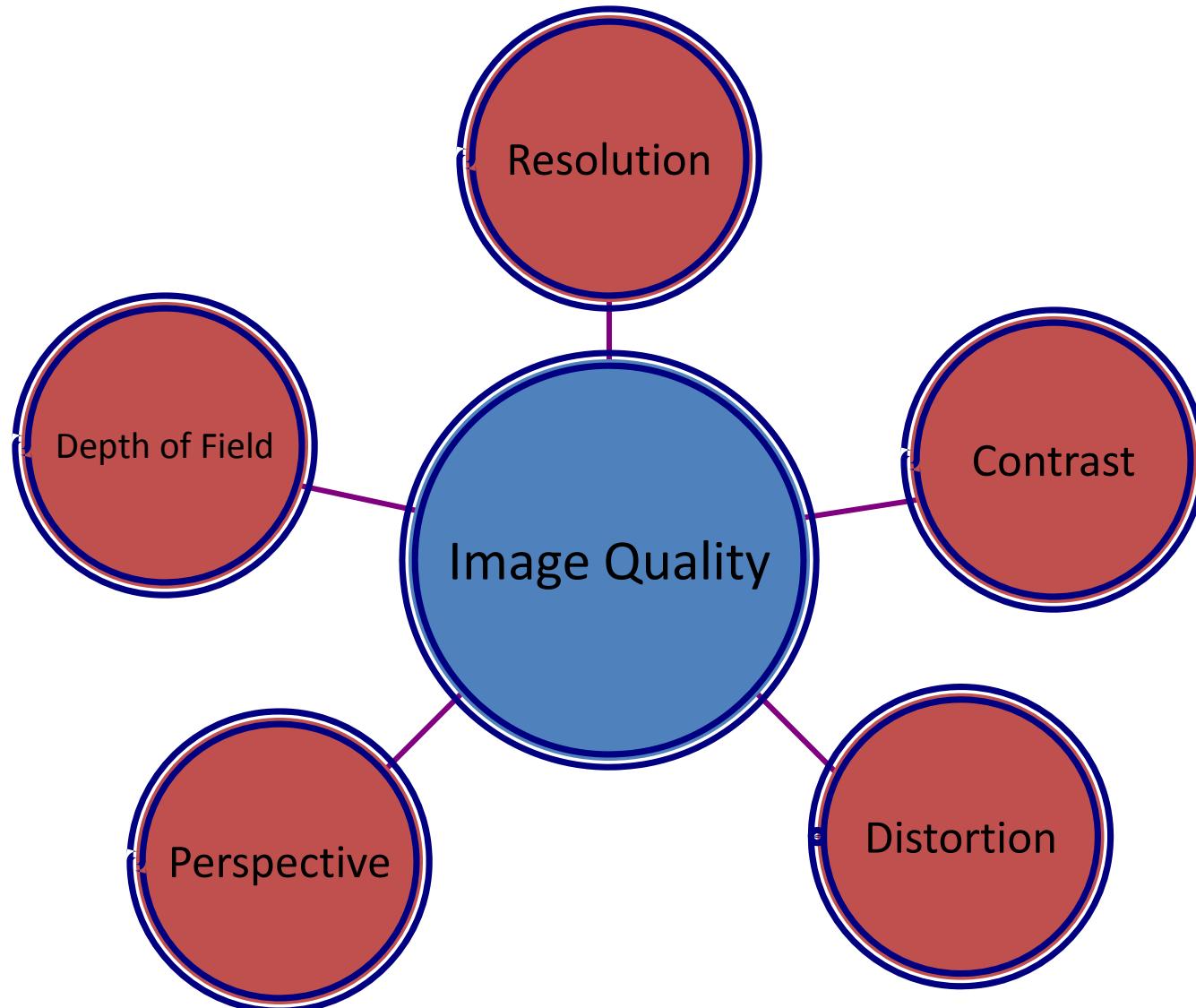
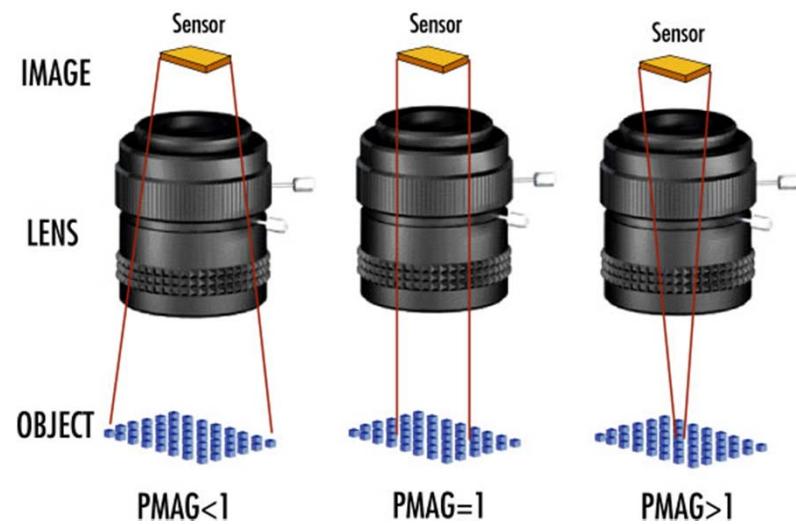
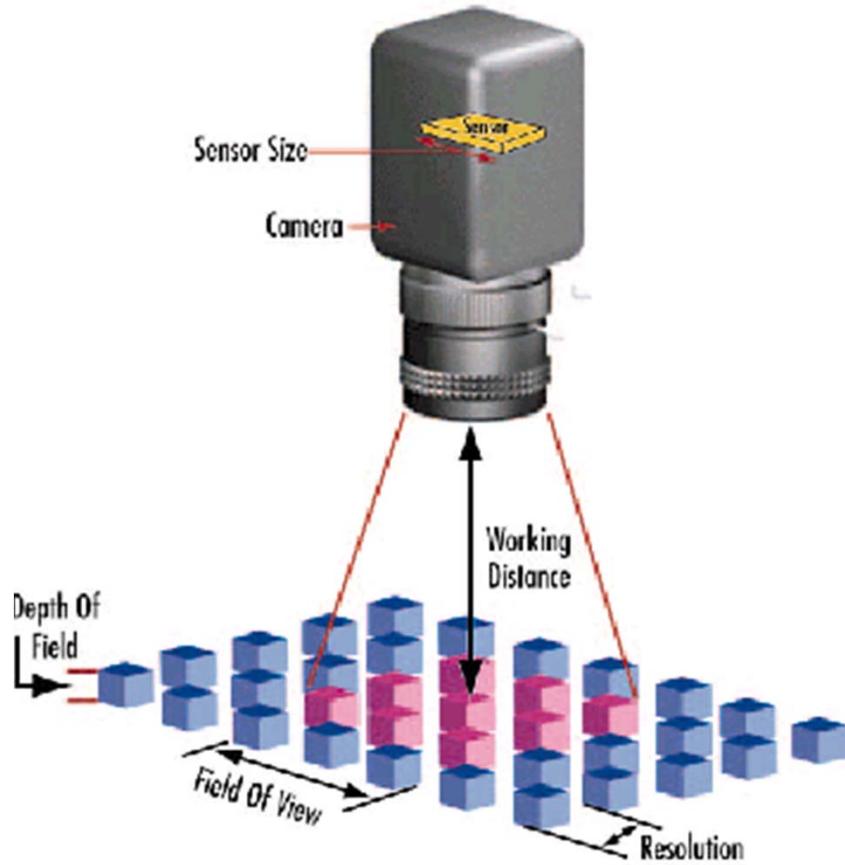


Image Quality

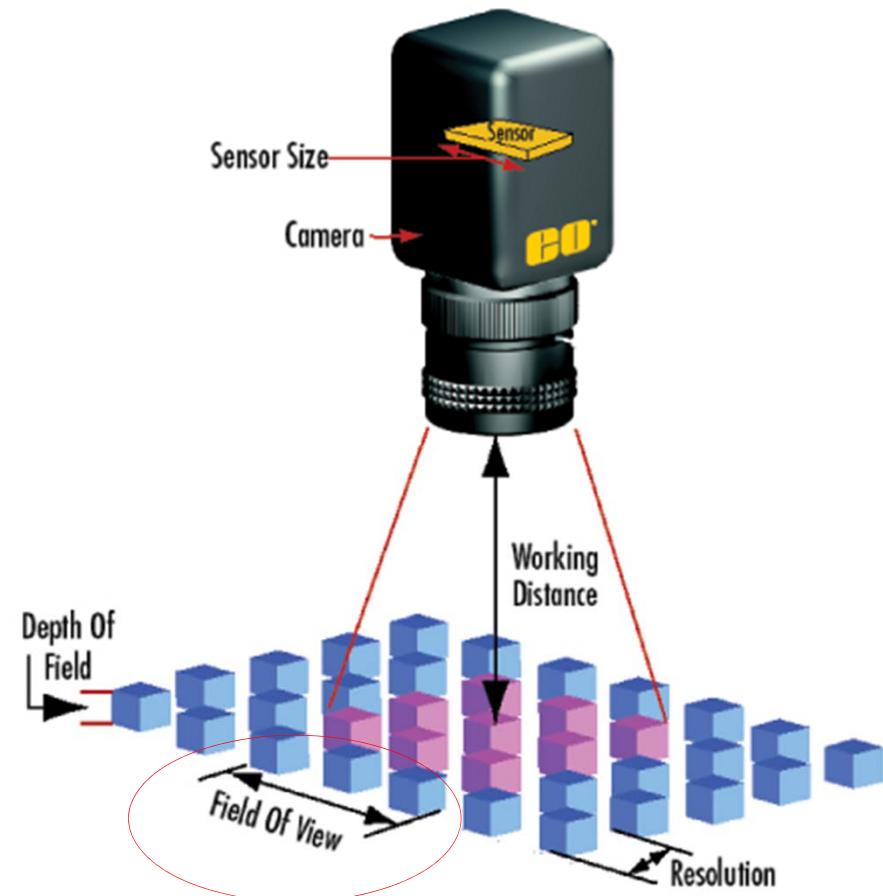


Fundamental Parameters of Imaging Systems



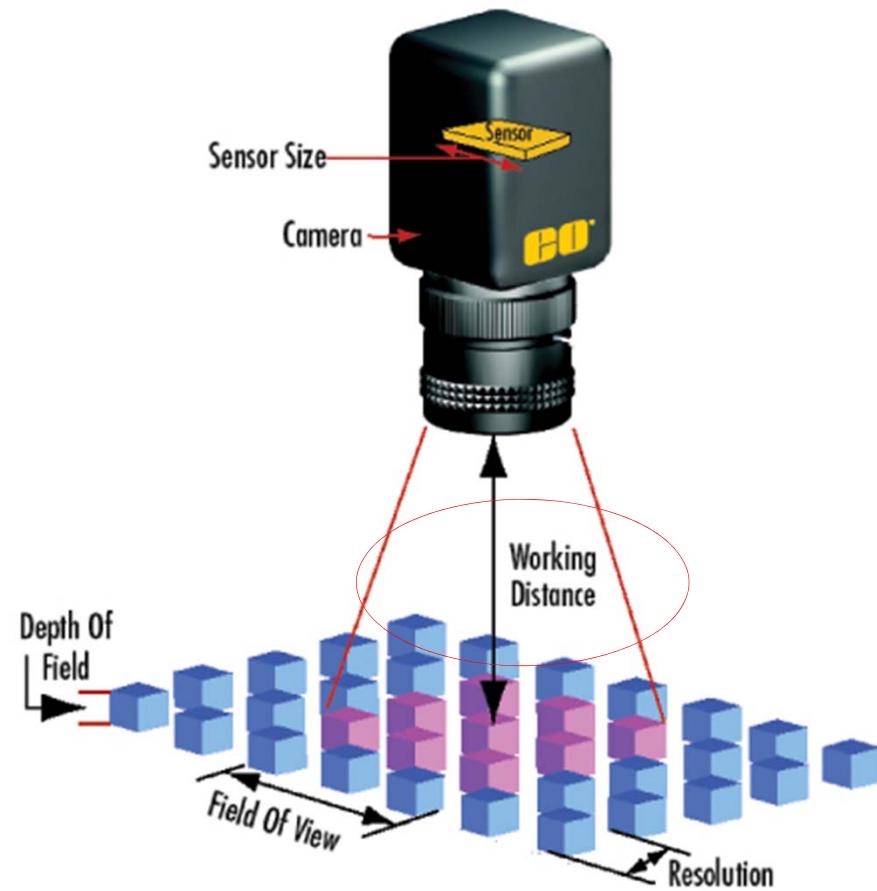
Glossary of Terms

Field Of View (FOV): The viewable area of the object

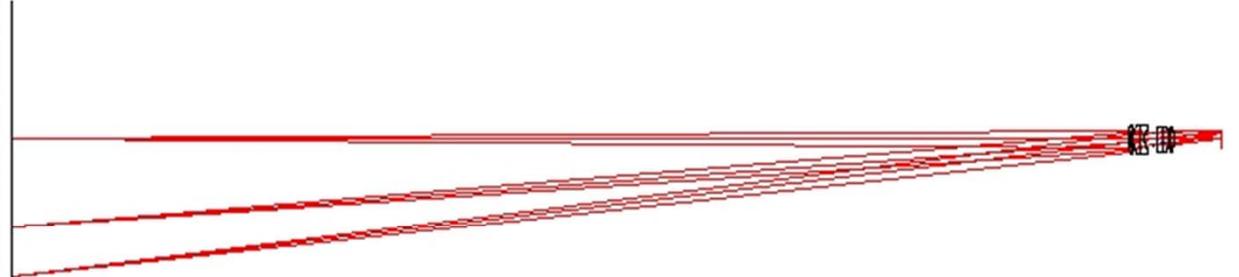


Glossary of Terms

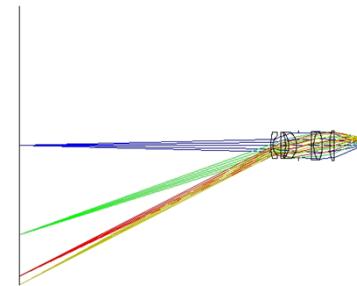
Working Distance (WD): The distance from the front of the lens to the object



Possible Effects of Working Distance Changes



75mm lens

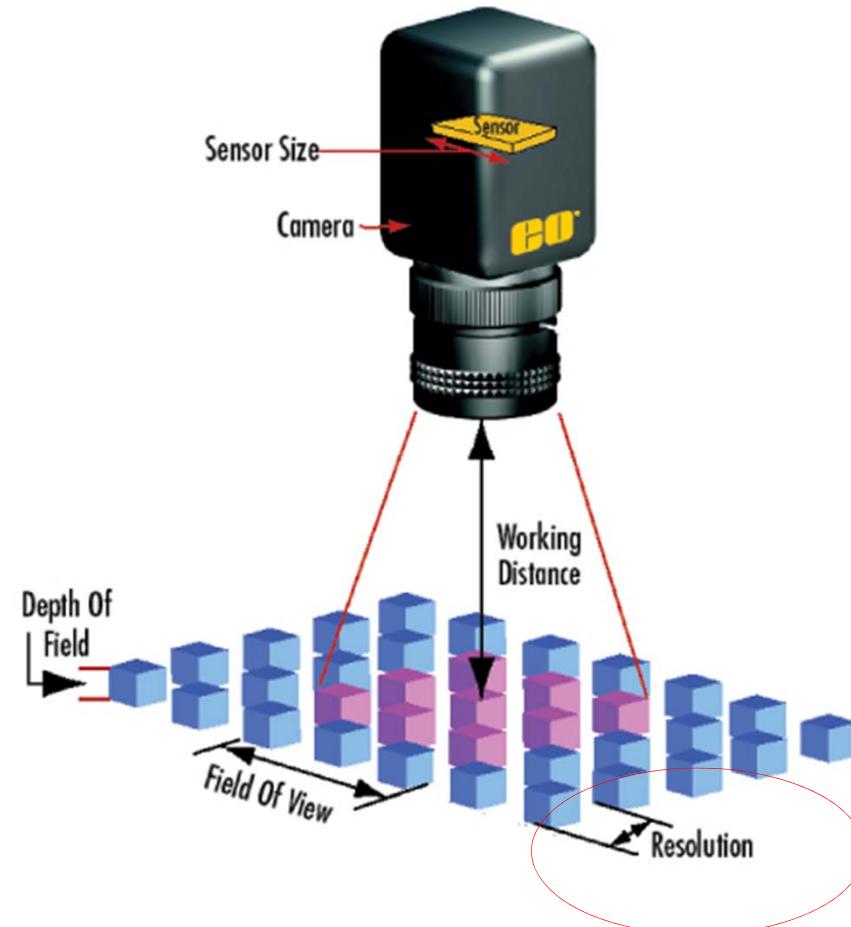


12mm lens



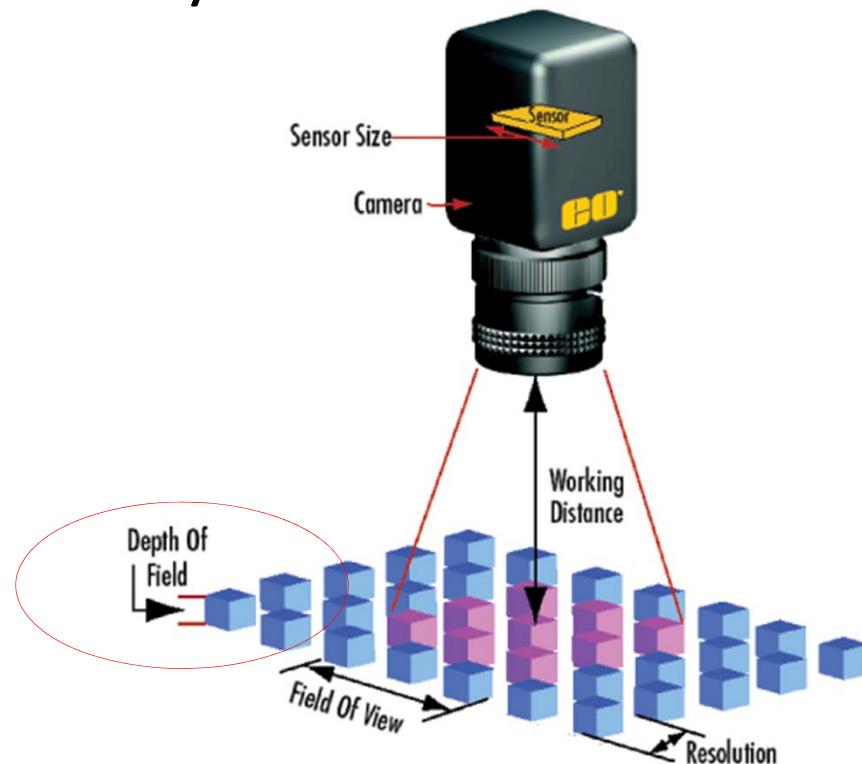
Glossary of Terms

Resolution: The minimum feature size of the object



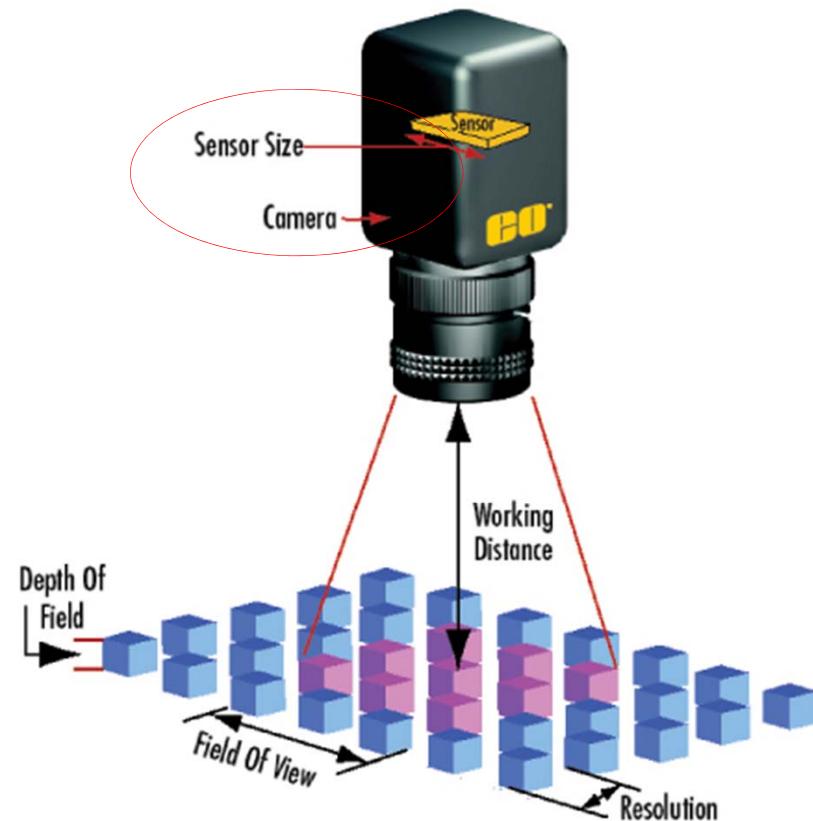
Glossary of Terms

Depth Of Field (DOF): The maximum object depth that can be maintained entirely in focus



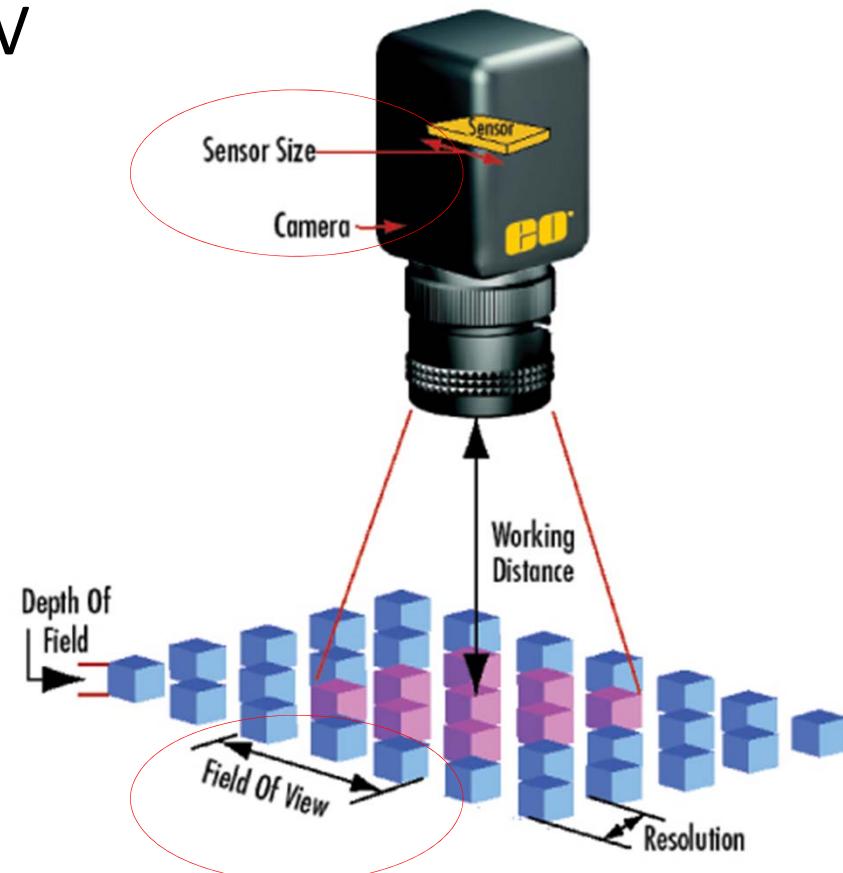
Glossary of Terms

Sensor Size: The size of a camera sensor's active area, typically specified in the horizontal dimension



Glossary of Terms

Primary Magnification (PMAG): The ratio between the sensor size and the FOV



Fundamental Parameters of an Imaging System

Field Of View (FOV): The Viewable area of the object under inspection. In other words, this is the portion of the object that fills the camera's sensor.

Working Distance (WD): The distance from the front of the lens to the object under inspection.

Resolution: The minimum feature size of the object under inspection.

Depth Of field (DOF): The maximum object depth that can be maintained entirely in focus. DOF is also the amount of object movement (in and out of focus) allowable while maintaining a desired amount of focus.

Sensor Size: The size of a camera sensor's active area, typically specified in the horizontal dimension. This parameter is important in determining the proper lens magnification required to obtain a desired field of view. The primary magnification (PMAG) of the lens defined as the ratio between the sensor size and the FOV. Although sensor size and field of view are fundamental parameters, it is important to realize that PMAG is not.



How we determine FOV

What specification of a lens helps me determine FOV

Focal length 8.5mm, 12mm, 25mm, etc.

Angular FOV 10° , 25° , etc

Magnification 0.25X, 0.5x, 2X, 10X etc



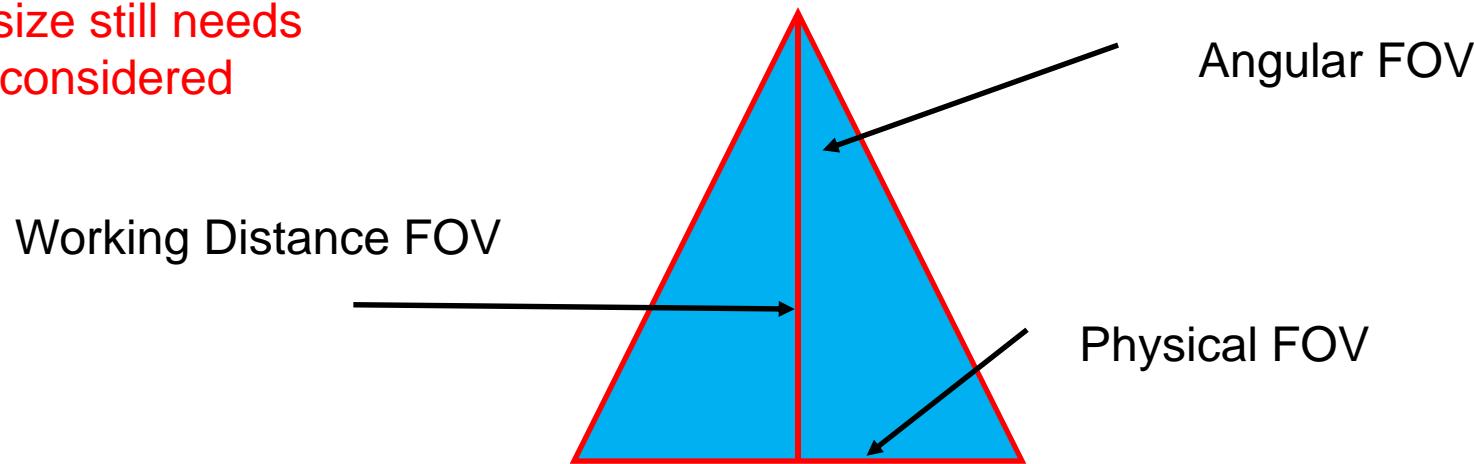
How we determine FOV, Roughly

What specification of a lens helps me determine FOV

FOV calculations with fixed focal lenses and angular FOV's:

Angular Field: $\text{Tan}(0.5 * \text{angular field in degrees}) = 0.5 \text{ FOV}/\text{WD}$

Chip size still needs
to be considered



Example: 12mm lens with angular FOV of 30.3 degrees, WD=300mm

Angular Field: $\text{Tan}(0.5 * 30.3) = 0.5 \text{ FOV}/300\text{mm} = \text{FOV } 162.5\text{mm}$

Actual from design 168mm



How we determine FOV

What specification of a lens helps me determine FOV

FOV calculations with fixed magnification:

FOV = Sensor Size/PMAG

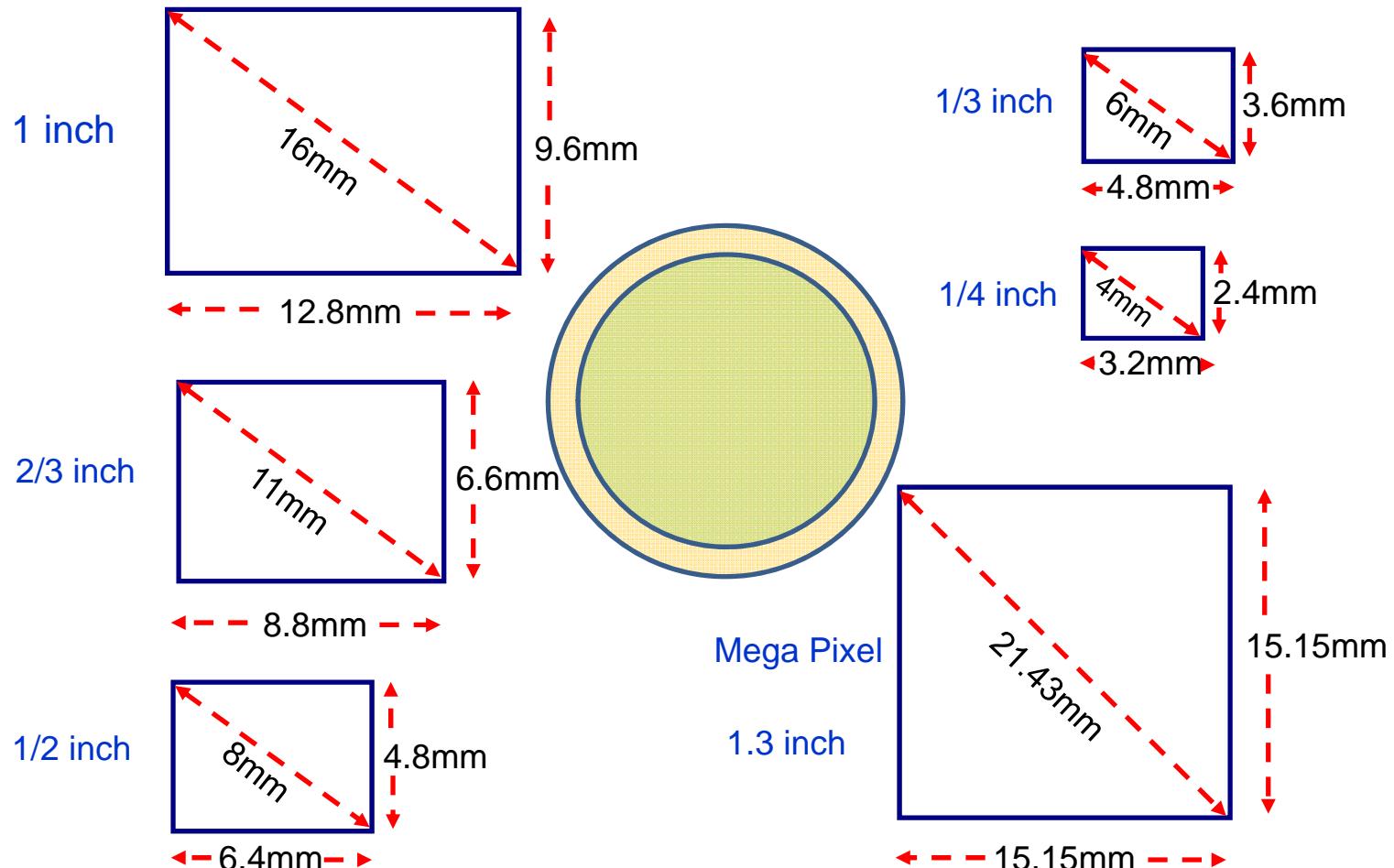
Example: Camera with $\frac{1}{2}$ inch Sensor, Lens with 0.5X PMAG

FOV = 6.4mm/0.5

FOV = 12.8mm



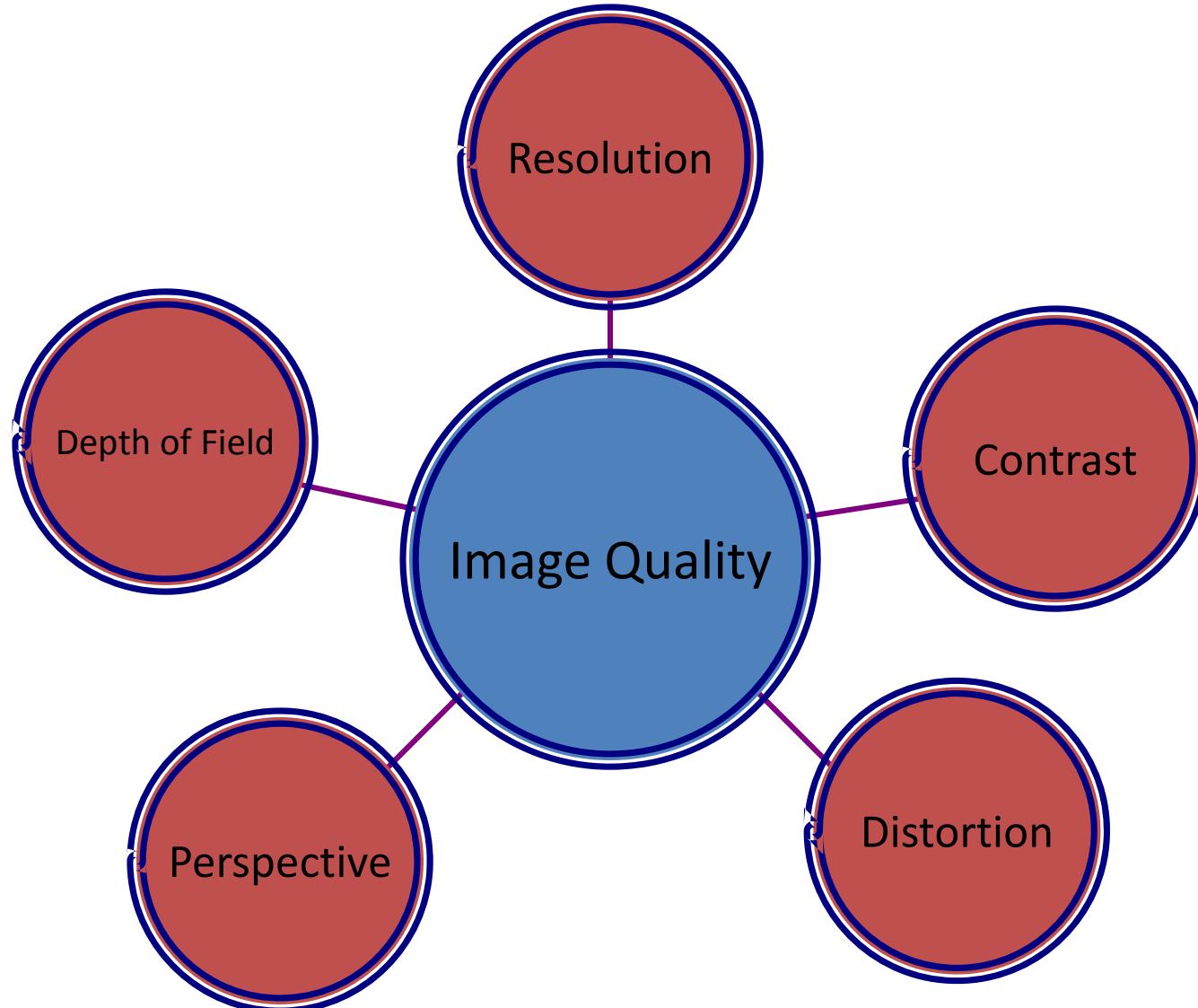
C-Mount Sensor Formats



Common Area Sensor (4:3 Aspect Ratio) Common Name = Old Videcon Tube Diameter

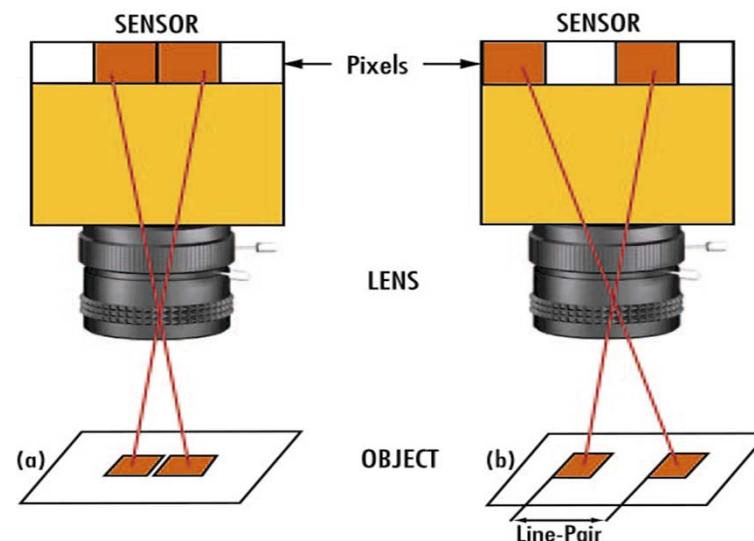


Image Quality



How Do We Define Resolution?

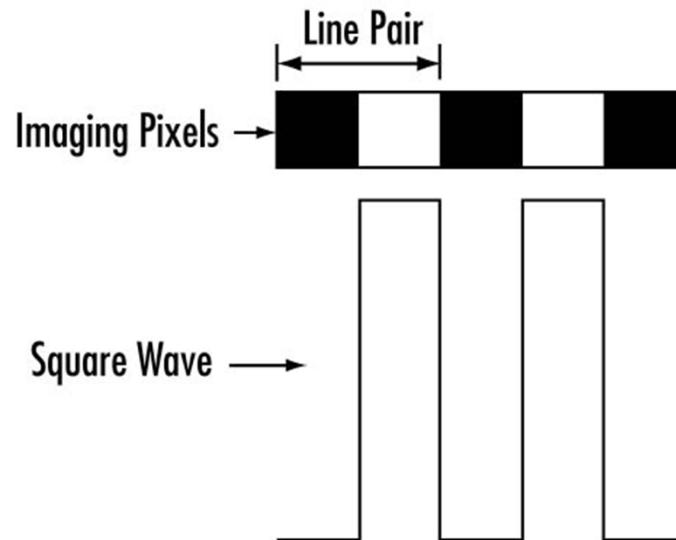
Resolution is a measurement of the imaging system's ability to reproduce object detail.



Exaggerated example in which a pair of squares are not resolved(a) and resolved (b). In figure (a) the two squares are imaged onto neighboring pixels and are indistinguishable from one another. Without any space between, they appear as one large rectangle in the image. In order to distinguish them a certain amount of white space is needed, as in figure (b). This can be represented by a line pair.



How Do We Measure Resolution In Optics?



Typical simplification of an object as Line Pairs formed by square waves

Frequency of lines is represented in line pairs over a linear spacing.

$$\text{Frequency or Line-pair(lp/mm)} = \frac{1}{\text{Spacing(mm)}}$$

$$\text{Line-pair(lp)} = 2 \times \text{Pixel}$$



How Do We Use Object Space and Image Space Resolution?

Object Space resolution defines the size elements in the object that can be resolved.

Image space resolution is the resolution at the image plane (CCD sensor).

Image space resolution and object resolution are related by the Primary Magnification (PMAG).

$$\text{Object Space Resolution}(\mu\text{m}) = \frac{\text{Image Space Resolution}(\mu\text{m})}{\text{PMAG}}$$

Object Space Resolution (lp/mm) = PMAG x Image Space Resolution (lp/mm).

FOV = Sensor Size/PMAG

Image Space Resolution is a combination of the lens resolution and the camera resolution.

Camera resolution (μm) = 2 x Pixel Size(μm) .



Example of Image Space Resolution

Image space resolution is characterized by the number of pixels contained in the camera

The sensor size and pixel size are constant so image space resolution is constant

- Note: The camera is not always the limiting factor when looking at system resolution

Example:

- Sensor size 10mm x 10mm
- Number of pixels 1000 x 1000
- Number of line pairs = $1000/2 = 500\text{lp}$
- The line lp/mm= $500\text{lp}/10\text{mm} = 50 \text{ lp/mm}$
- Image Space resolution = $1/50 \text{ lp/mm} = 20 \mu\text{m}$



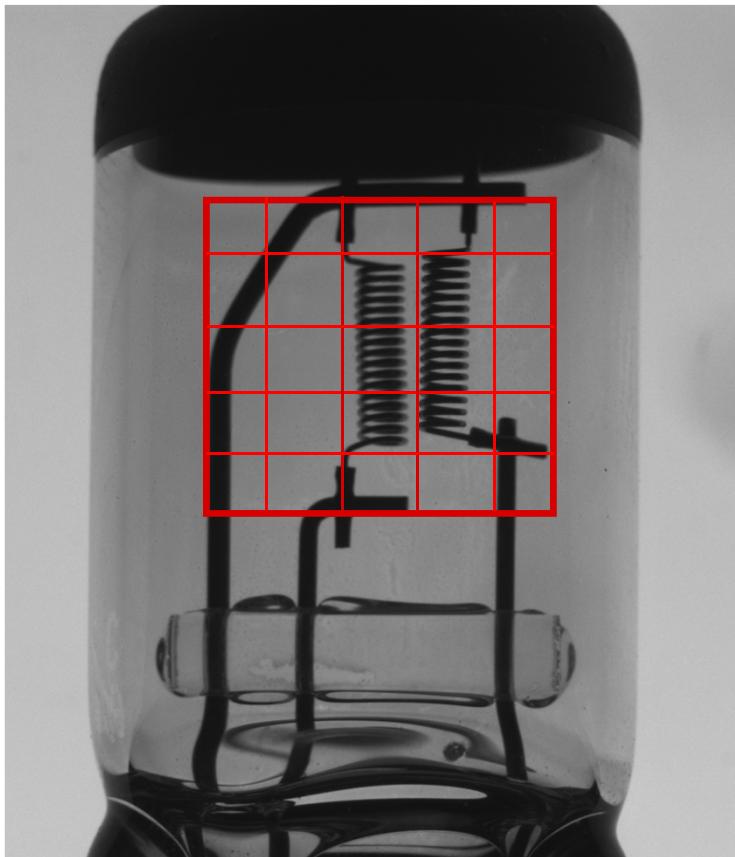
Example of Object Space Resolution

Image space and object space resolution are related by the lenses primary magnification (PMAG)

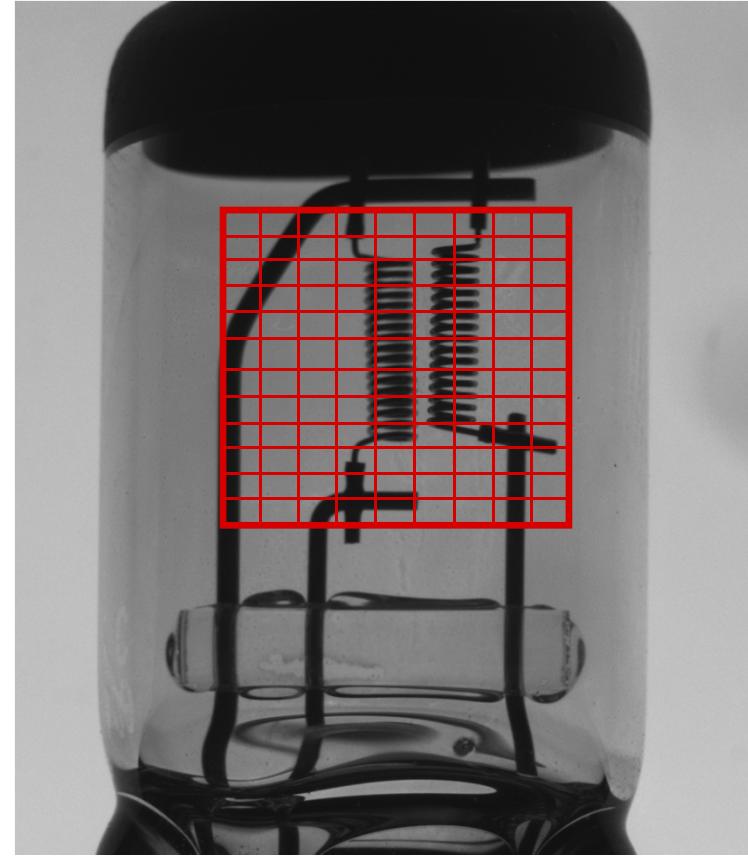
- **Image space resolution = 20 μm**
- **PMAG of 2**
- **Object space resolution = $20 \mu\text{m}/2 = 10 \mu\text{m}$**
- **FOV = $10\text{mm}/2 = 5\text{mm}$**
- **Object space res in line pairs = $50 \text{ lp/mm} \times 2 = 100 \text{ lp/mm}$**
- **PMAG of 0.5**
- **Object space resolution = $20 \mu\text{m}/0.5 = 40 \mu\text{m}$**
- **FOV = $10\text{mm}/.5 = 20\text{mm}$**
- **Object space res in line pairs = $50 \text{ lp/mm} \times 0.5 = 25 \text{ lp/mm}$**



Example: Field of View and Resolution



640 x 480 pixel
(0.3 megapixels)



1600 x 1200 pixel
(2 megapixels)



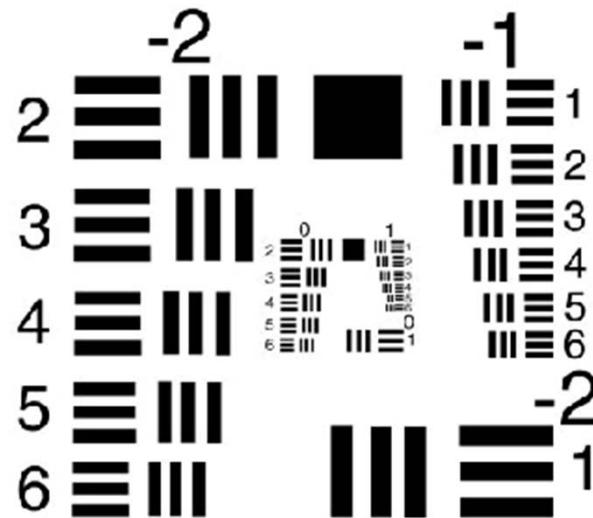
How Is Resolution Tested?

By imaging a test target, a limiting resolution can be found.

Targets consist of varying frequencies.

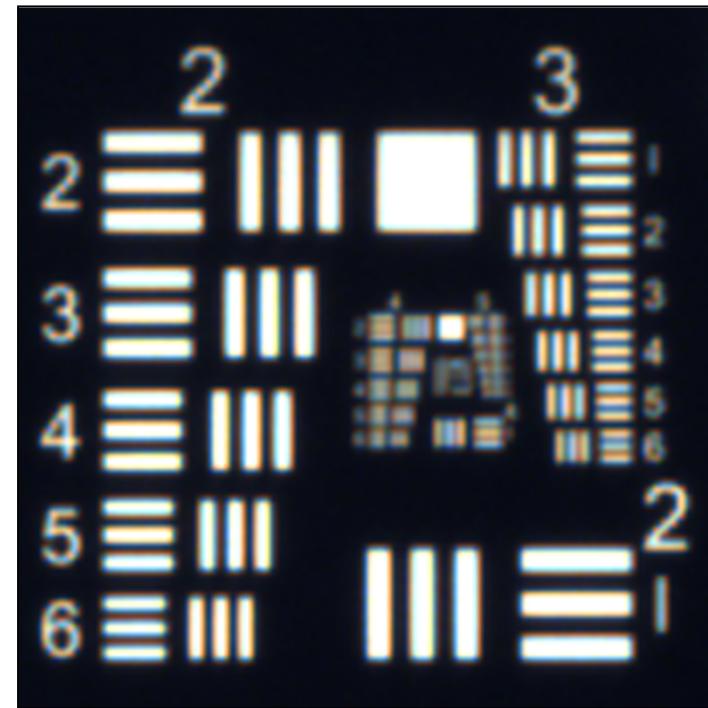
A common test target is the bar target.

- Bar targets have sets of line pairs.
- Orthogonal bars allow tests of astigmatic errors.
- Bar targets are limited by a finite number of steps in frequency.



Resolution Comparison Same Lens Different Camera

The images below are of the same target at the same magnification, using the same lens and identical lighting conditions. The image on the left is created with a high resolution color analog camera, while the image on the right is created with a high resolution color digital camera.



Same Resolution Camera Different Lenses

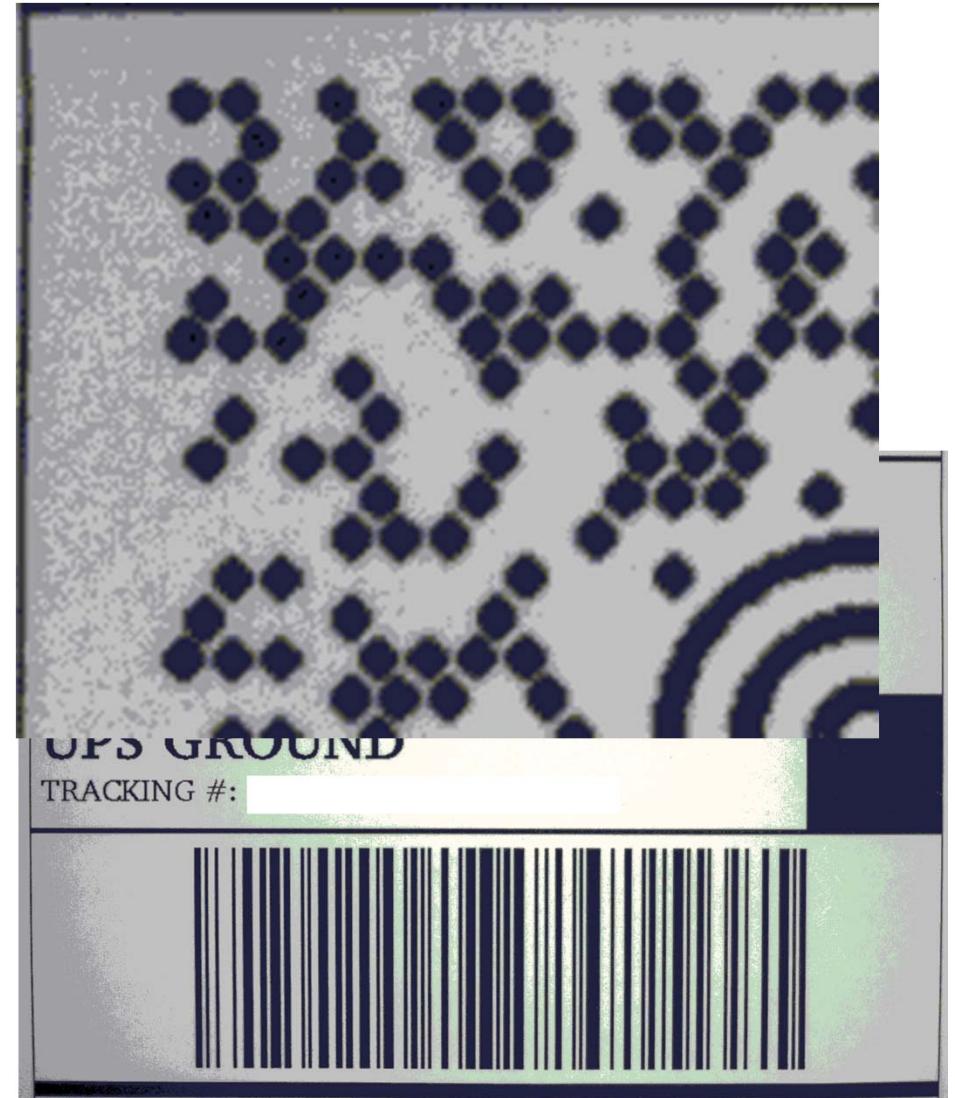
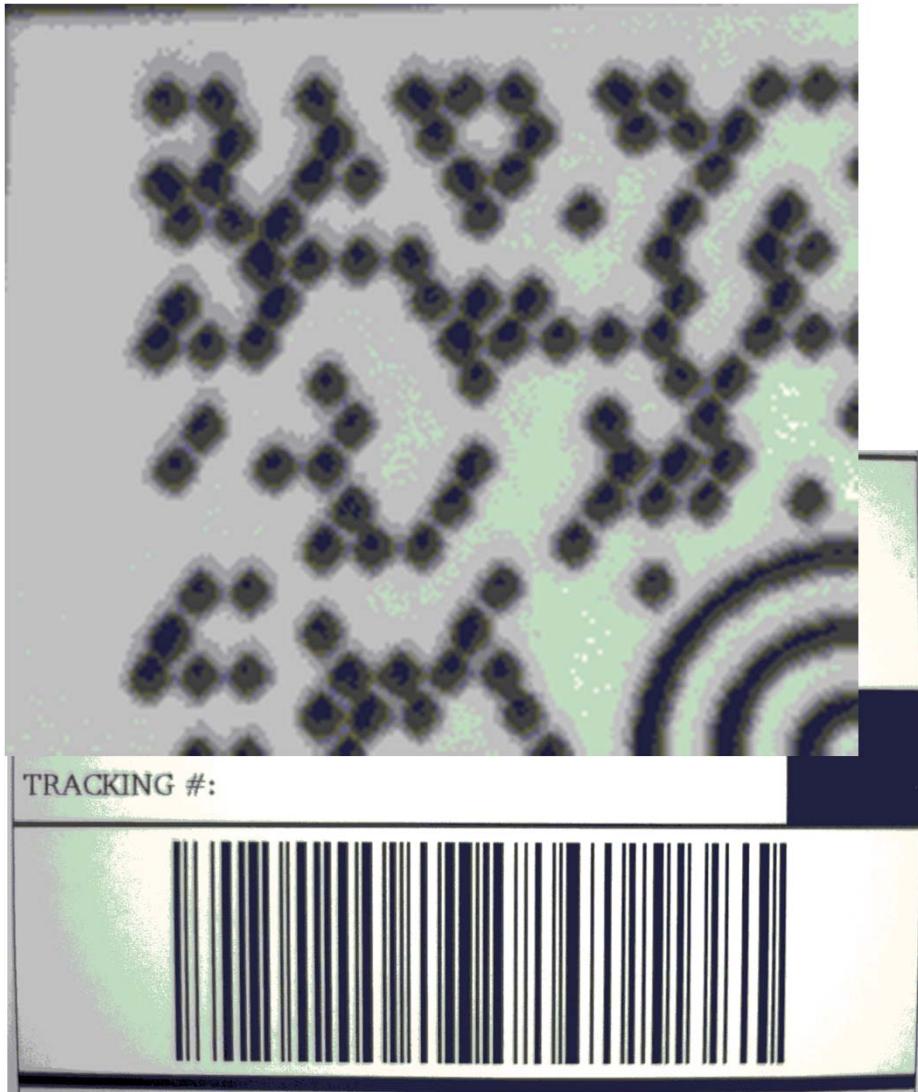
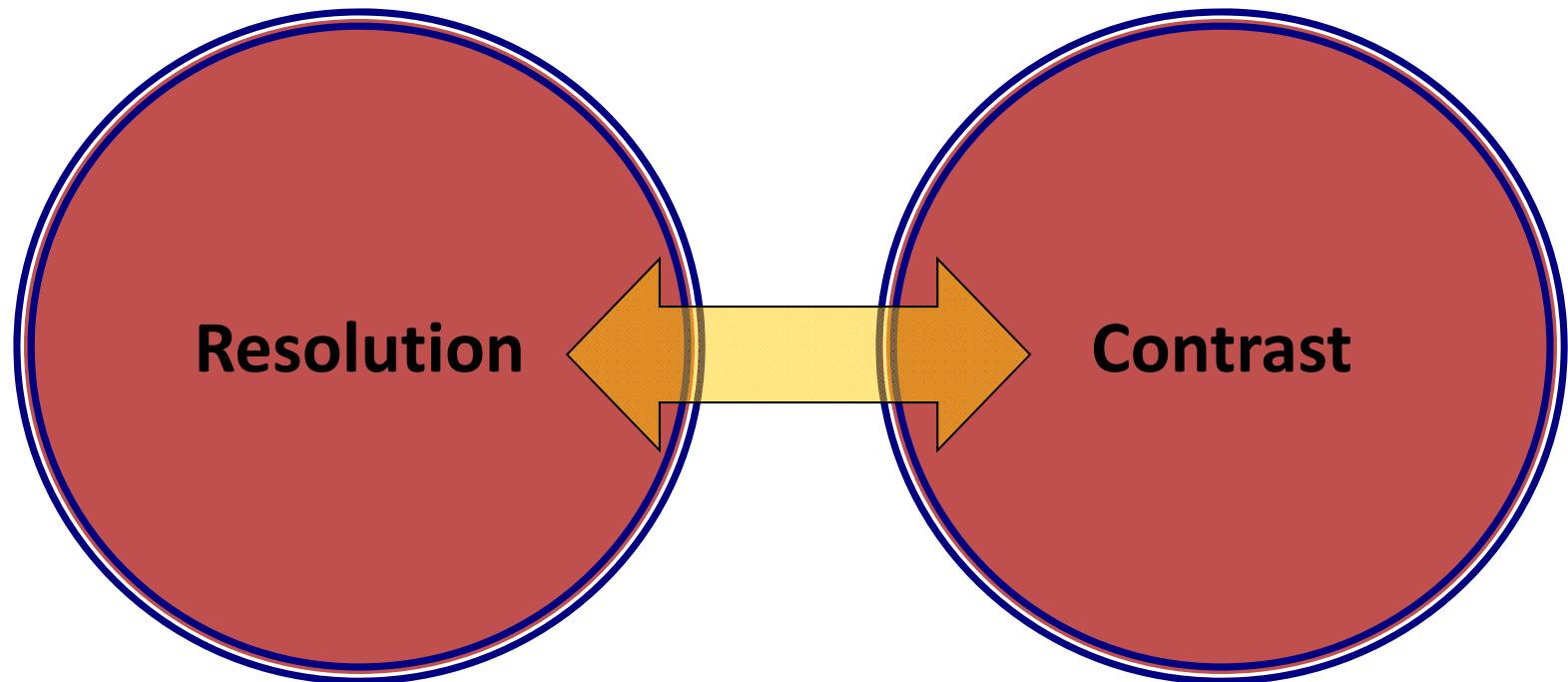
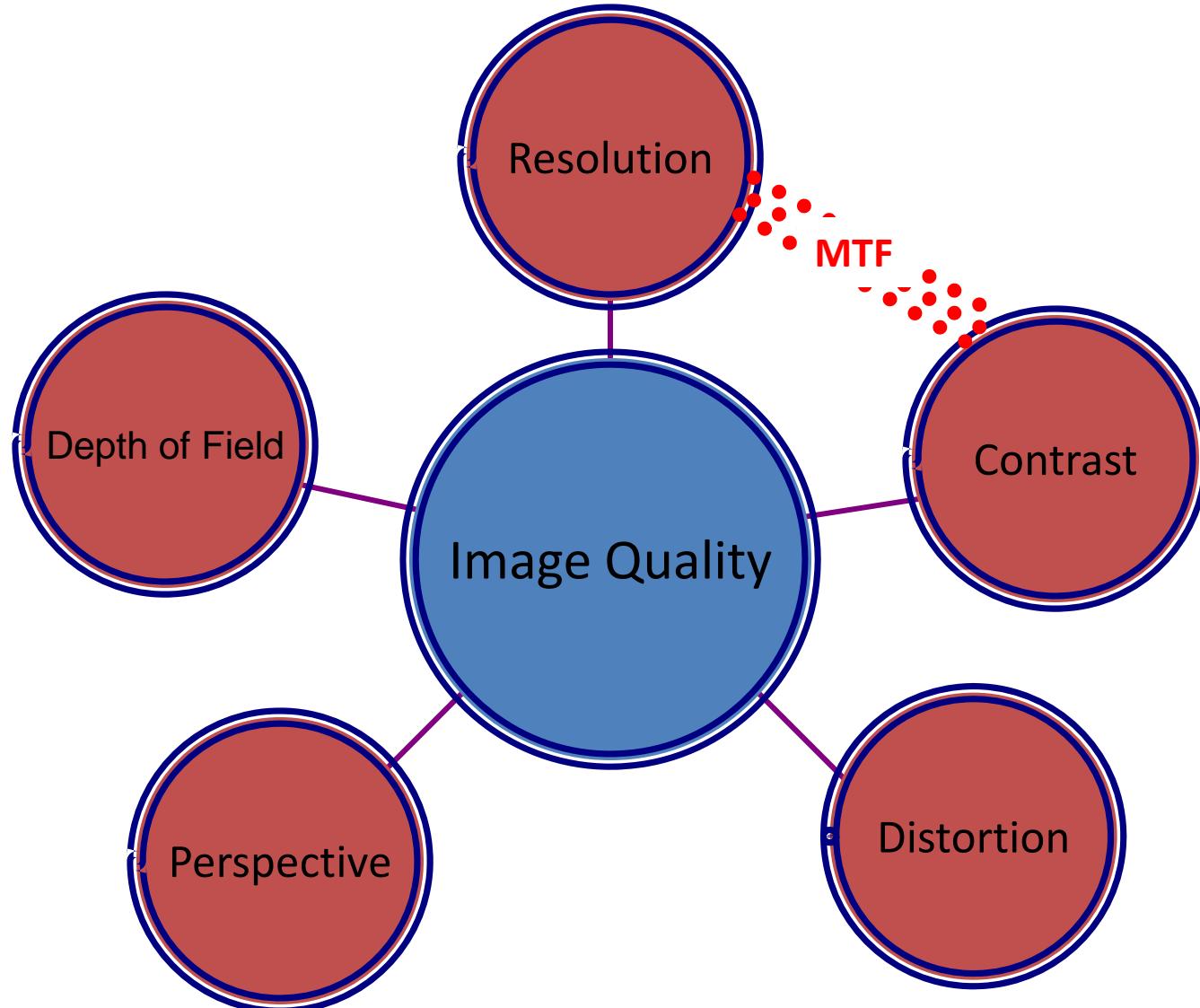


Image Quality



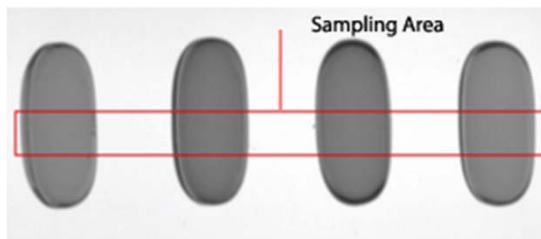
Review of Basics



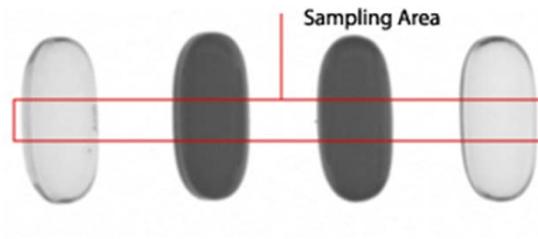
Color Filtering with a Monochrome Camera

No

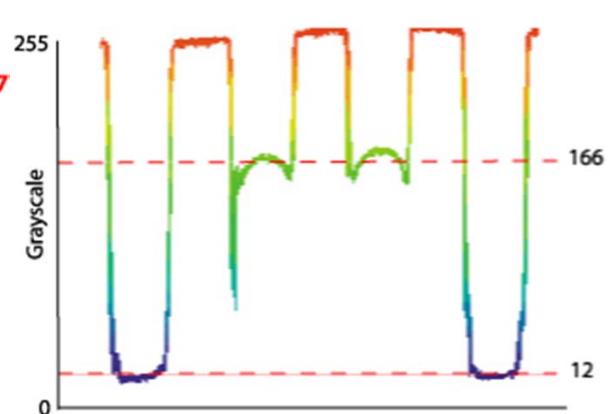
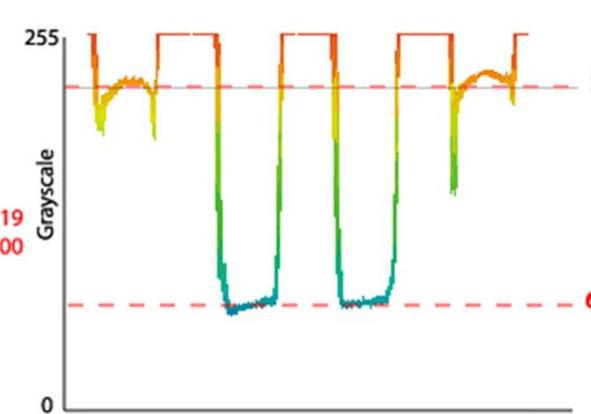
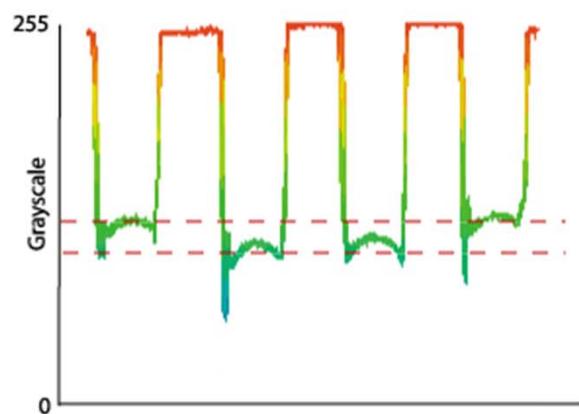
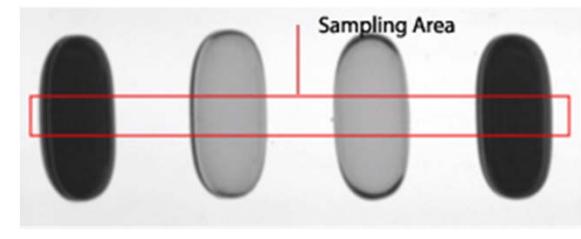
No Filter



Red Filter



Green Filter



Examples of Different Contrast Images



Problems with low contrast affects final resolution.

Makes image processing and thresholding more difficult.



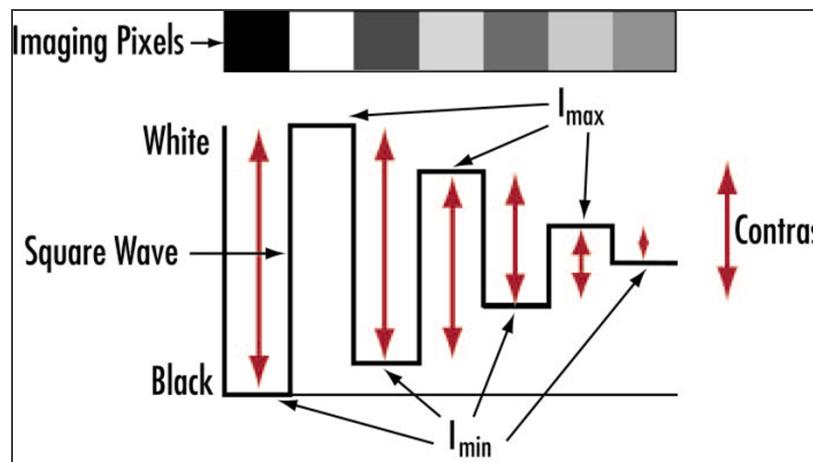
What Is Meant By Contrast?

Contrast describes the separation in intensity between blacks and whites.

$$\% \text{ Contrast} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

Reproducing object contrast is as important as reproducing object resolution.

For an image to appear well defined black details need to appear black and the white details appear white.



The greater the difference in intensity between a black and white line, the better the contrast.



How Are Contrast and Resolution Linked?

Resolution and contrast are closely linked.

Resolution is defined at a specific contrast.

The typical limiting contrast of 10-20% is often used to define resolution of a CCD imaging system.

For the human eye a contrast of 1-2% is often used to define resolution.



How Does Contrast Depend On Frequency?

Suppose two dots are placed close to each other and imaged through a lens.

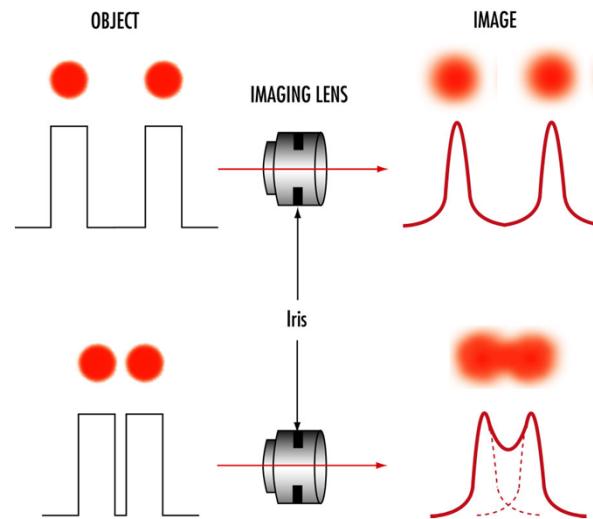
The two spots will blur slightly.

Moving the spots closer causes the blur to overlap and contrast is decreased.

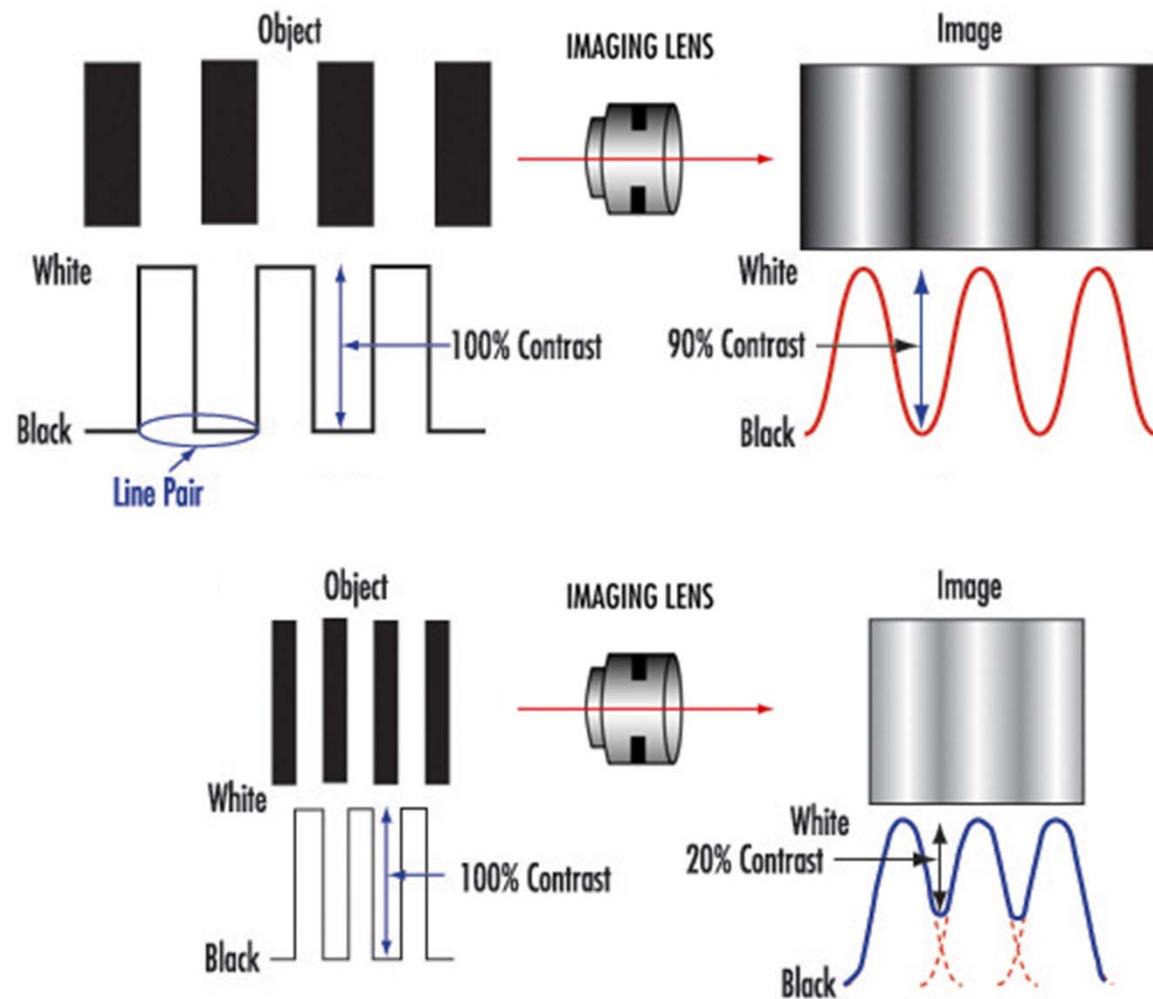
When the spots are close enough that the contrast becomes limiting, the spacing is our resolution.

At each spacing of the spots we obtain a specific contrast.

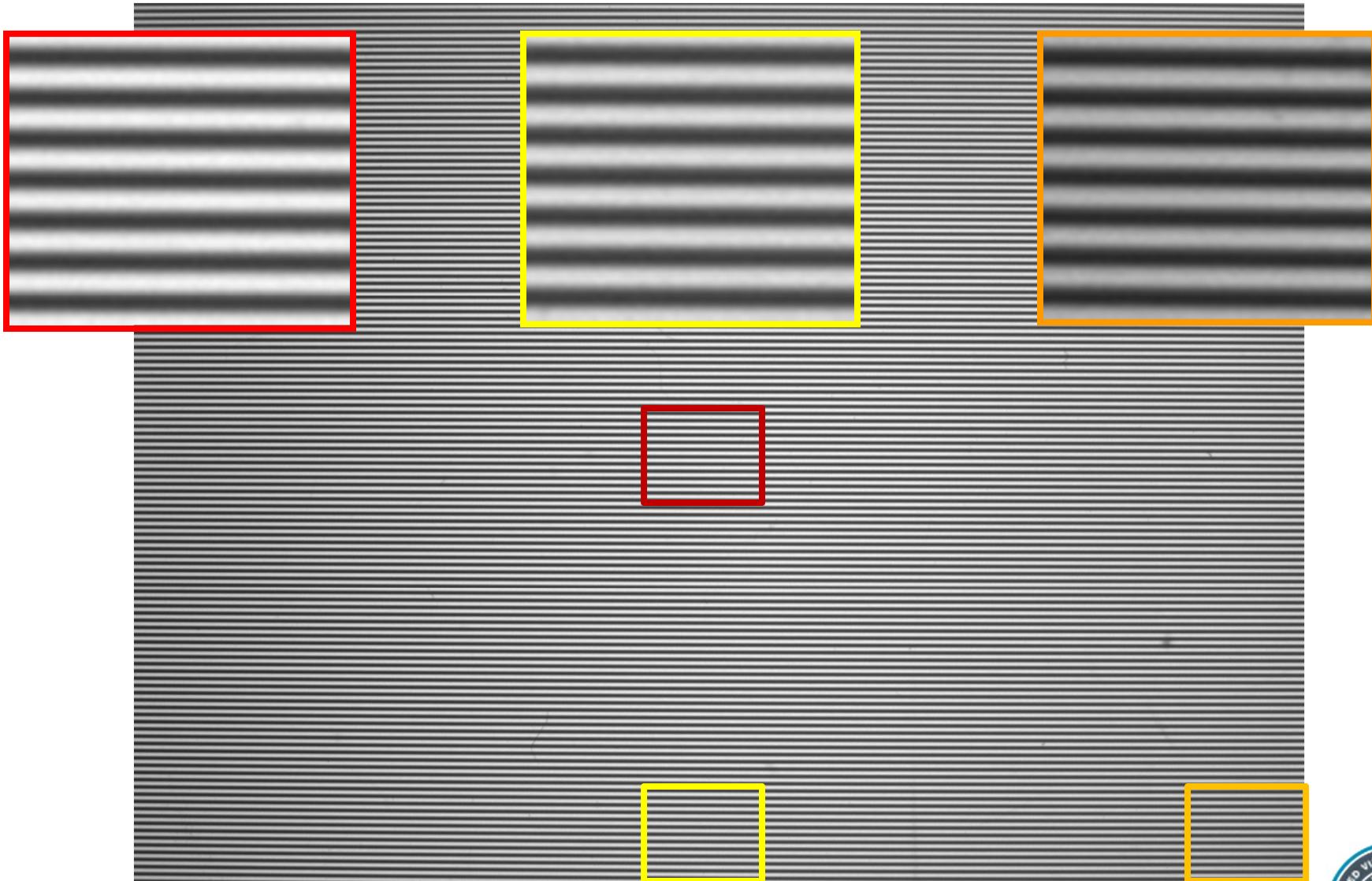
We can plot this information in the form of a Modulation Transfer Function (MTF).



Frequency and Modulation Transfer Function (MTF)



Lens Comparison Testing Ronchi Ruling



Lens #1 Test

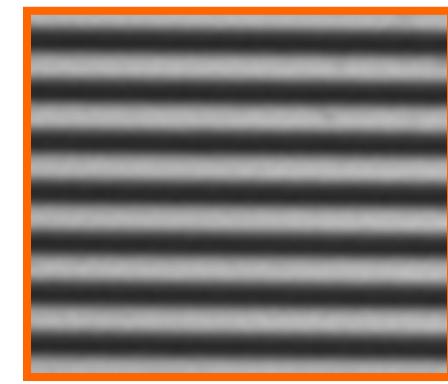
16mm Ronchi Test, 1.5 inch FOV 4 lp/mm object space resolution, 0.157 pmag, f1.4



Center 59%

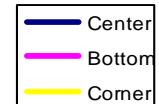
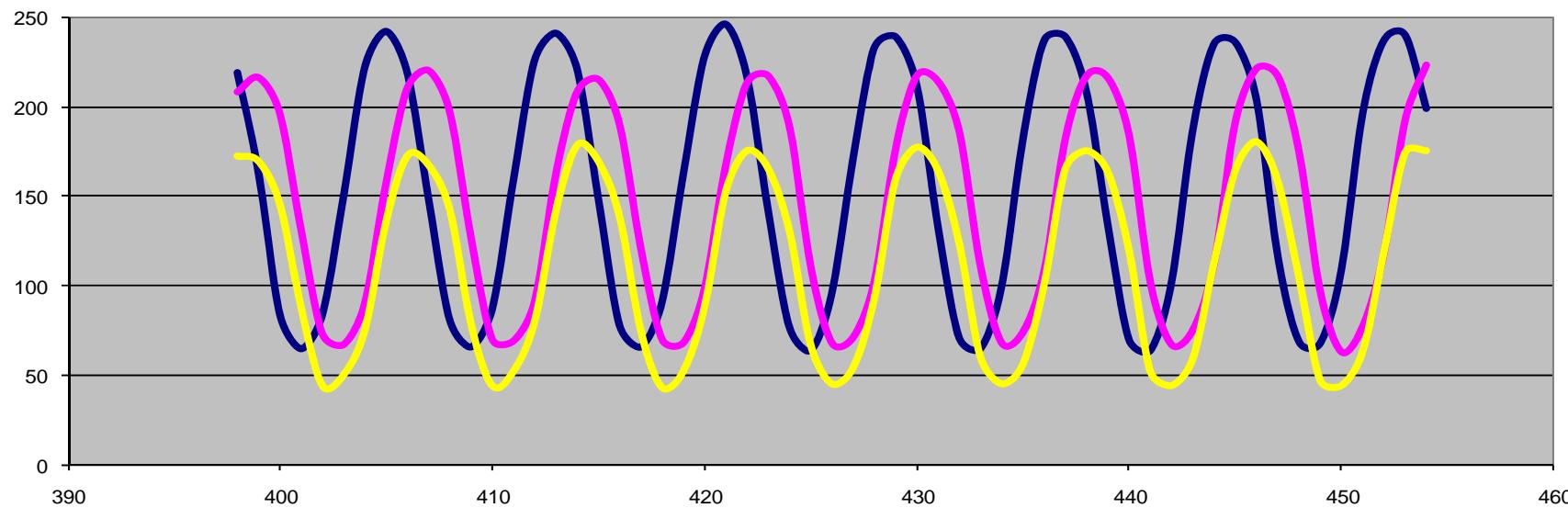


Bottom Middle 56%



Corner 62%

F1.4 1.5 Inch FOV

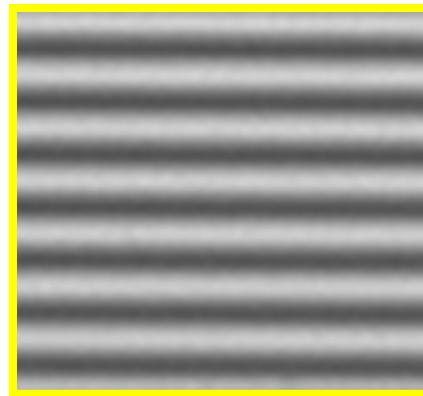


Lens #2 Test

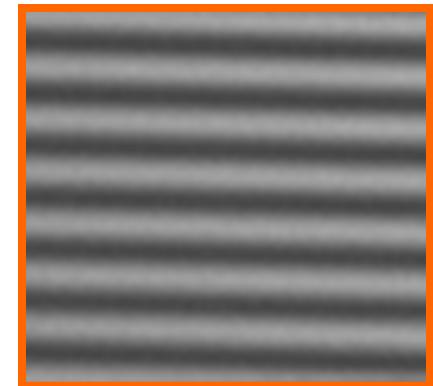
16mm Ronchi Test, 1.5 inch FOV 4 lp/mm object space resolution, 0.157 pmag, f1.4



Center 47%

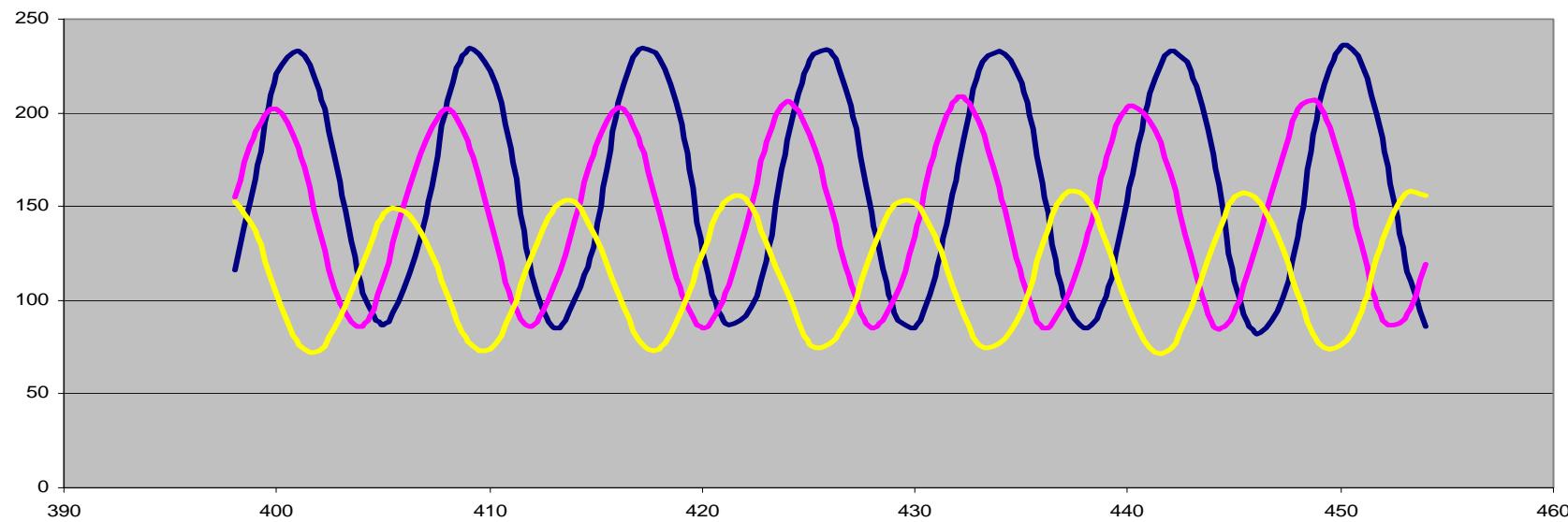


Bottom Middle 42%



Corner 37%

F1.4 1.5 Inch FOV

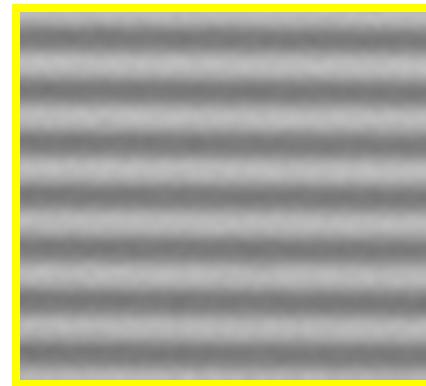


Lens #3 Test

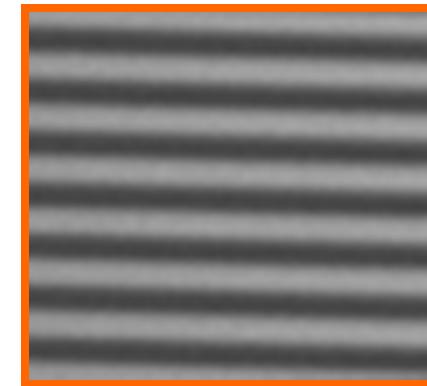
16mm Ronchi Test, 1.5 inch FOV 4 lp/mm object space resolution, 0.157 pmag, f1.4



Center 52%

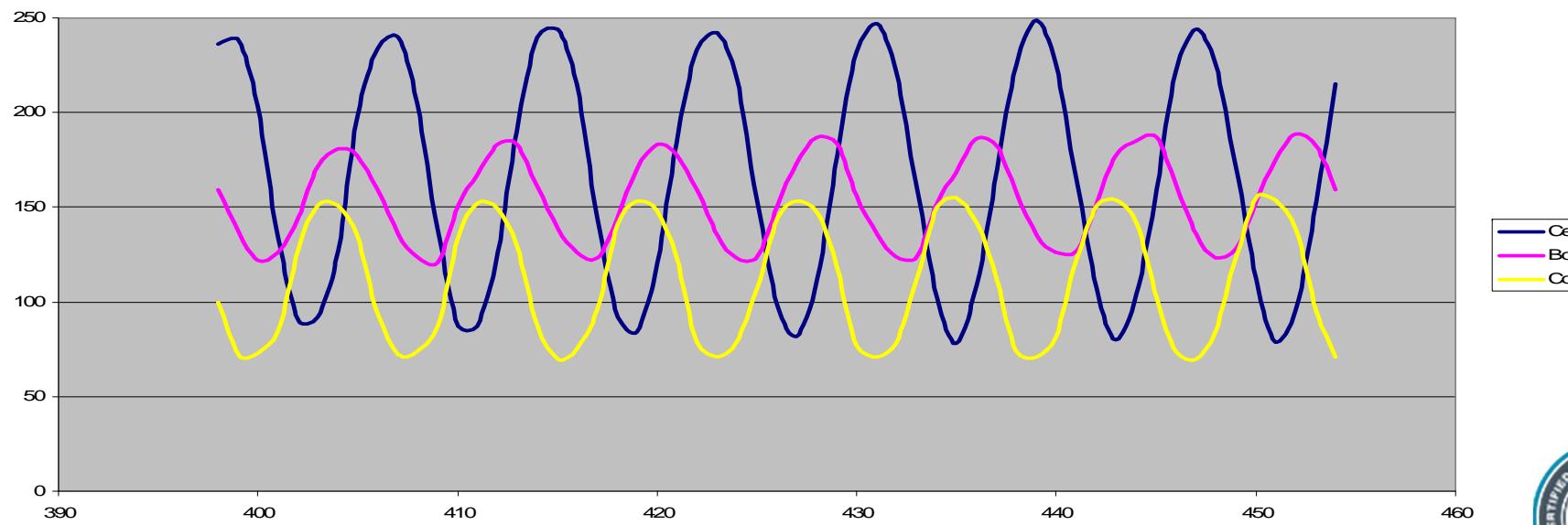


Bottom Middle 22%



Corner 36%

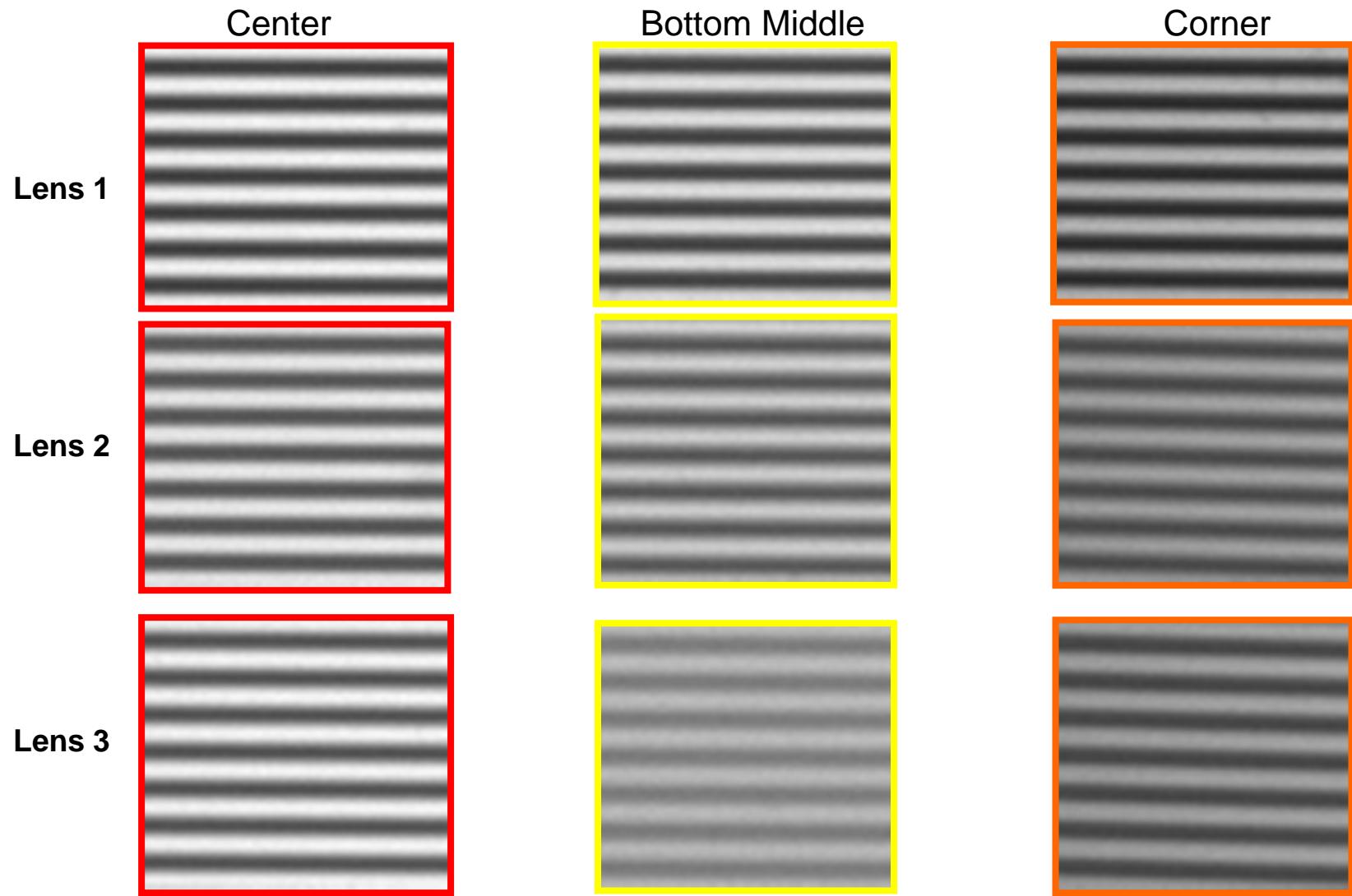
F1.4 1.5inch FOV



Center
Bottom
Corner



Image Comparison F1.4



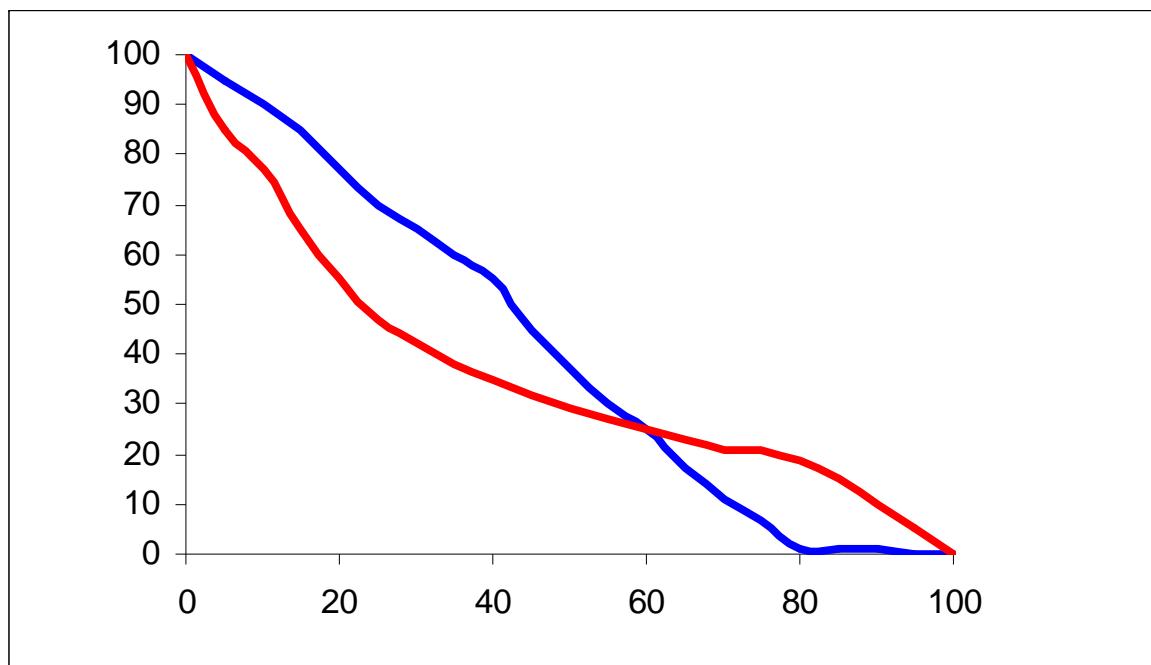
What is a Better MTF?

Depends on the application.

Depends on the detector.

Is limiting resolution important?

Is high contrast at low frequencies important?

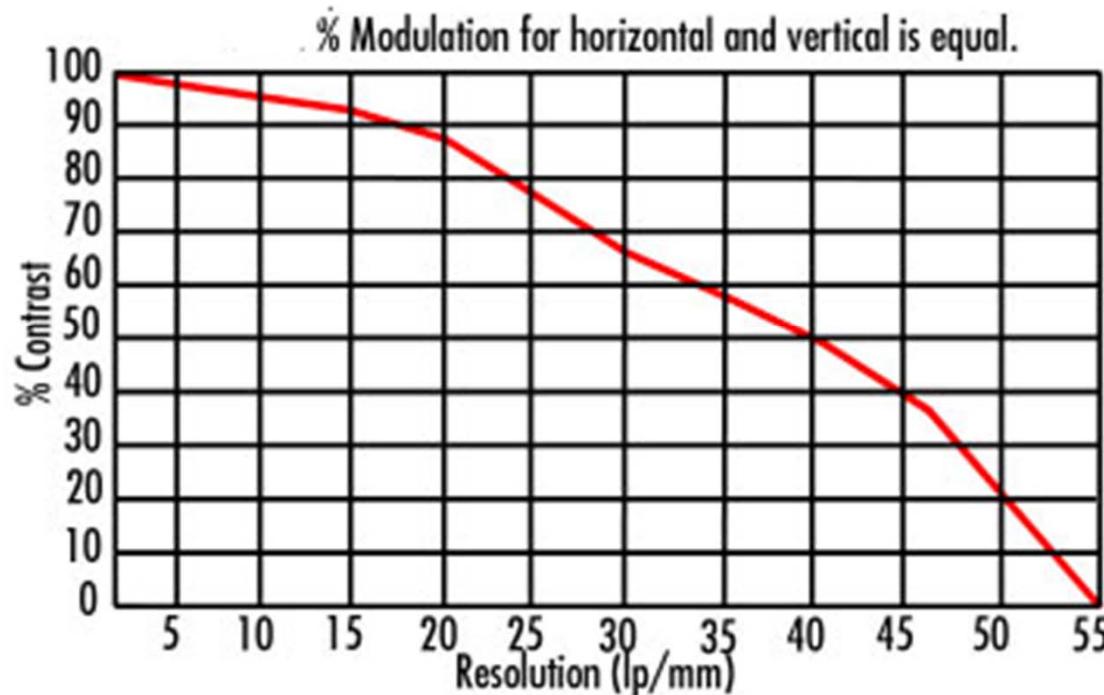


Are Lenses The Only Things With MTF's?

Each component of an imaging system has an MTF associated with it.

Cameras, cables, monitor, capture boards, and eyes all have MTFs.

Below is an example of the MTF of a typical CCD camera.



How Do Individual MTFs Form A System MTF?

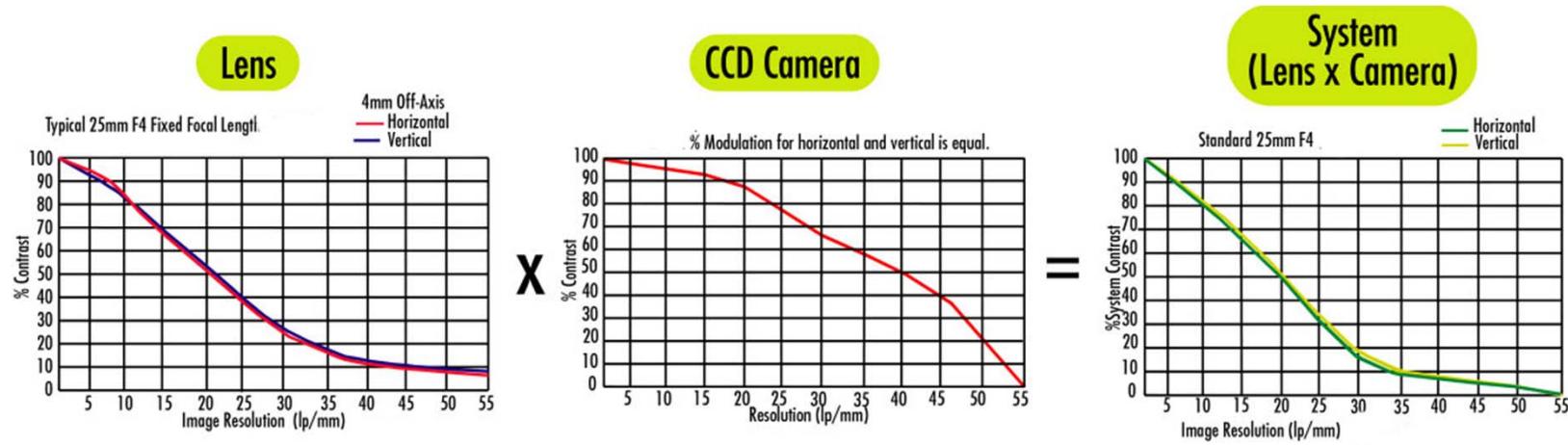
A rough estimate of system resolution can be found using the weakest link.

This assumes that the system resolution will be determined by the lowest resolution of its components.

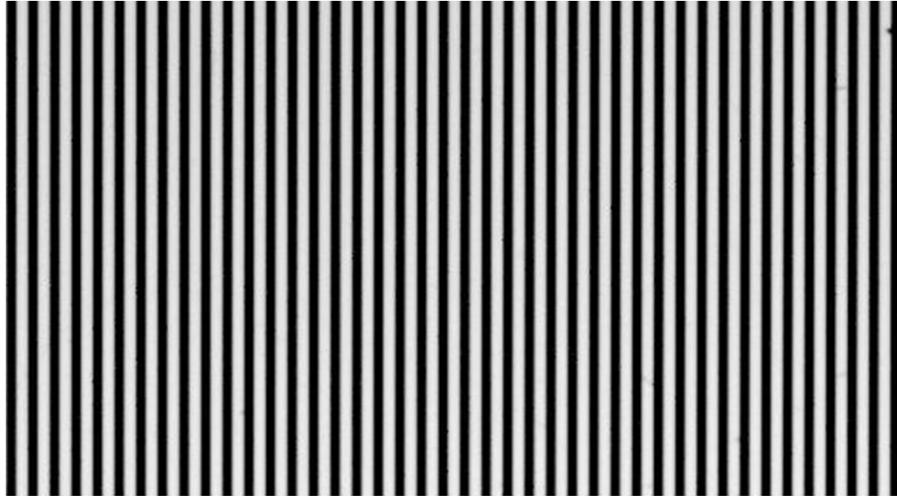
A more accurate system resolution is one where the MTFs of each component are looked at and combined as a whole.

Each component has its own MTF (lens, camera, cables, capture board, and monitor).

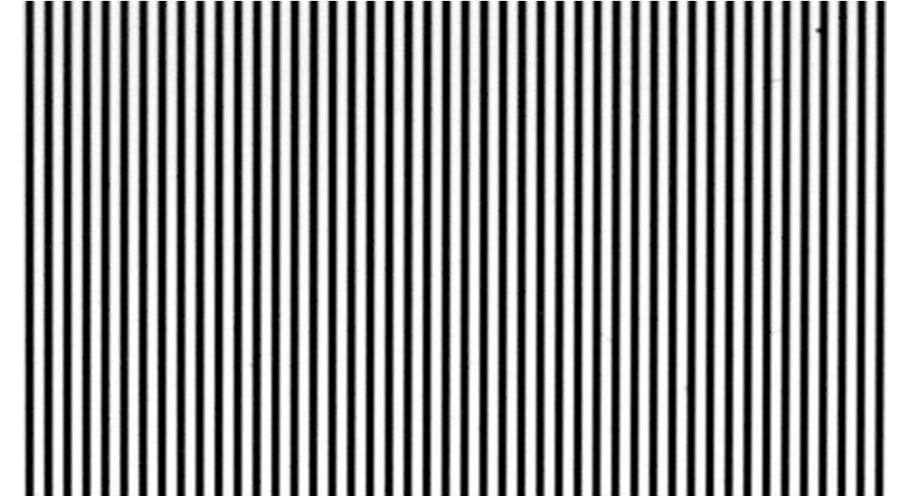
By multiplying each MTF we get a System MTF.



Lens Contrast and Resolution Comparison



Lens A



Lens B

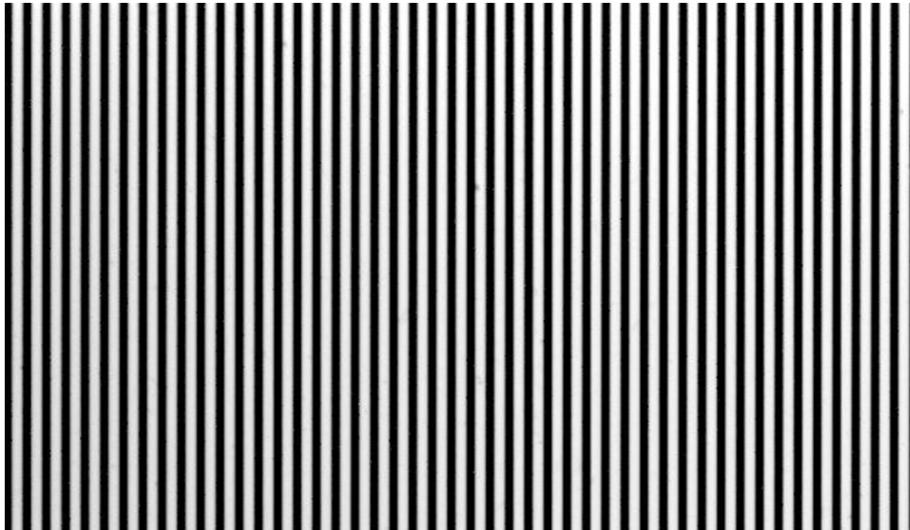
Center of image

0.02 inch resolution

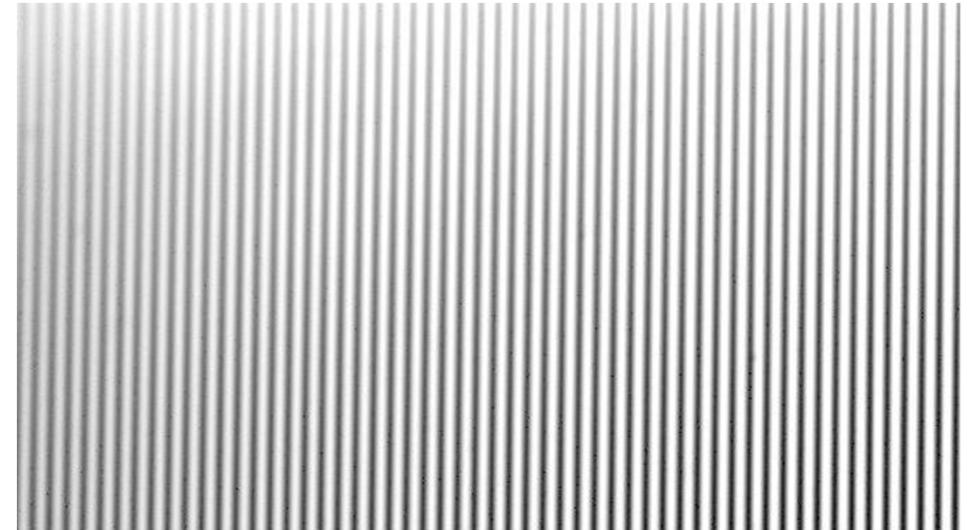
Lens B has about 5% higher contrast than this frequency



Lens Contrast and Resolution Comparison



Lens A



Lens B

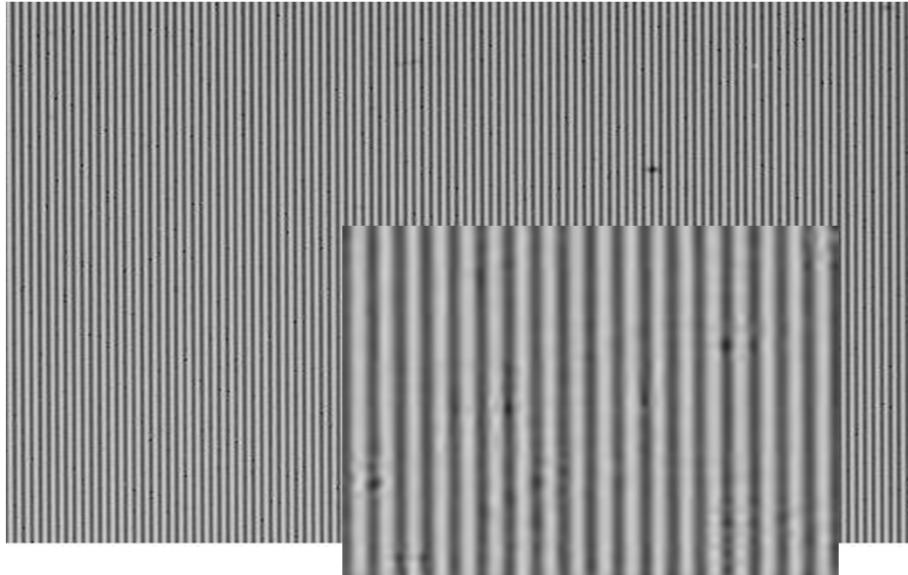
Corner of image

0.02 inch resolution

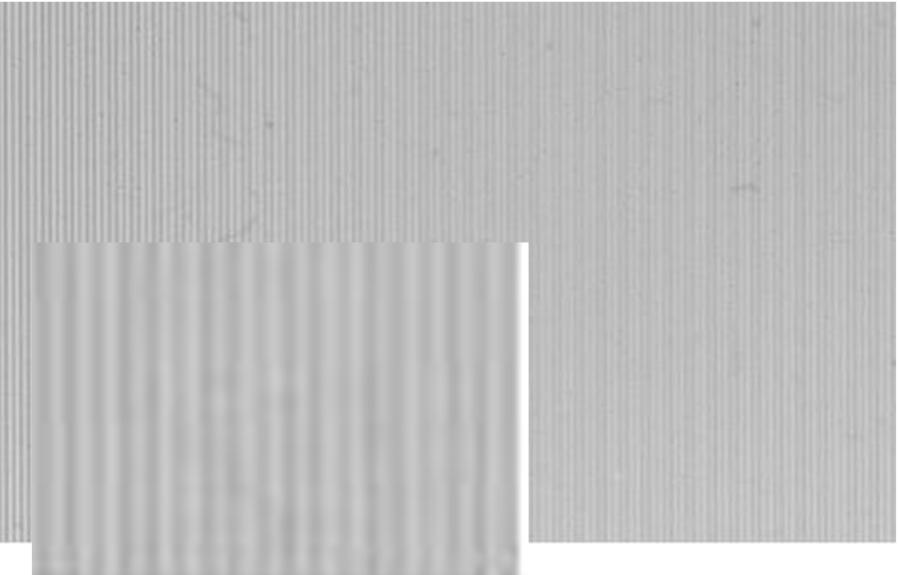
Lens A has about 35% higher contrast than this frequency



Lens Contrast and Resolution Comparison



Lens A



Lens B

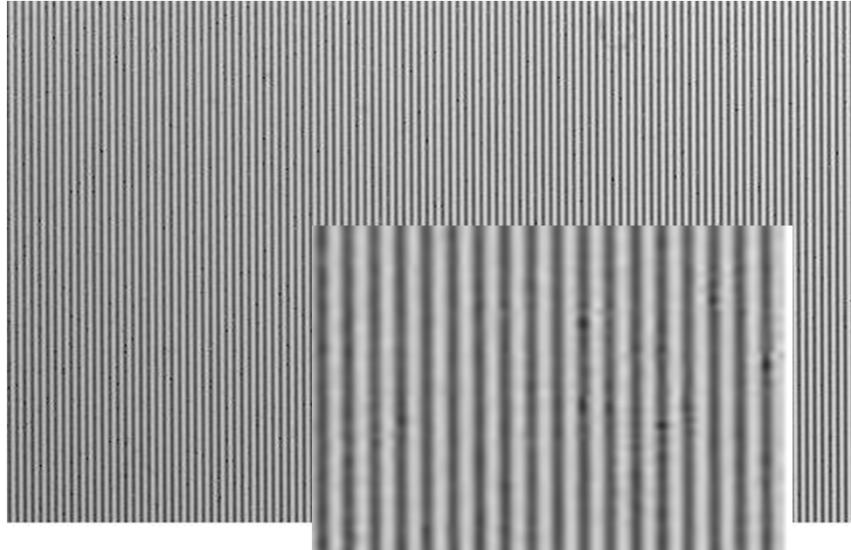
Center of image

0.0067 inch resolution

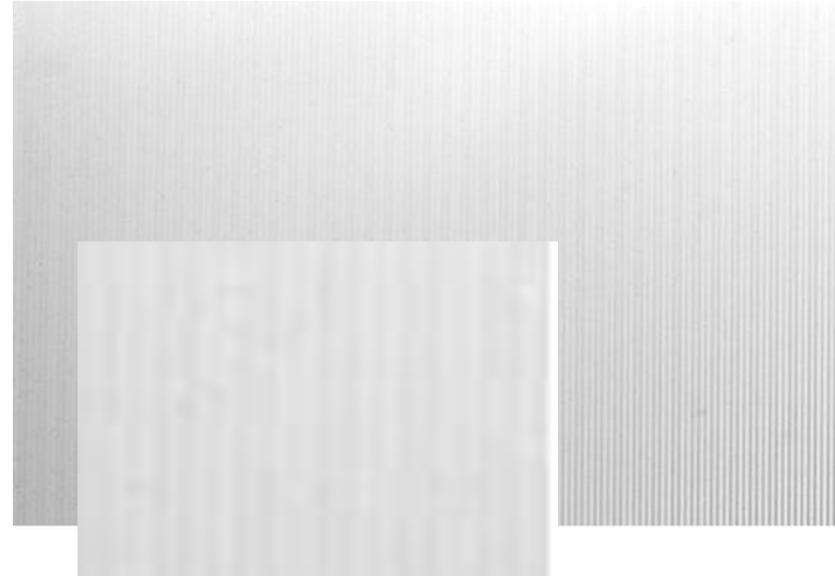
Lens has about 40% higher contrast than this frequency



Lens Contrast and Resolution Comparison



Lens A



Lens B

Corner of image

0.0067 inch resolution

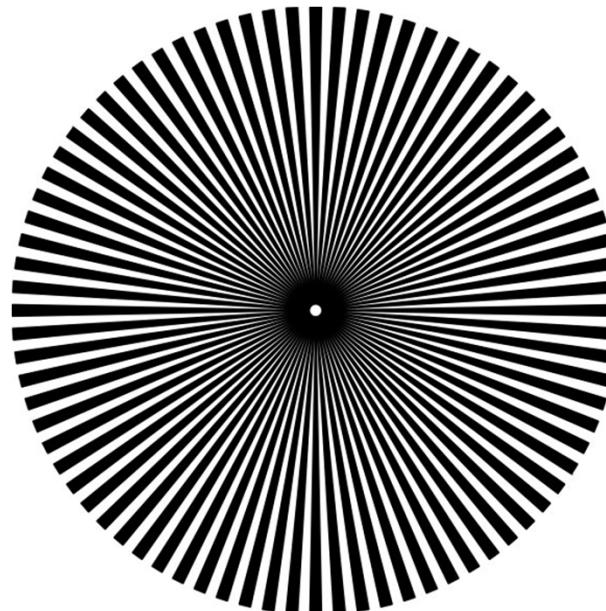
Lens A has about 50% higher contrast than this frequency



The Star Target

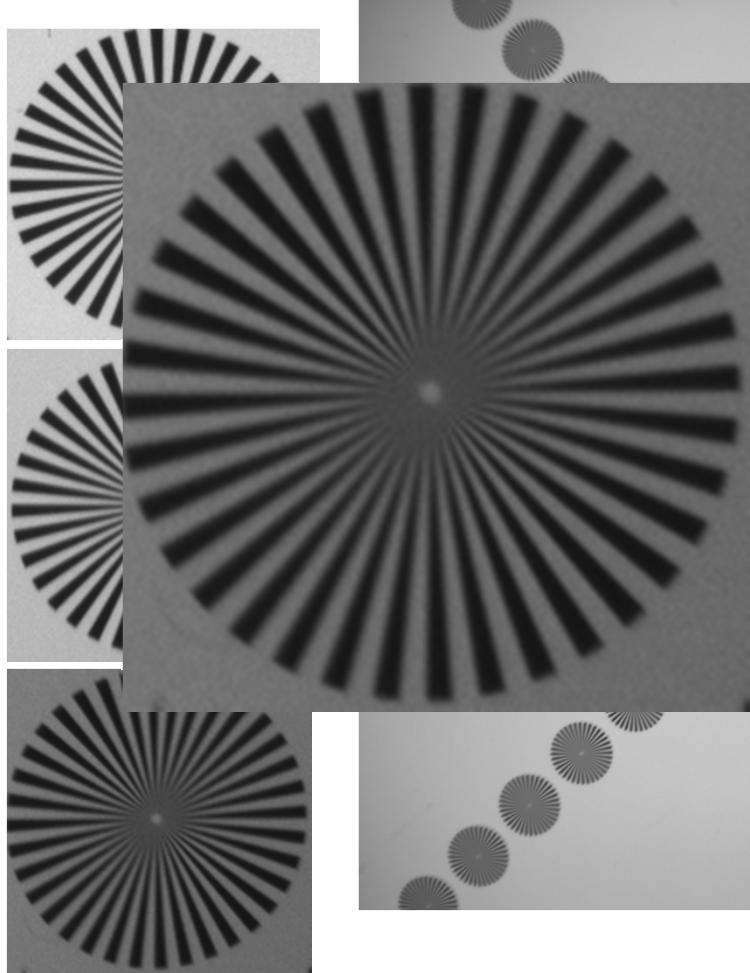
Another common target is the star target.

- Circular pattern of black and white wedges.
- Radial pattern allows tests of astigmatic errors.
- Wedges have continuous frequencies that can be calculated by radial distance.

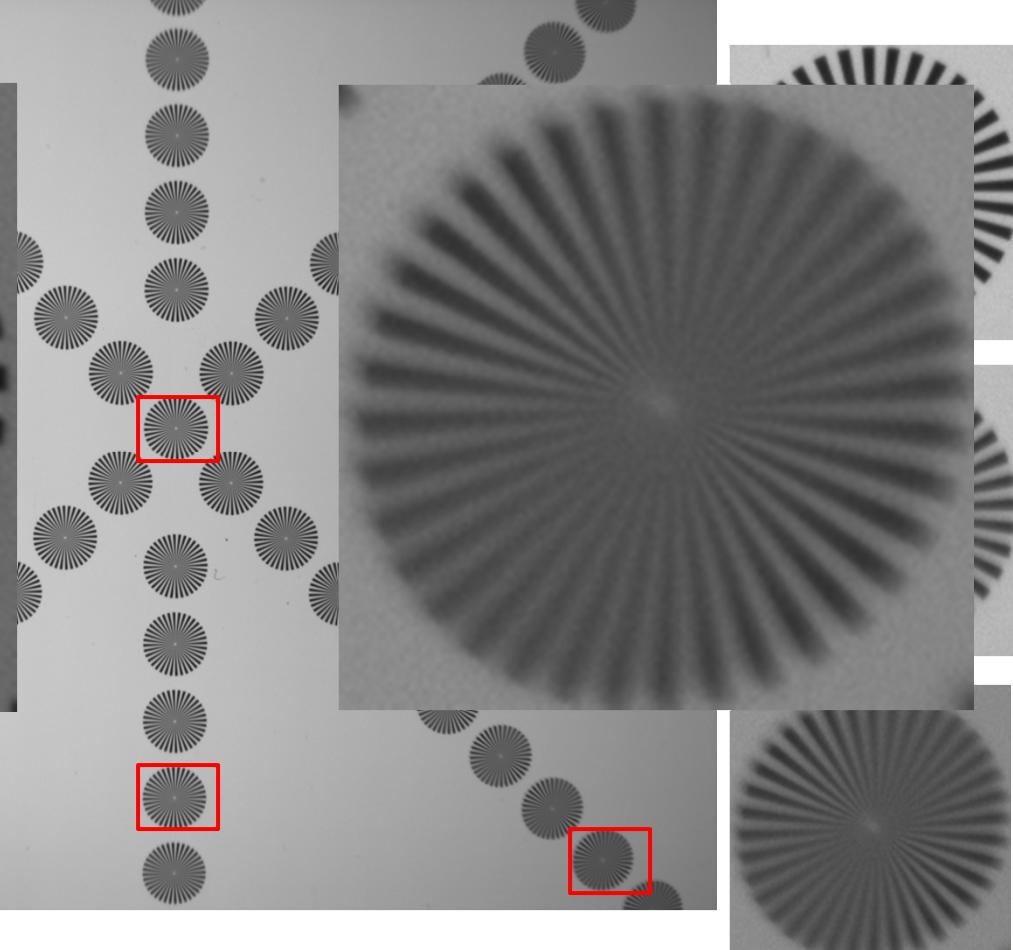


Star Target Image Quality Test

Lens 1



Lens 2



What else can affect MTF?

Many things

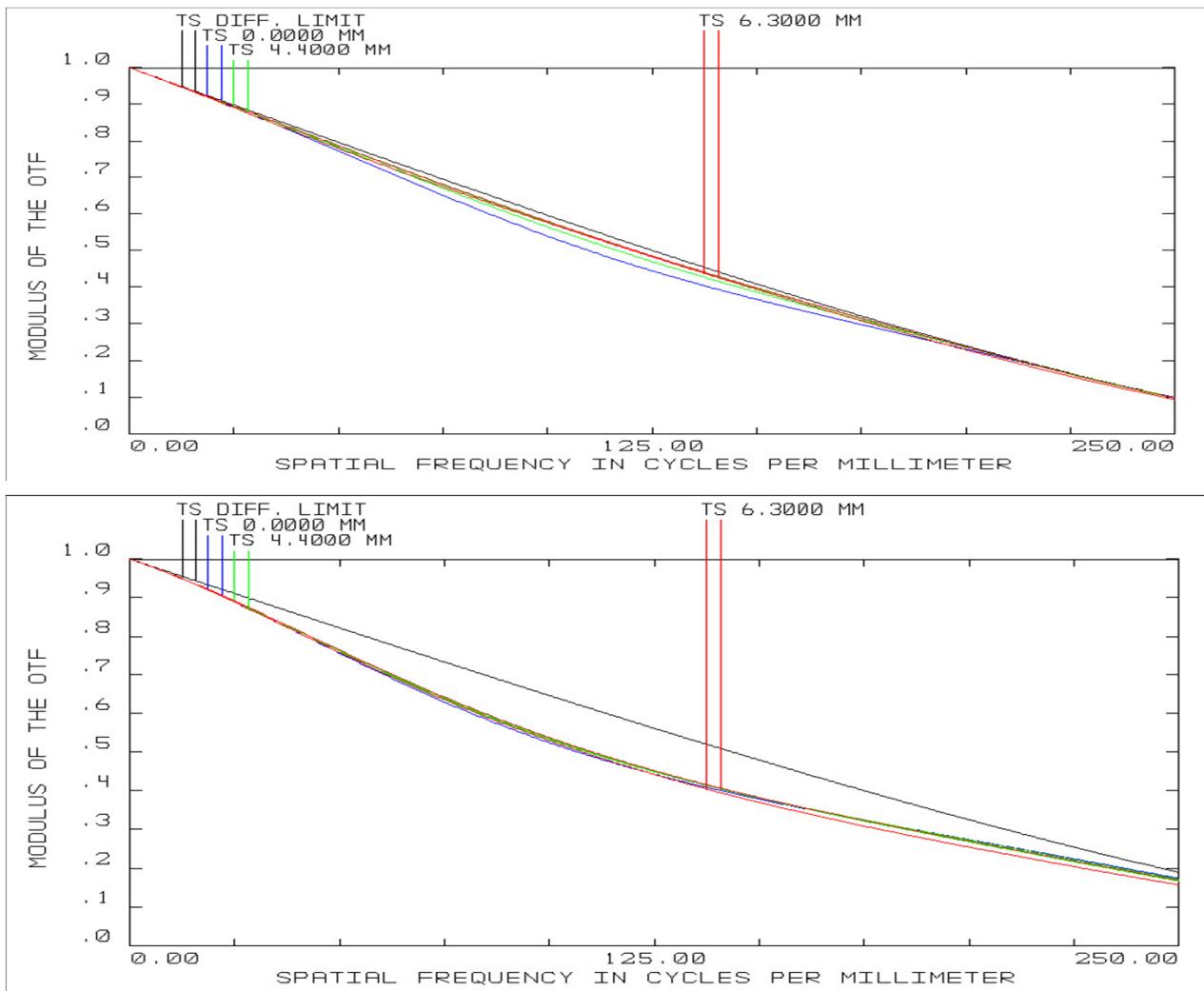
- Working distance
- Wavelength
- F/#
- Aberrations



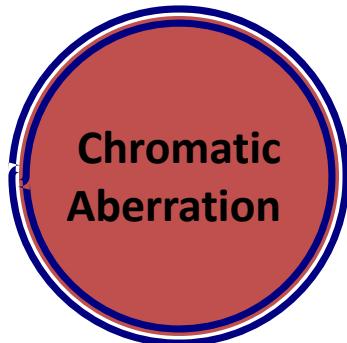
How is MTF affected by Wavelength?

The wavelength will directly affect the MTF that a lens will produce

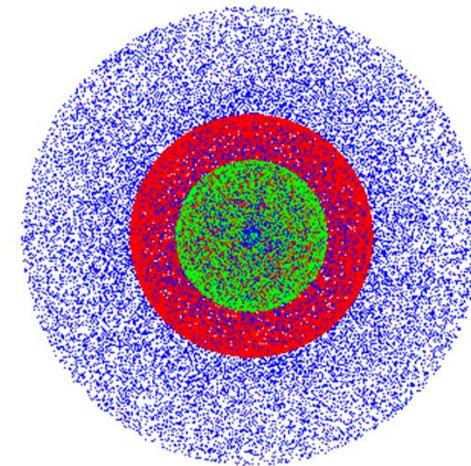
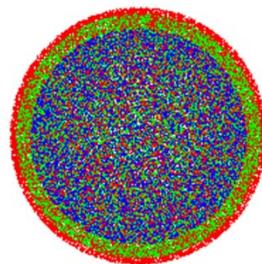
The top graph is at 660nm and the bottom is with white light



How is MTF Affected by Wavelength?



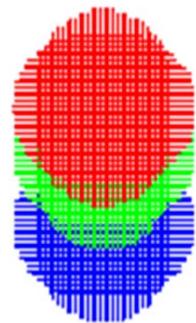
On Axis Chromatic Aberrations (Axial Color)



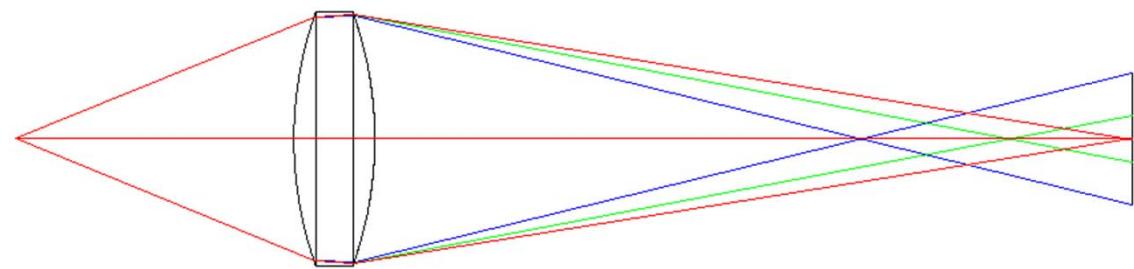
How is MTF affected by Wavelength?



Chromatic aberrations can be both on axis and off axis



Lateral Color



Axial Color

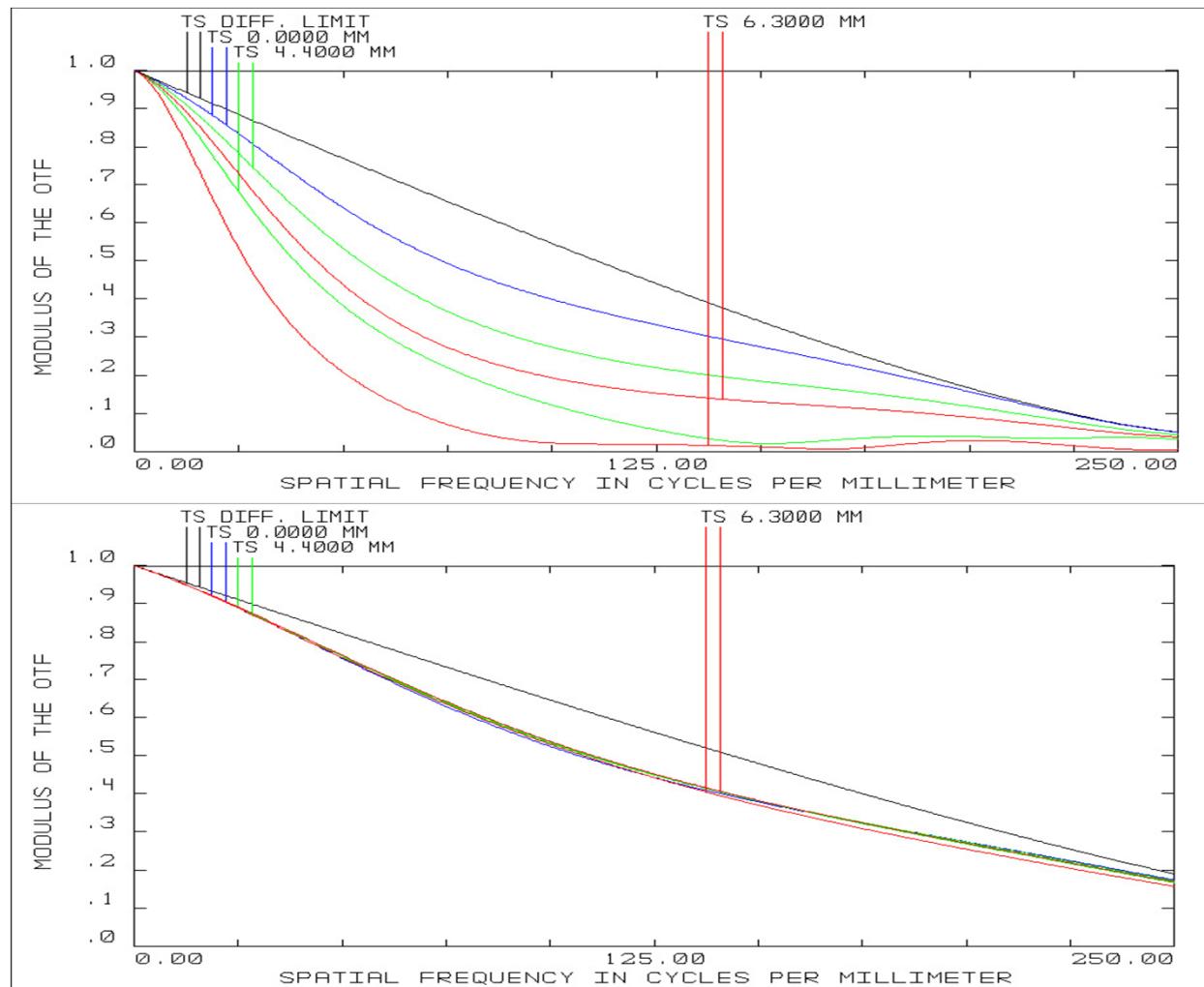


MTF is also affected Working Distance

A comparison at the same wavelength but different working distances can also show problems

The top graph is at 6 inch working distance while the bottom is at a 14 inch working distance

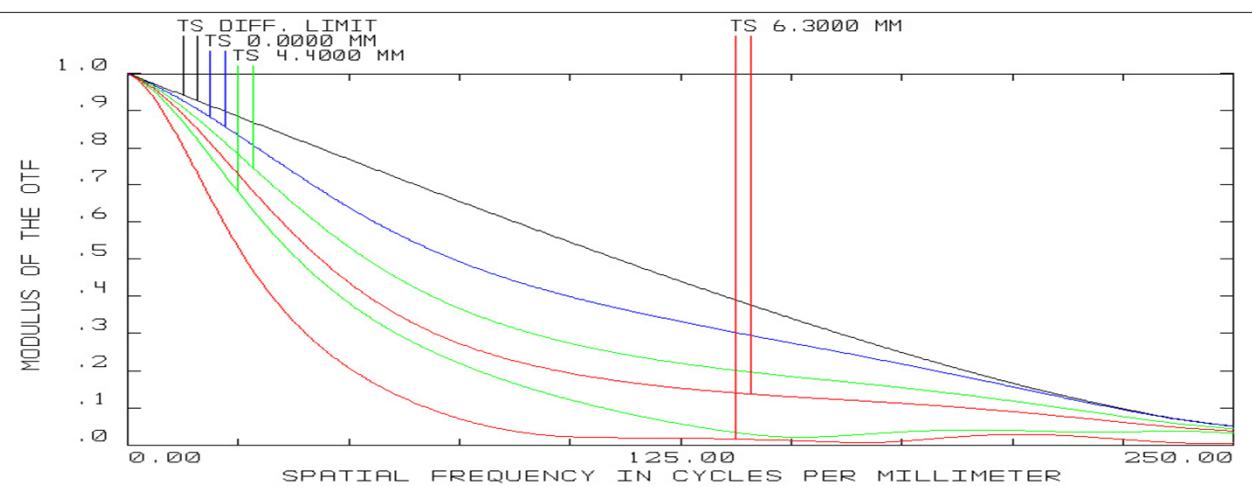
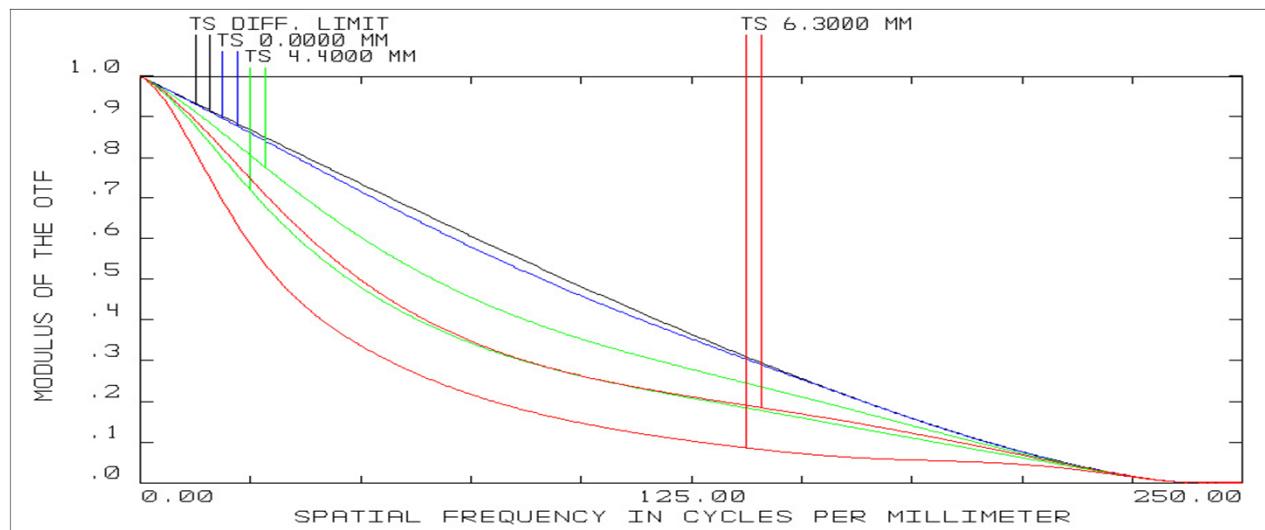
What we are seeing is the problems associated with moving too far beyond the lens design and the design form



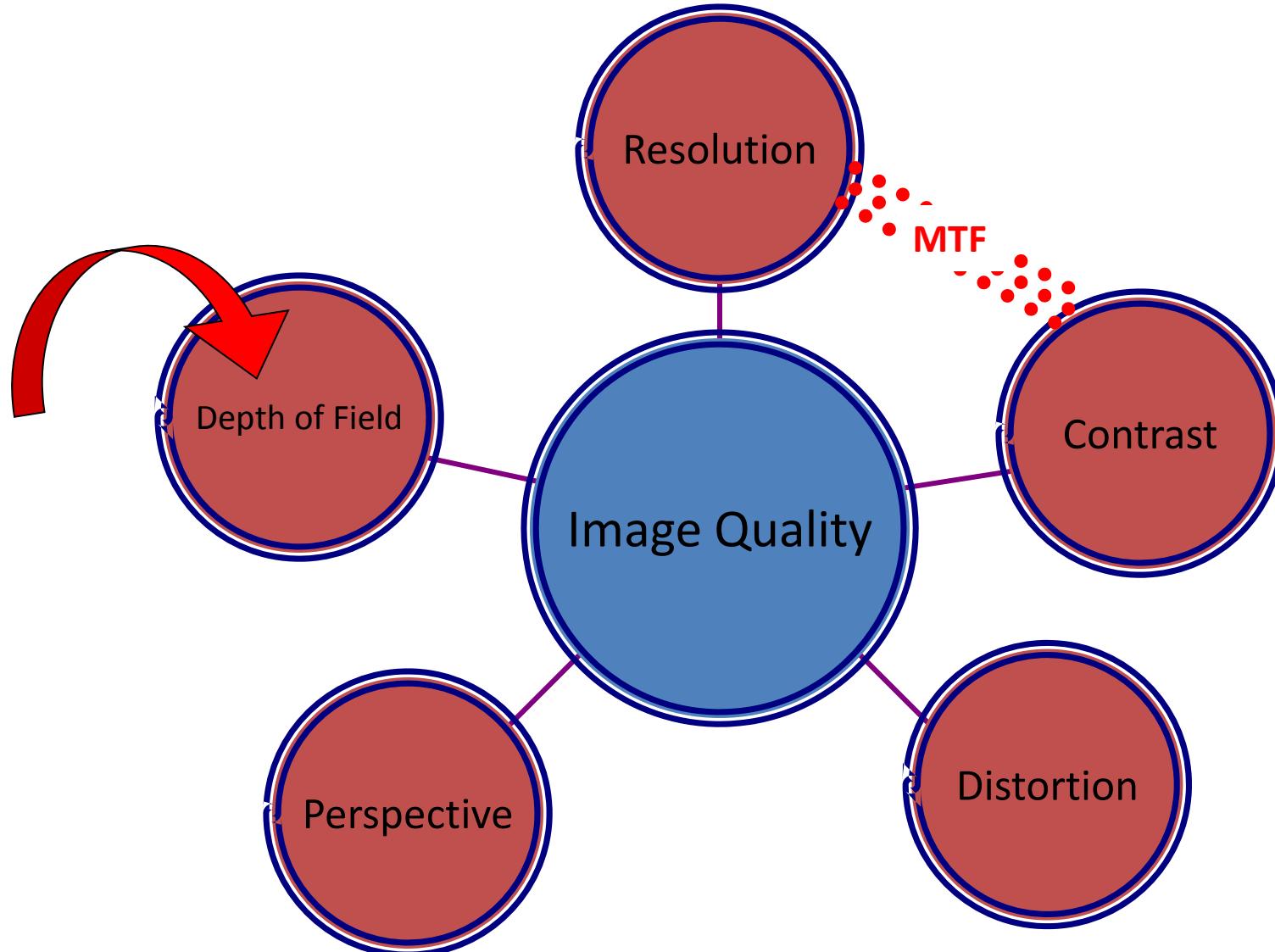
How is MTF affected by Wavelength and Working Distance?

Notice that the same effect occurs at shorter working distances when the wavelength is changed

Again the top graph is at 660nm and the bottom is for white light



Review of Basics



What Is F/# ?

Different definitions of F/#

Infinite conjugate F/# = Focal length/ Diameter

Image Space close conjugate F/# = Image distance/ Diameter

Object Space close conjugate F/# = Object distance/ Diameter

The same lens used at infinite conjugate and close conjugate will have a lower close conjugate F/# than infinite conjugate F/#

*By conjugate, we mean spacing between Object and the lens, an infinite conjugate lens has collimated light entering it.



How Does Diffraction Affect Performance?

Not even a perfectly designed and manufactured lens can accurately reproduce an object's detail and contrast.

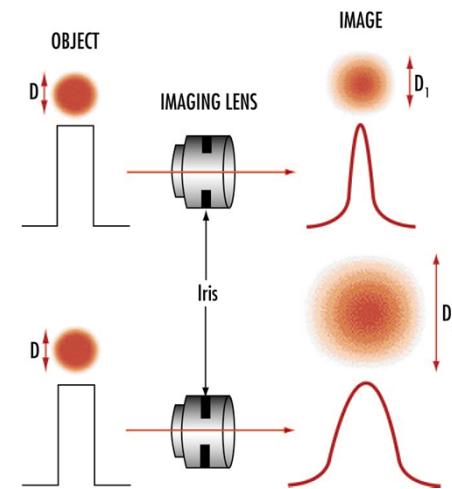
Diffraction will limit the performance of an ideal lens.

The size of the aperture will affect the diffraction limit of a lens.

The smallest achievable spot of a lens = $1.22 \times \text{wavelength of light} \times (\text{F}/\#)$.

F/# describes the light gathering ability of an imaging lens (lower F/# lenses collect more light).

As lens aperture decreases, F/# increases.



Is Diffraction Always The Limiting Factor In A Lens?

Diffraction is not the only cause of image resolution and contrast decreasing.

Many lenses do not operate at the diffraction limit.

Optical errors (aberrations) and manufacturing tolerances often limit performance.

Often the performance of a non-diffraction limited lens can be improved by increasing its F/#, until it is diffraction limited.



F/# Points To Consider

Although two lenses have the same F/#, and thus the same diffraction limit, they do not necessarily have similar performance.

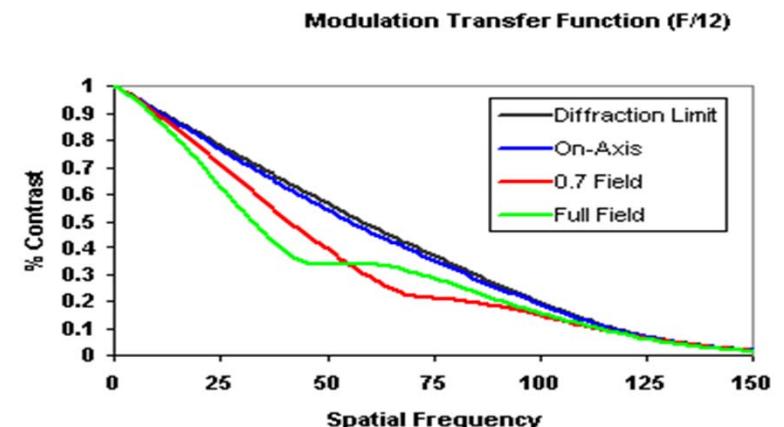
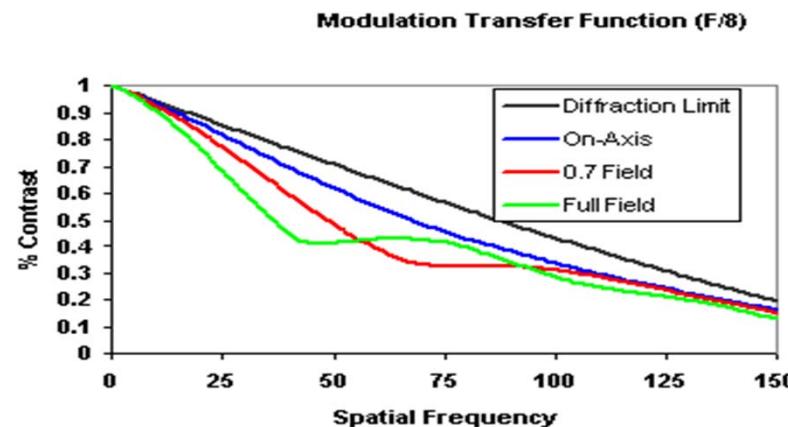
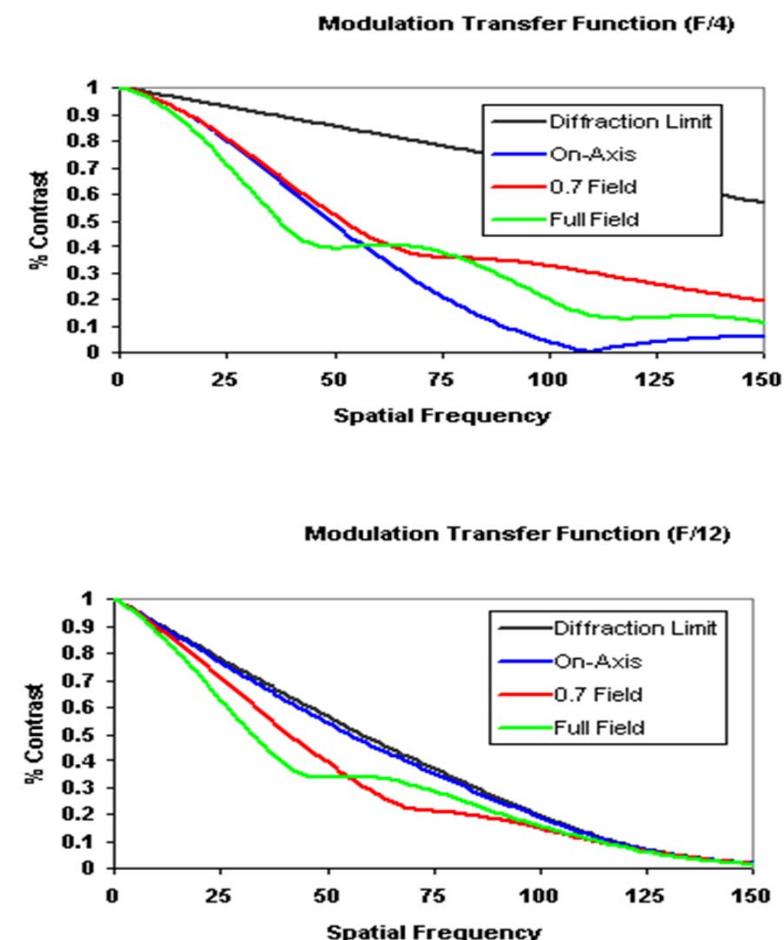
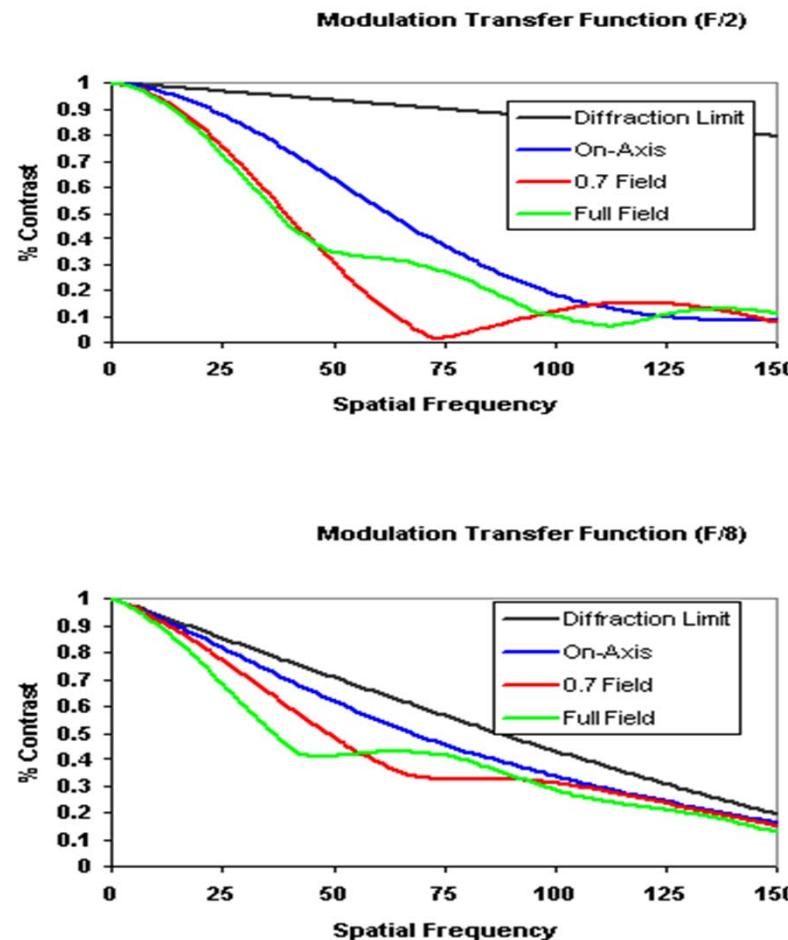
The overall diameter of a machine vision lens is directly proportional to the ratio of the working distance and F/#.

$$\text{Diameter} \propto \frac{\text{Working Distance}}{\text{F}/\#}$$

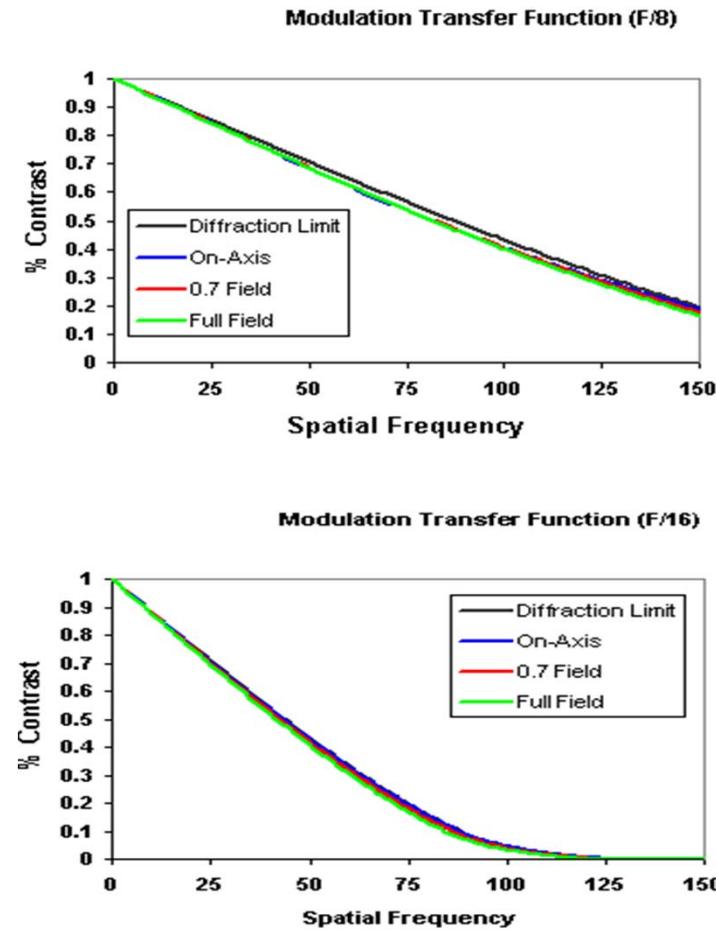
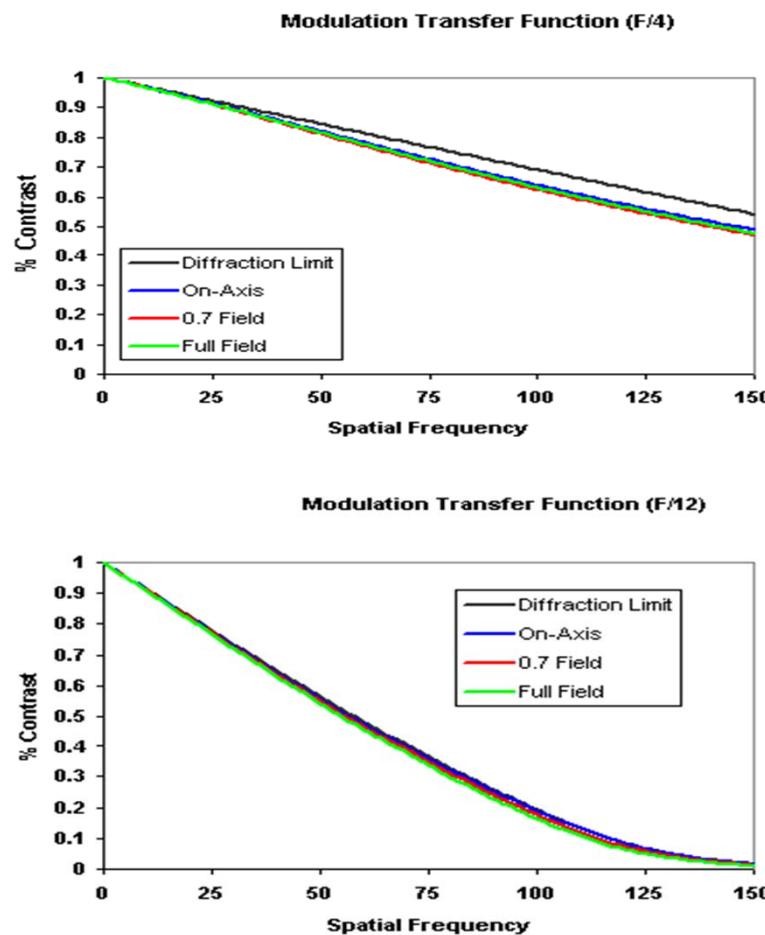
Aberrations lead to diminishing returns as the F/# of a lens is continually decreased.



Resolution vs. F/#, Typical 6mm Lens



Does Increasing the F/# Always Improve Performance?



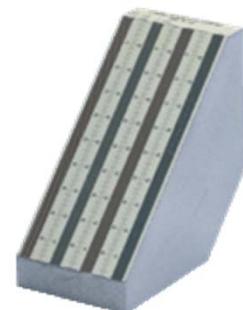
Depth Of Field Points To Remember

The depth of field (DOF) of a lens is its ability to maintain a desired amount of image quality as the object is moved from best focus position.

DOF also applies to objects with depth, since a lens with high DOF will allow the whole object to be imaged clearly.

As the object is moved either closer or further than the working distance, both contrast and resolution suffer.

The amount of depth must be defined at both a contrast and a resolution.



How Can Apertures Be Used To Improve Depth Of Field?

If we express our resolution as an angularly allowable blur (ω) we can define depth of field geometrically.

Below we see how two lenses with different F/#s have very different DOF values.

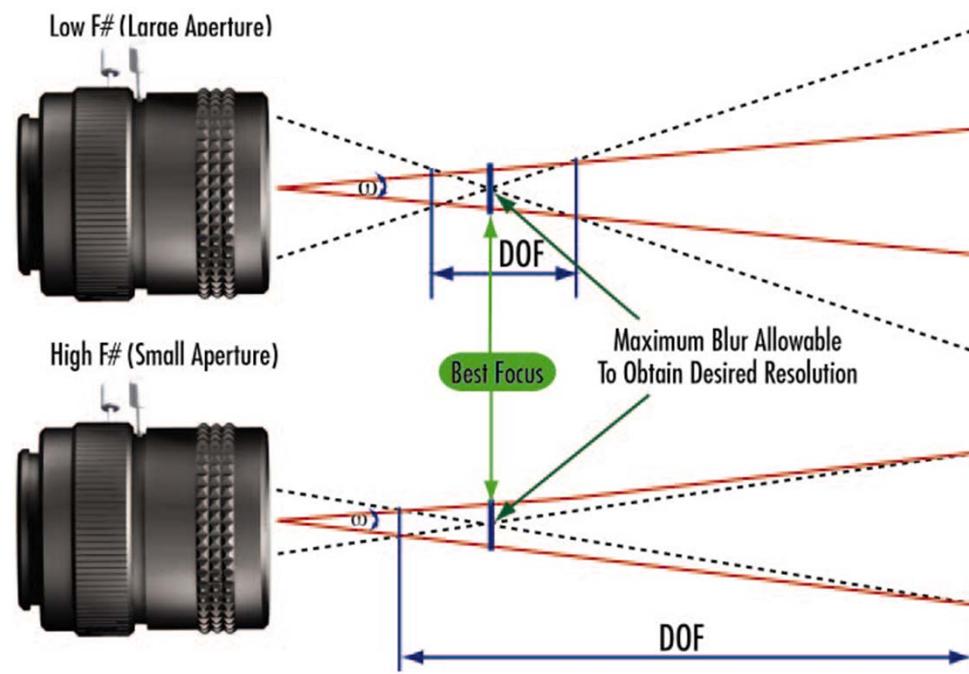


Illustration adapted from Smith, Modern Optical Engineering: The Design Of Optical Systems, New York, McGraw-Hill, 1990



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.

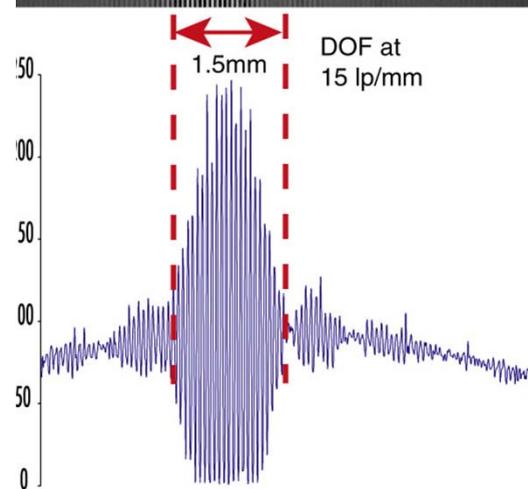
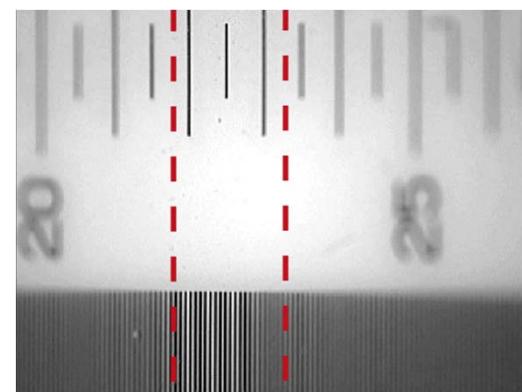
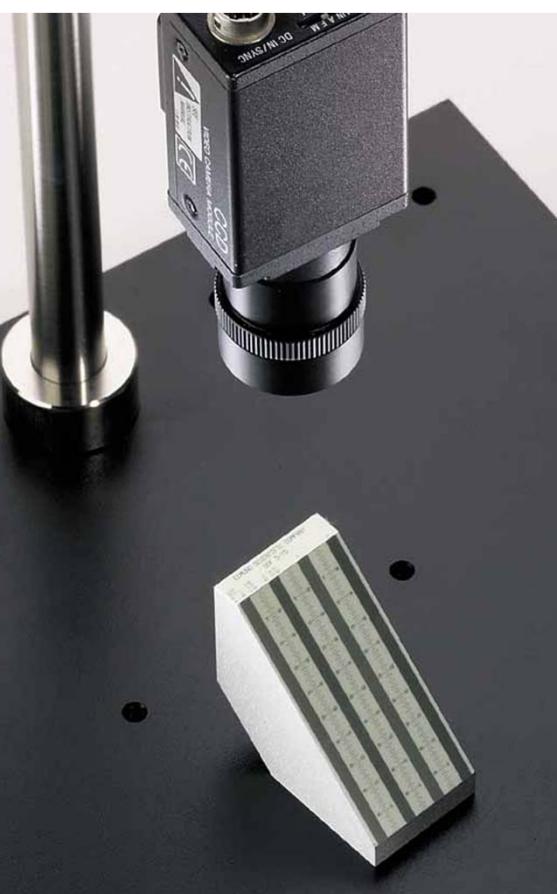
Increasing the F/# to increase the depth of field may limit the overall resolution of the imaging system. Therefore, the application constraints must be considered.

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 of the image obtained.



How Do We Test Depth Of Field?



To the left is an image of DOF test target, object space resolution being tested is 15 lp/mm at a contrast of less than 10%.

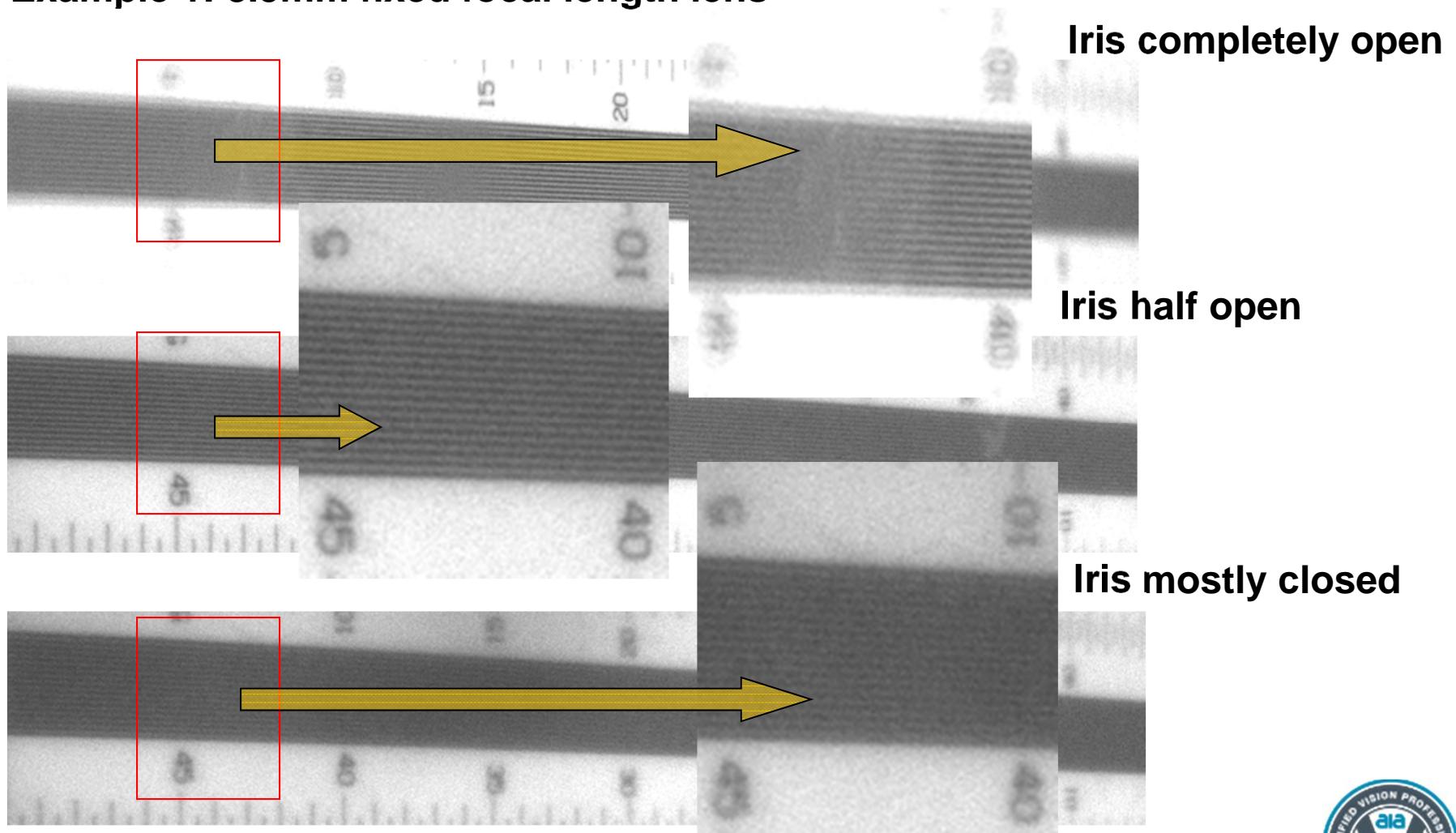
We can either see visually where the image blurs out or we can look at a line spread function and calculate contrast from the grayscale values.



Case Study

effects on resolution and depth of field with changing aperture setting

Example 1: 8.5mm fixed focal length lens

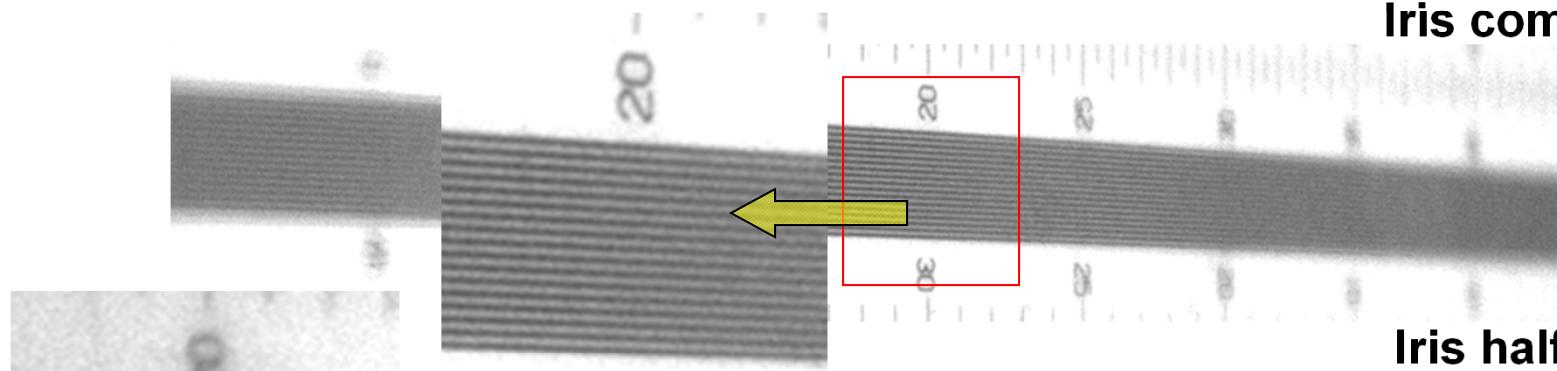


Case Study

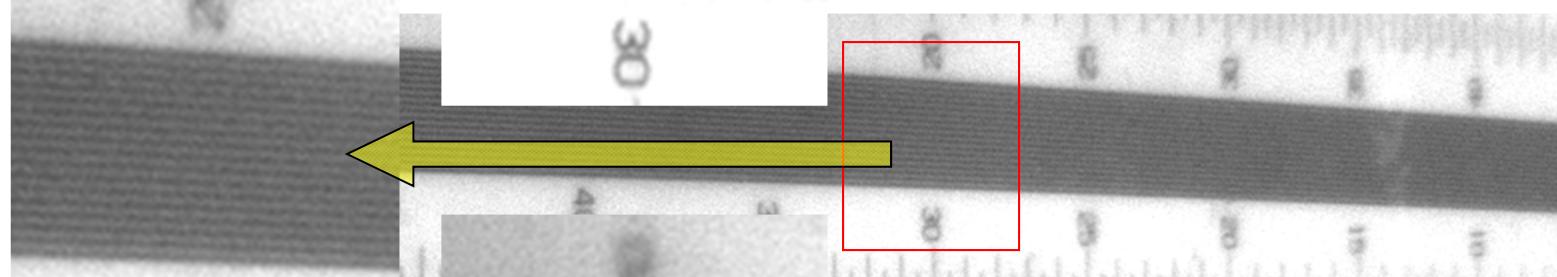
effects on resolution and depth of field with changing aperture setting

Example 1: 8.5mm fixed focal length lens

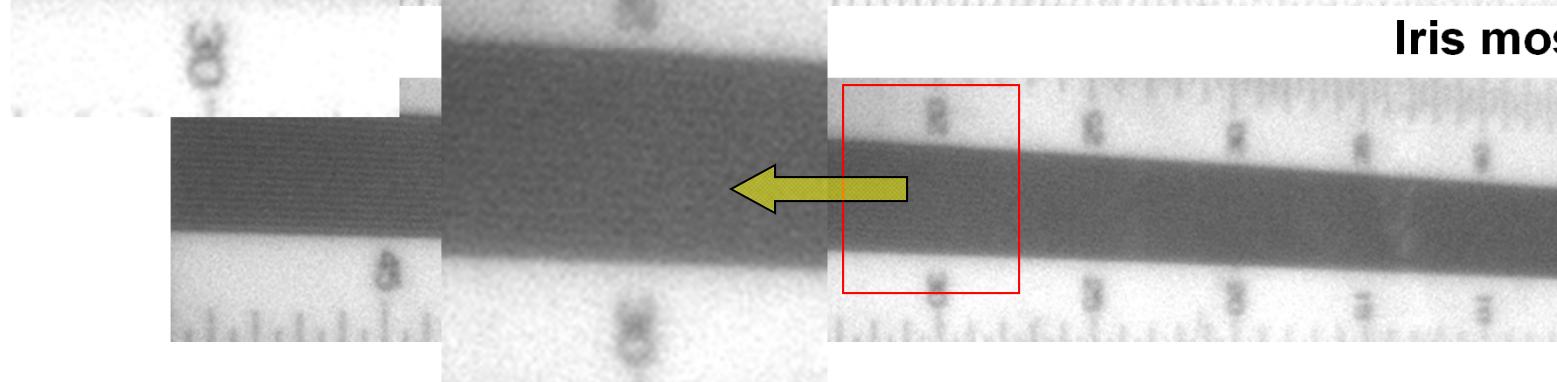
Iris completely open



Iris half open



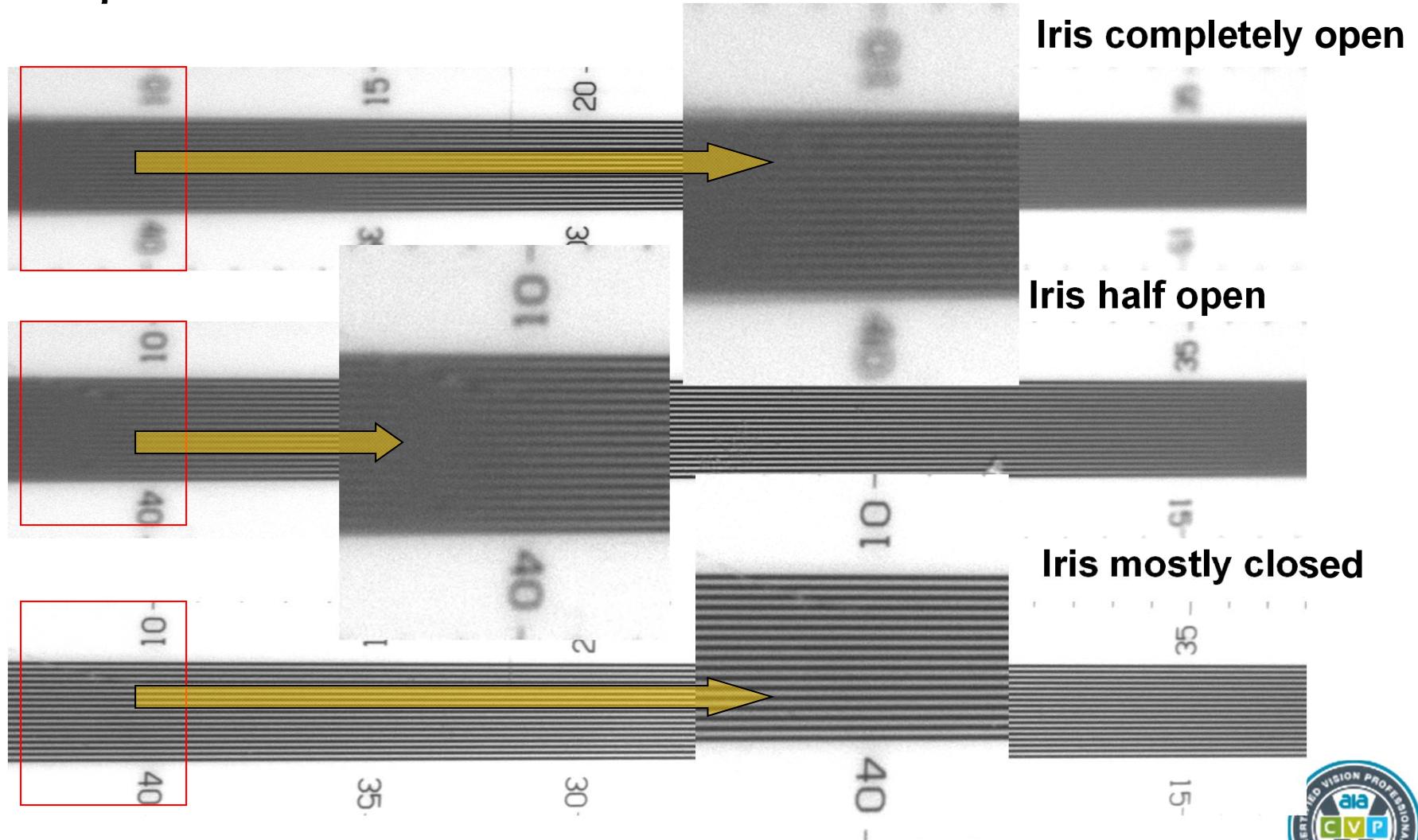
Iris mostly closed



Case Study

effects on resolution and depth of field with changing aperture setting

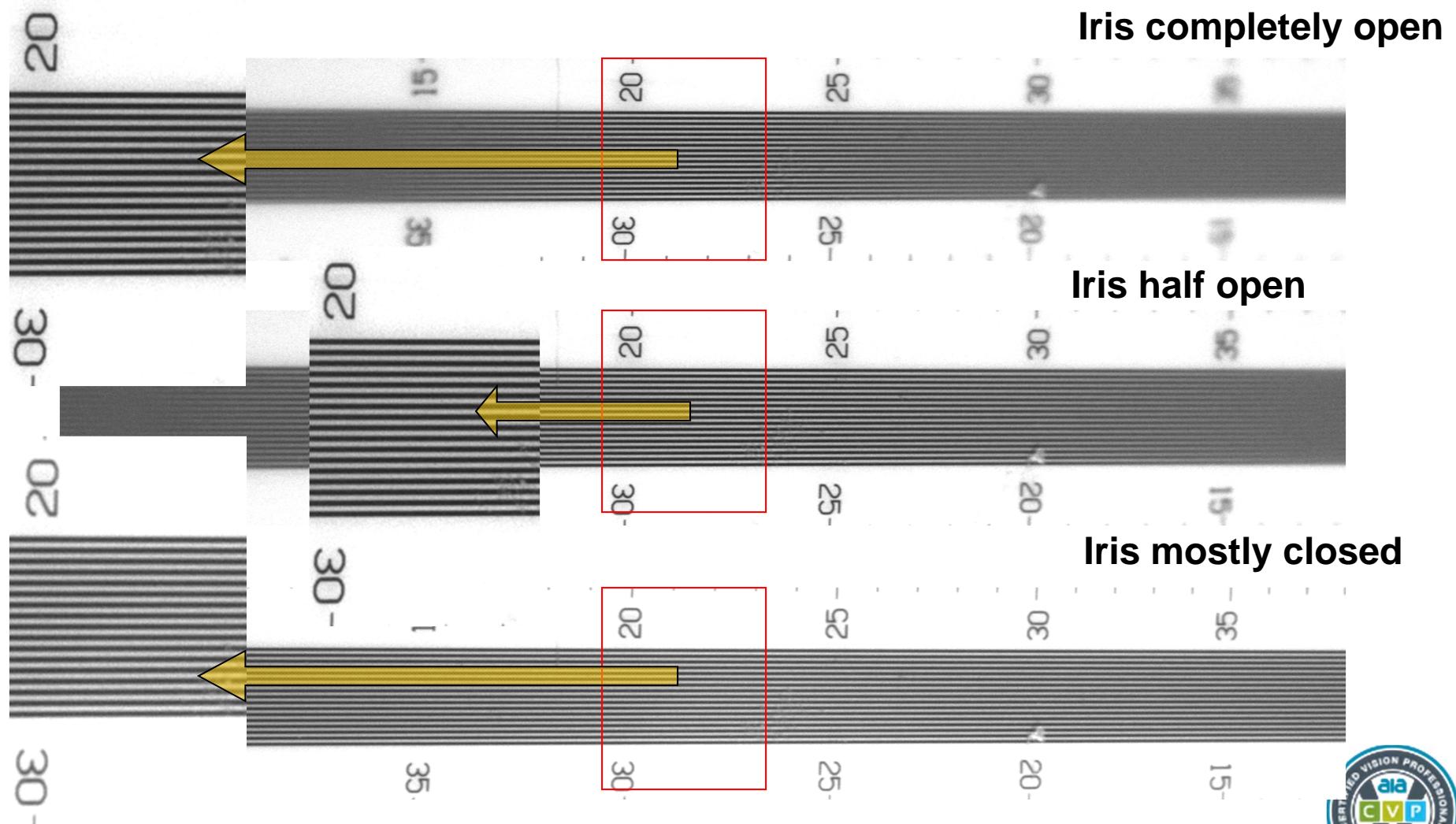
Example 1: 50mm Double Gauss lens



Case Study

effects on resolution and depth of field with changing aperture setting

Example 1: 50mm Double Gauss lens



Review of Basics



Distortion

Nature of Distortion:

Geometric Aberration

- No information is lost
(except due to detector resolution limits)

Not necessarily monotonic

Consistency across manufacturing

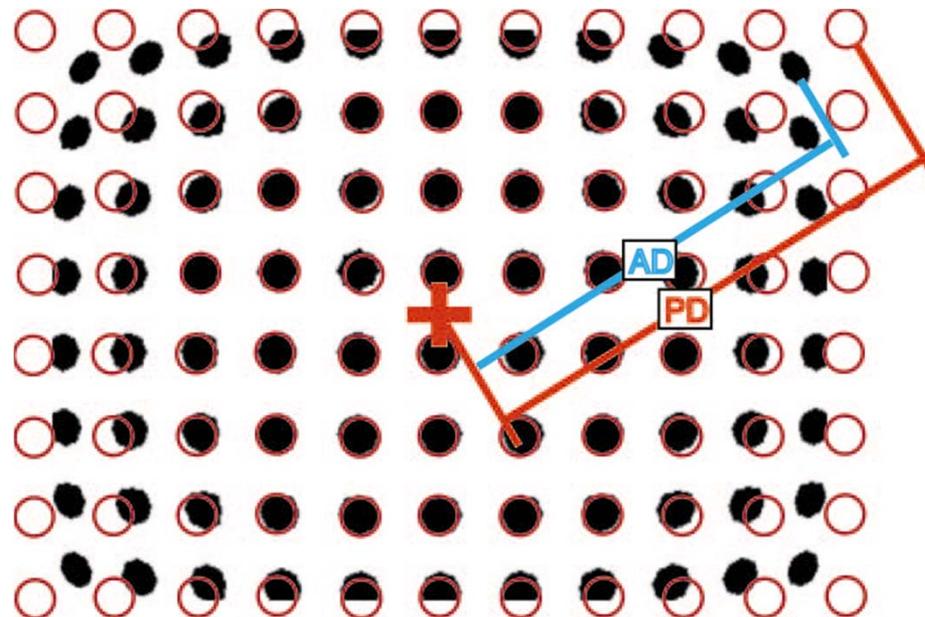
Rule of Thumb:

2-3% visually undetectable



How Is Distortion Measured?

$$\% \text{ Distortion} = \frac{(AD - PD) \times 100}{PD}$$



Above is an example of negative distortion.

AD is Actual Distance that an image point is from center of the field.

PD is the Predicted Distance that an image point would be from the center of the field if no distortion were present.

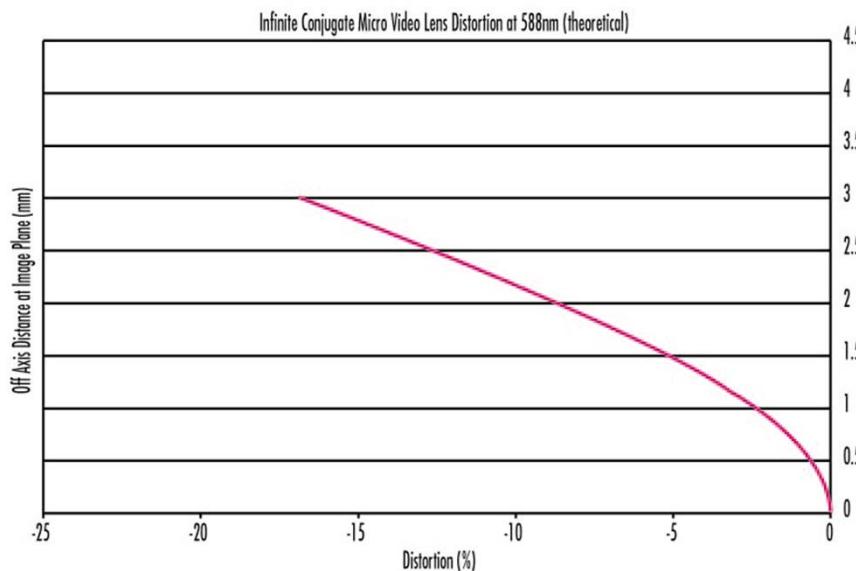


Specifying Distortion

Percent Distortion at the extreme edge of the field is used to determine maximum distortion in a lens.

Distortion changes with image position, so to accurately predict the effects of distortion a plot of % distortion vs. distance from center of the image.

Below is the distortion plot for a 4.3mm video lens.



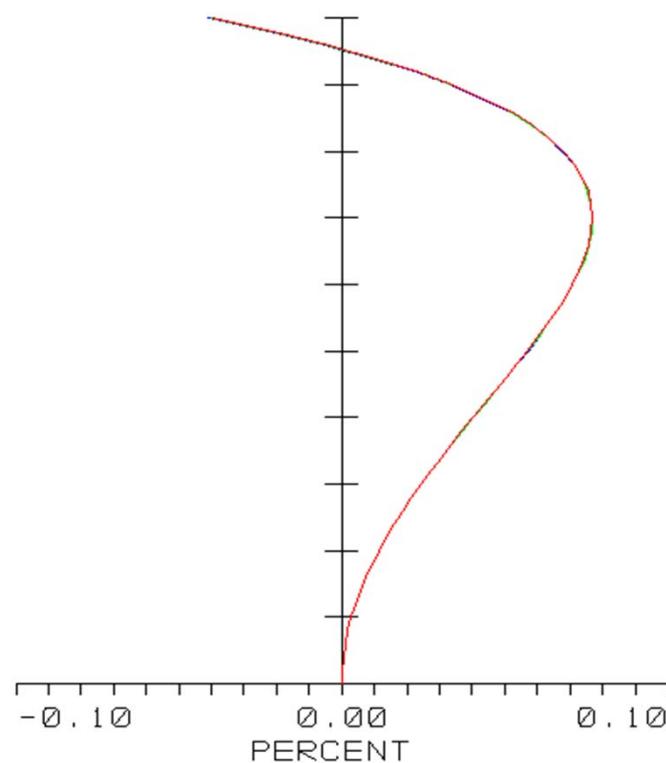
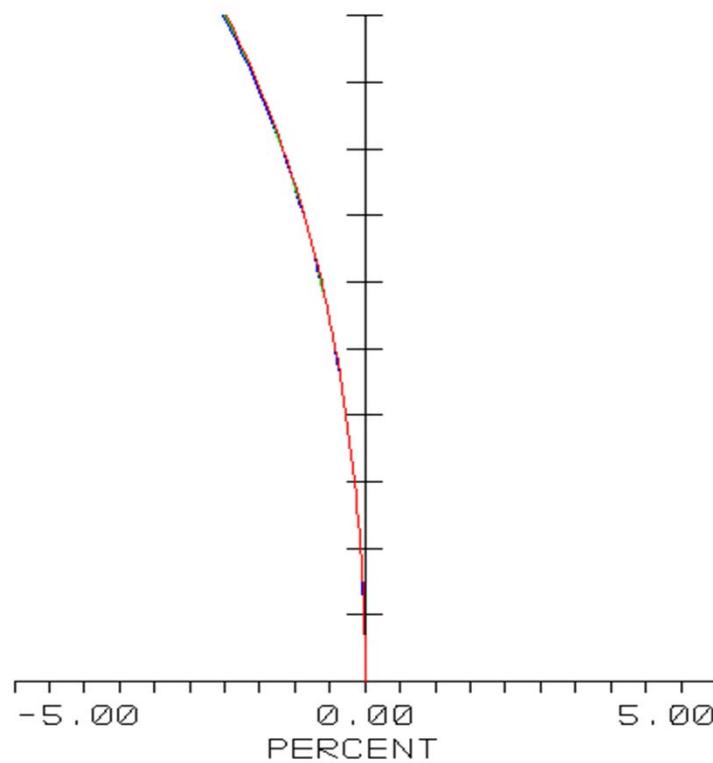
Distortion exists in all lenses but, can be fairly well corrected.

It's more difficult to correct for this aberration in short focal length(wide angle) lenses.



Distortion

Monotonic?

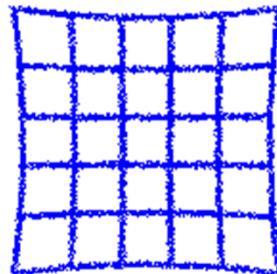


Distortion

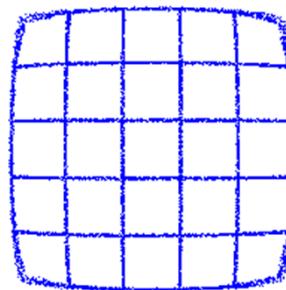
Types of Distortion

Symmetric

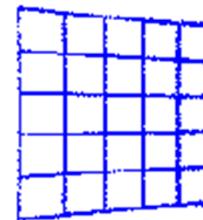
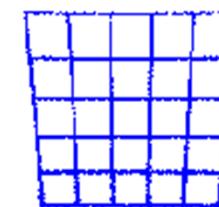
Pincushion



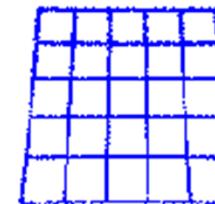
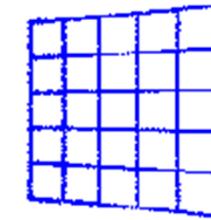
Barrel



Asymmetric

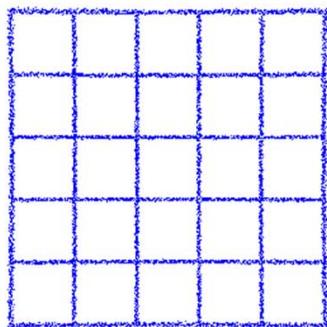
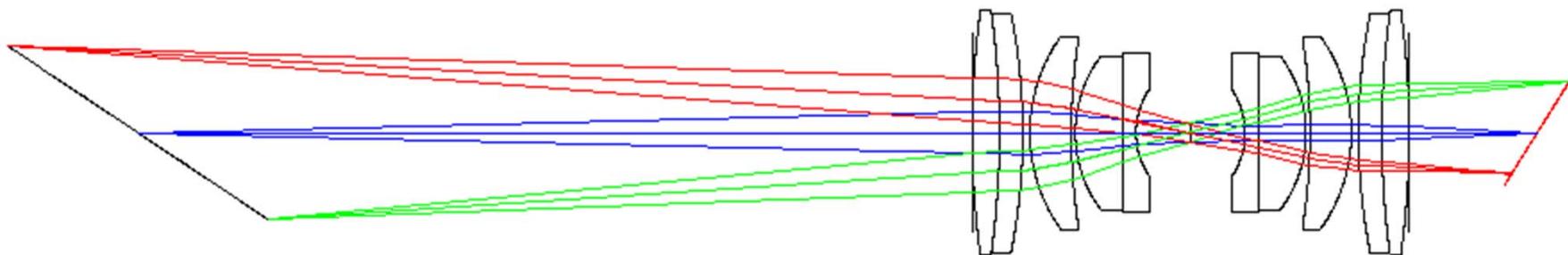


Keystone

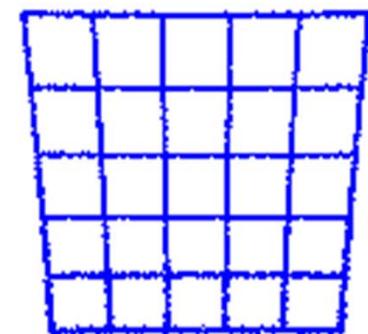


Distortion

Keystone



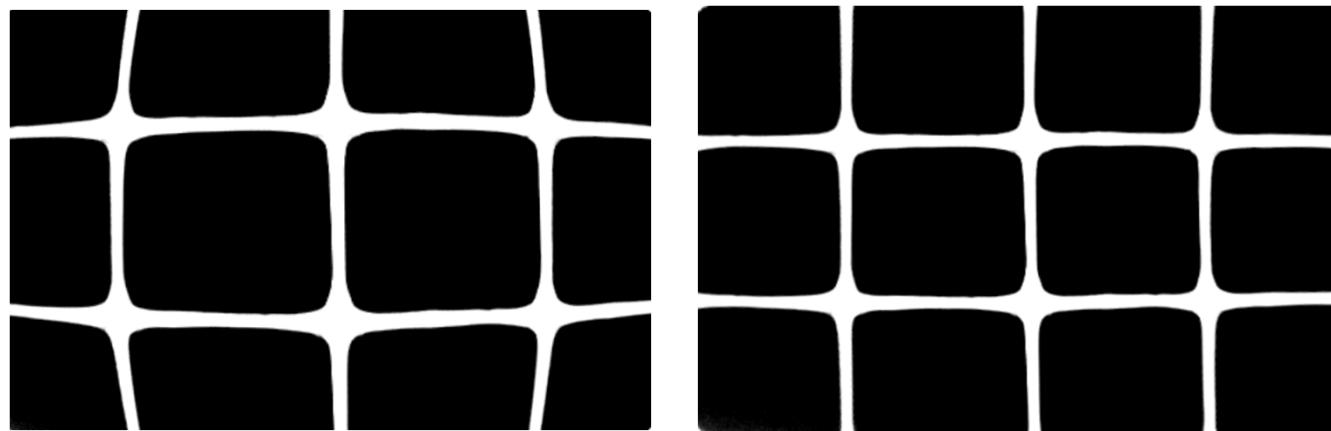
Scheimpflug condition...great focus (longitudinal magnification), change in magnification with field.



How Can Distortion Be Corrected?

Software can be used to correct for distortion because no information was lost only misplaced.

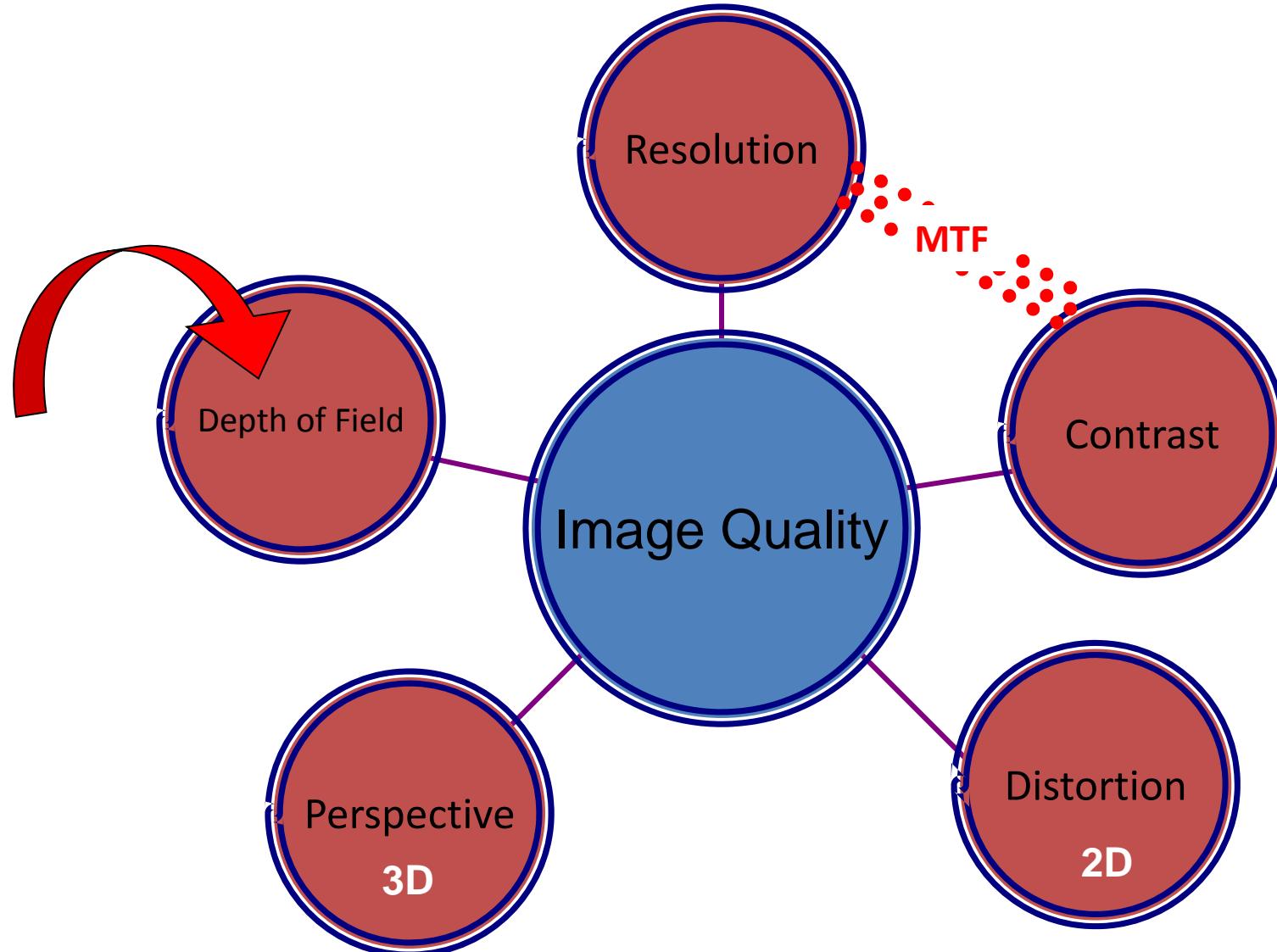
By knowing how far the information was misplaced software can be used to replace the information in the correct position.



Above is an image from a 4.3mm video, first without any software correction, then with distortion removed with software.



Review of Basics



What Is Perspective Error?

Perspective error, also called parallax, is change in magnification with a change in working distance.

This is how we perceive distance with our eyes.

Objects that are far away appear smaller than objects close up.

Though useful for perceiving distance, this is harmful when trying to make measurements.

Telecentric lenses are designed to minimize perspective error.

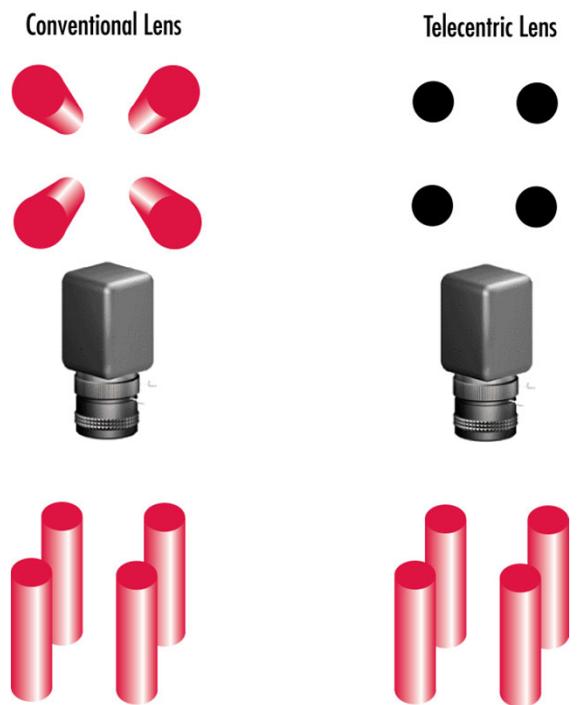


Illustration to the right shows the difference in images in a telecentric and conventional lens.



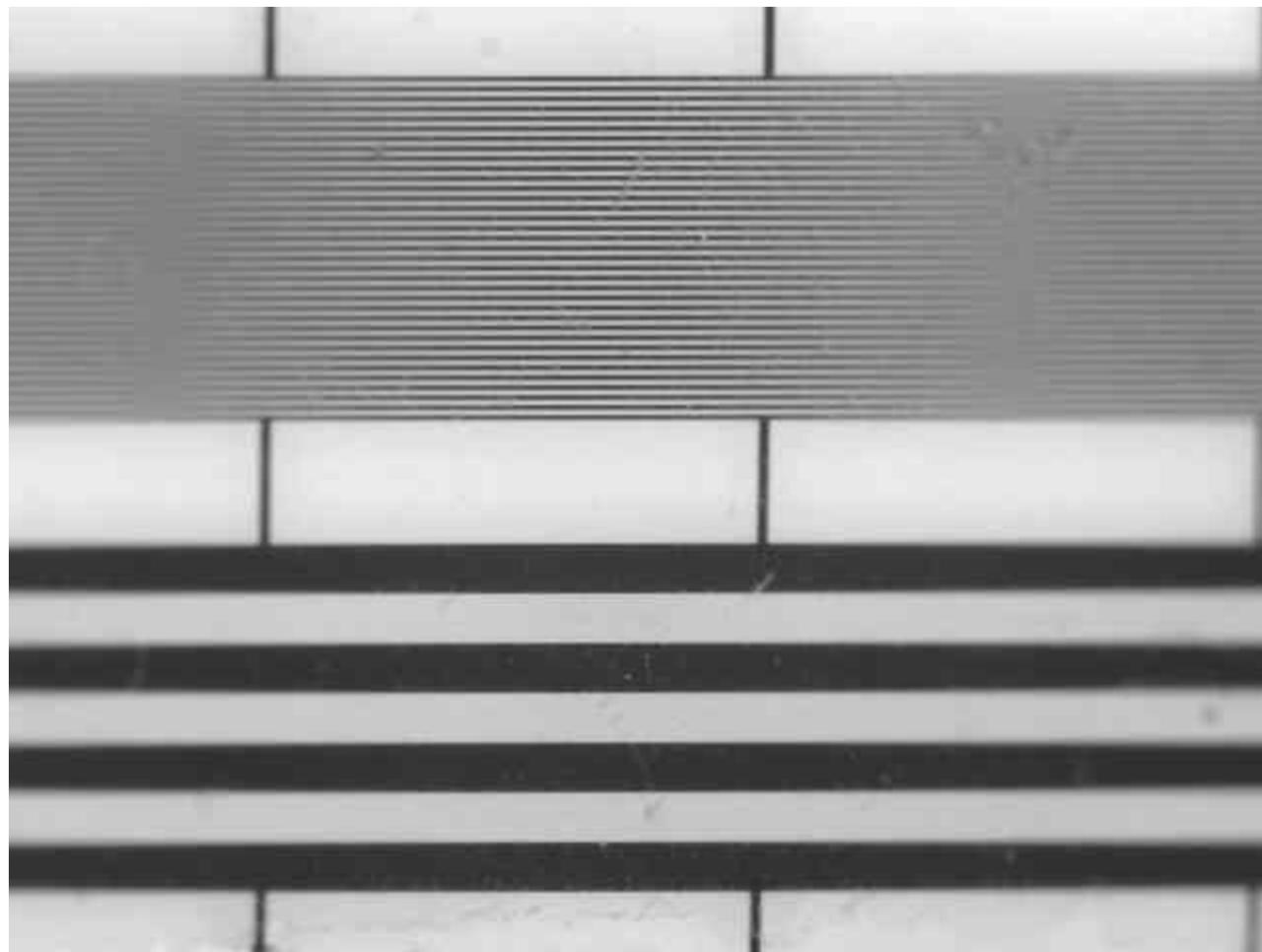
Examples of Telecentric Error

Test piece is the depth of field target looking at the parallel lines running down the 45 degree target.

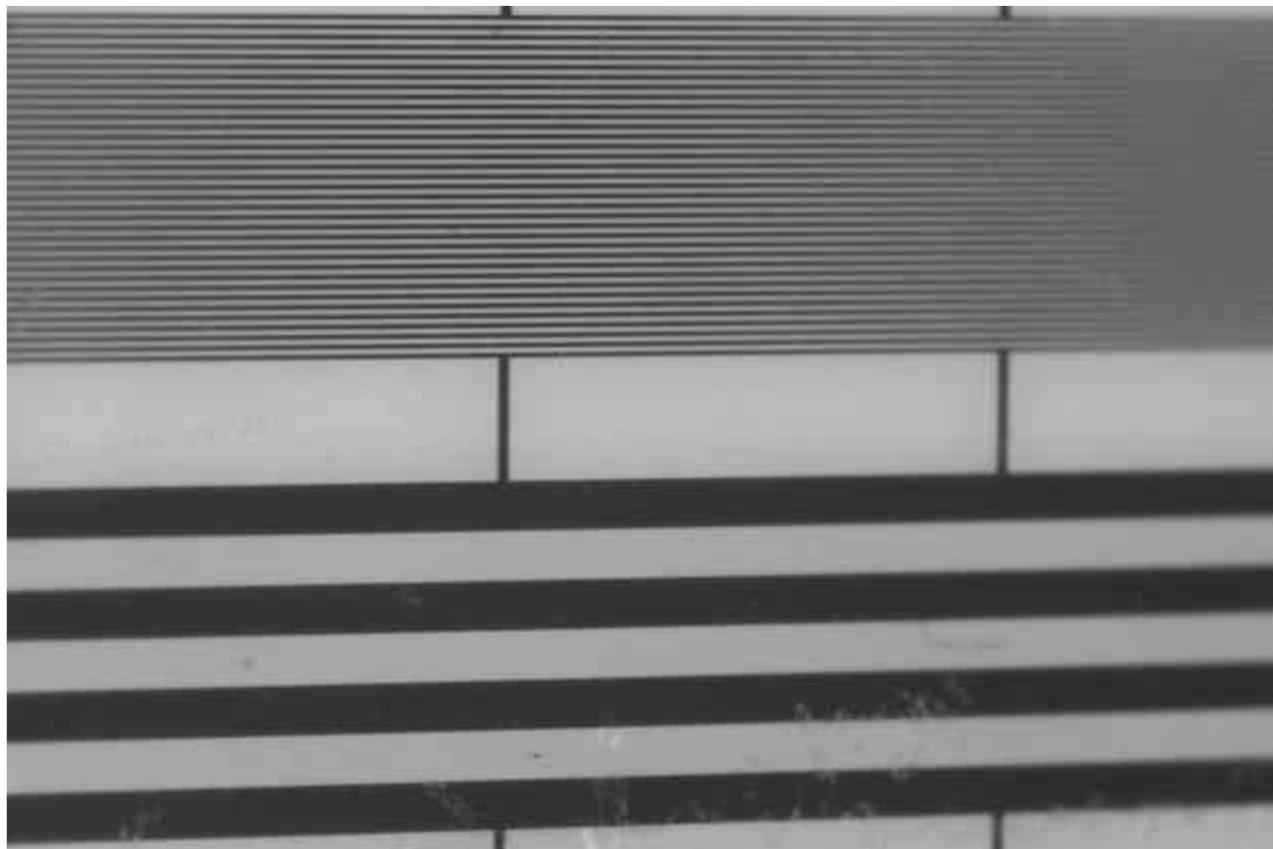
Telecentricity is demonstrated by the line converging as they get farther from the lens.



Measurement With a Telecentric Lens



Measurement With a Non-Telecentric Lens



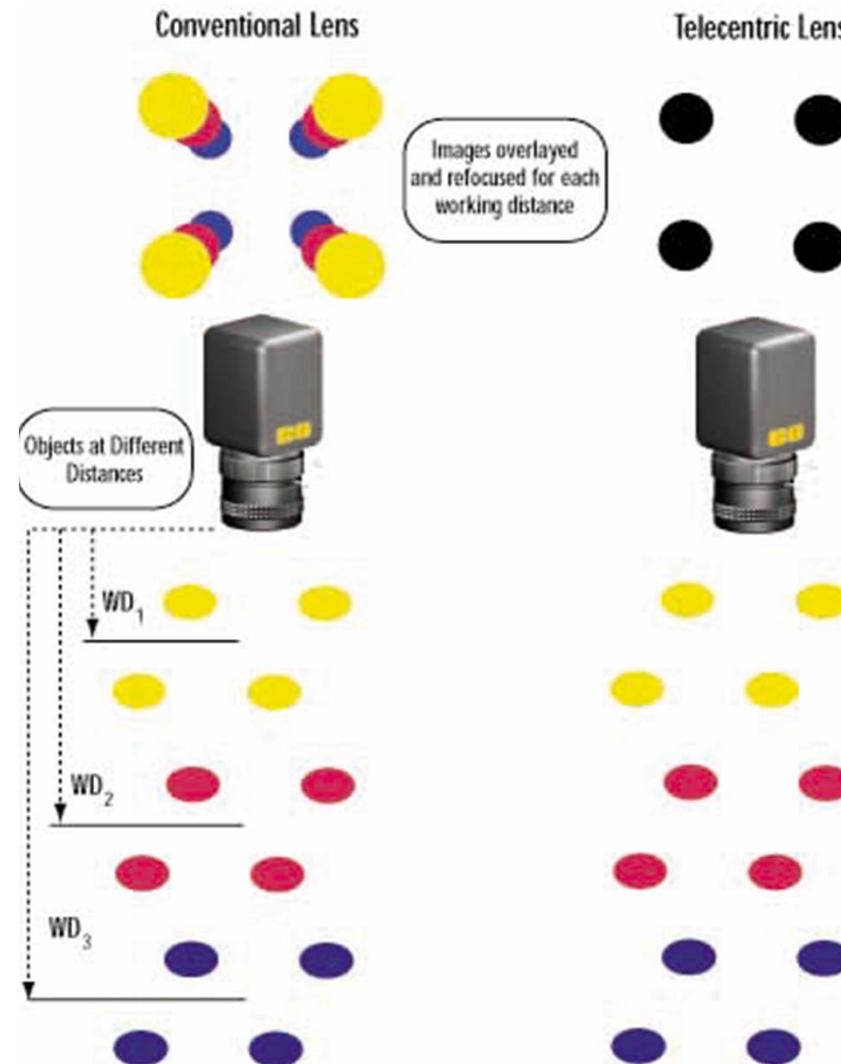
]] Telecentric error



Comparison Telecentric to Non Telecentric Lenses

As can be seen in the diagram, as working distance increases magnification decreases for the conventional lens

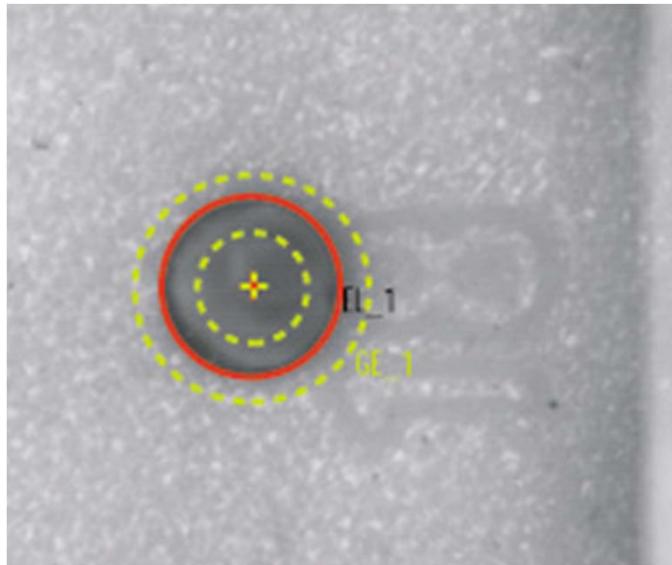
In the telecentric lens magnification is maintained



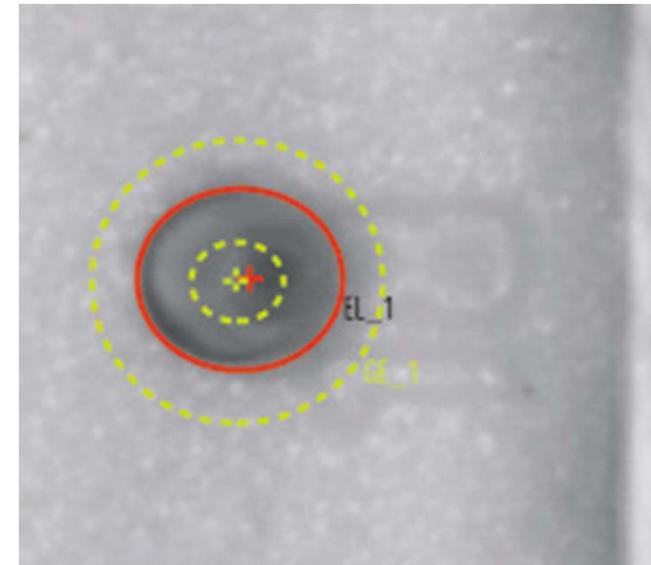
Telecentric Lenses are Useful in Many Applications

Even when the image is out of focus a Telecentric lens can be very useful because there is no change in magnification, with working distance equal blurring will occur.

This allows for accurate center positions to be determined.



Telecentric Lens

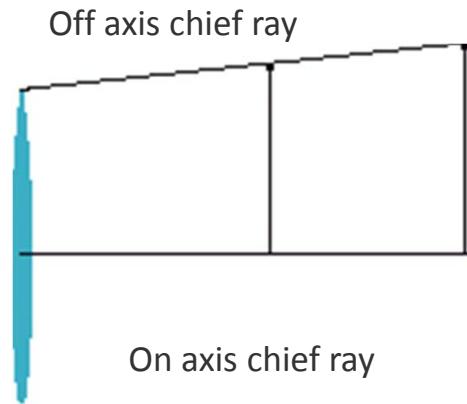


Conventional Lens

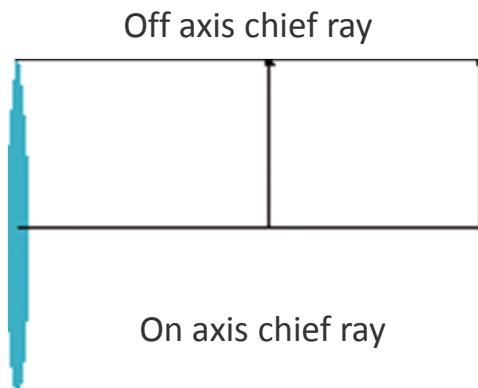


Why Does Perspective Error Occur?

Chief ray= ray that goes through the center of the aperture stop.



In a conventional lens the angle between chief rays at different image heights causes the parallax error.



In a telecentric lens, the chief rays are all parallel.



What Are The Limitations of Telecentric Lenses?

The field of view of a telecentric lens is limited by the diameter of the front lens.

The need for the chief rays to be parallel constrains the telecentric region to be smaller than the lens diameter.



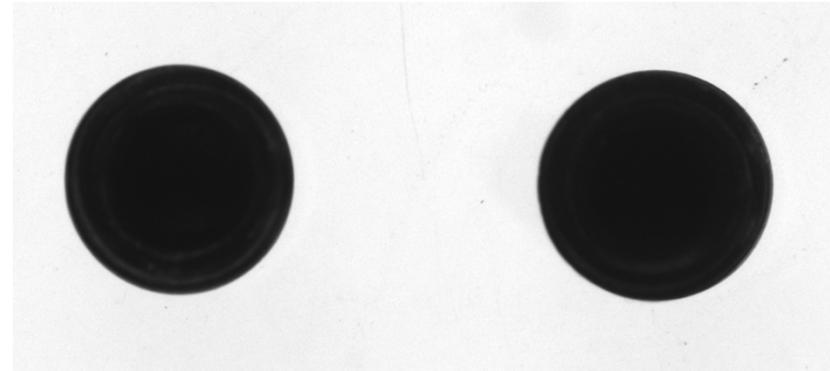
All telecentric lenses can only meet their telecentric specifications over a specific range of working distances.

Because magnification is constant for a telecentric lens, different lenses are needed for different fields of view.



Case Study

Screw Measurements
Diameter
Distance Between Parts

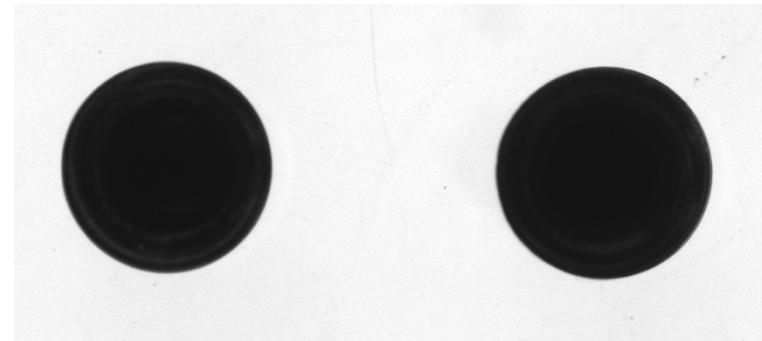


Center Comparison

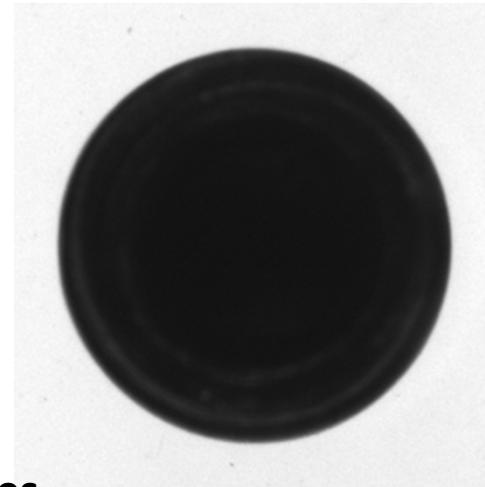
Center of FOV



6.5mm Fixed Focal Length Lens



Telecentric Lens



Close Up Images

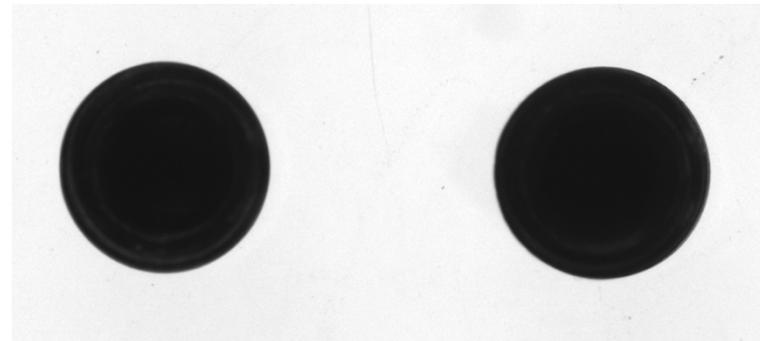


Comparison Defocus, 5mm Working Distance Change

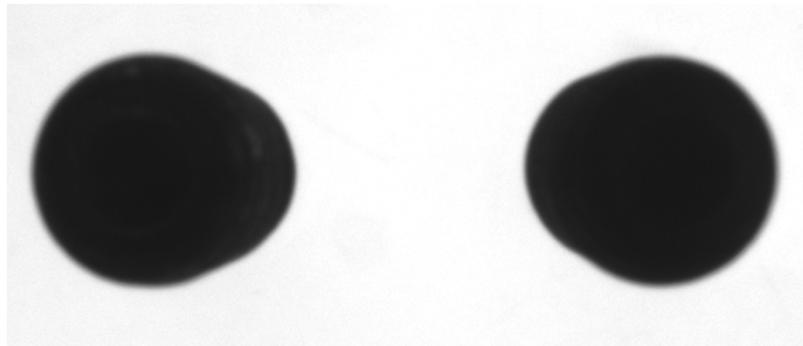
Center of FOV



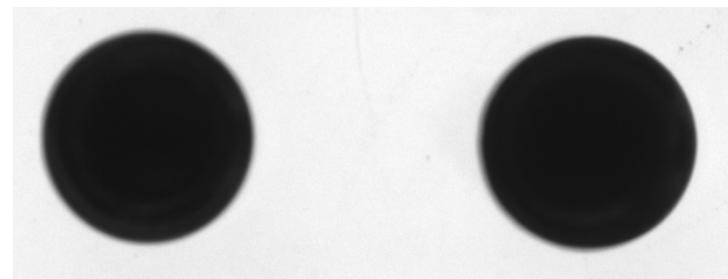
6.5mm Fixed Focal Length Lens



Telecentric Lens

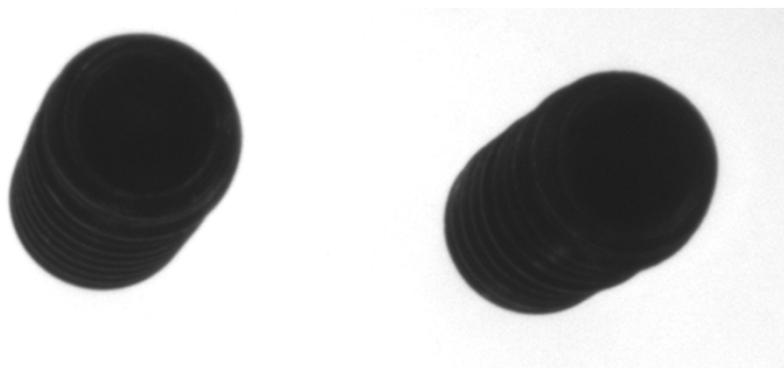


5 mm closer to the screws

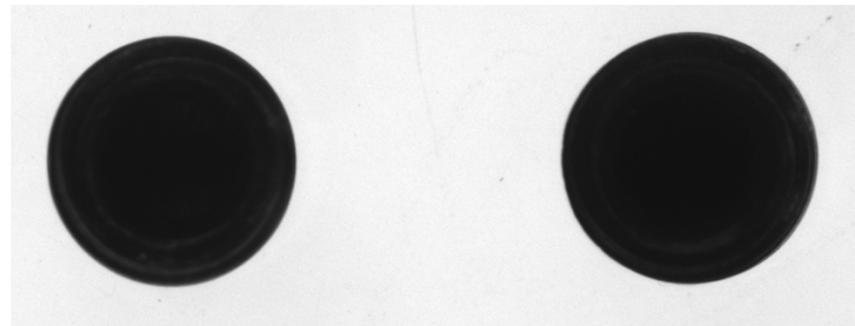


Corner Comparison

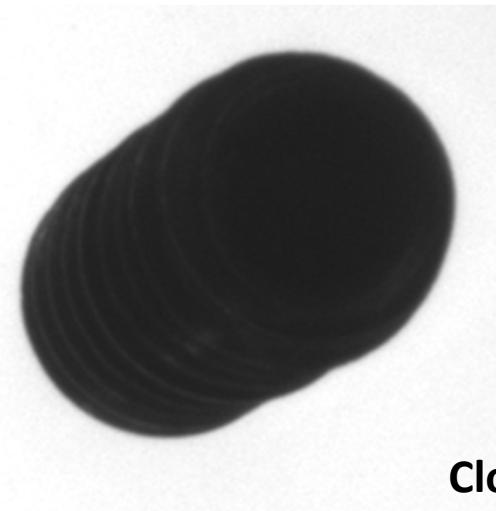
Corner of FOV



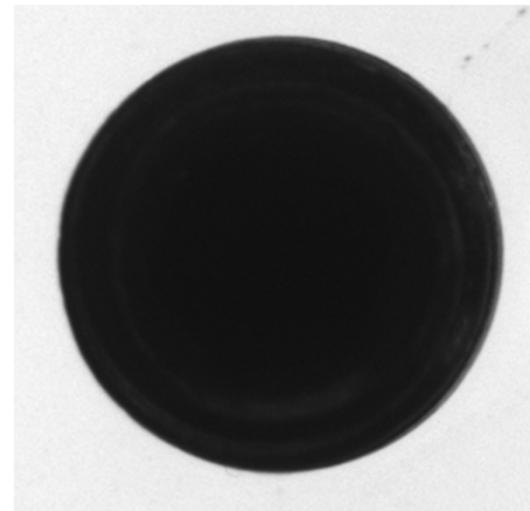
6.5mm Fixed Focal Length Lens



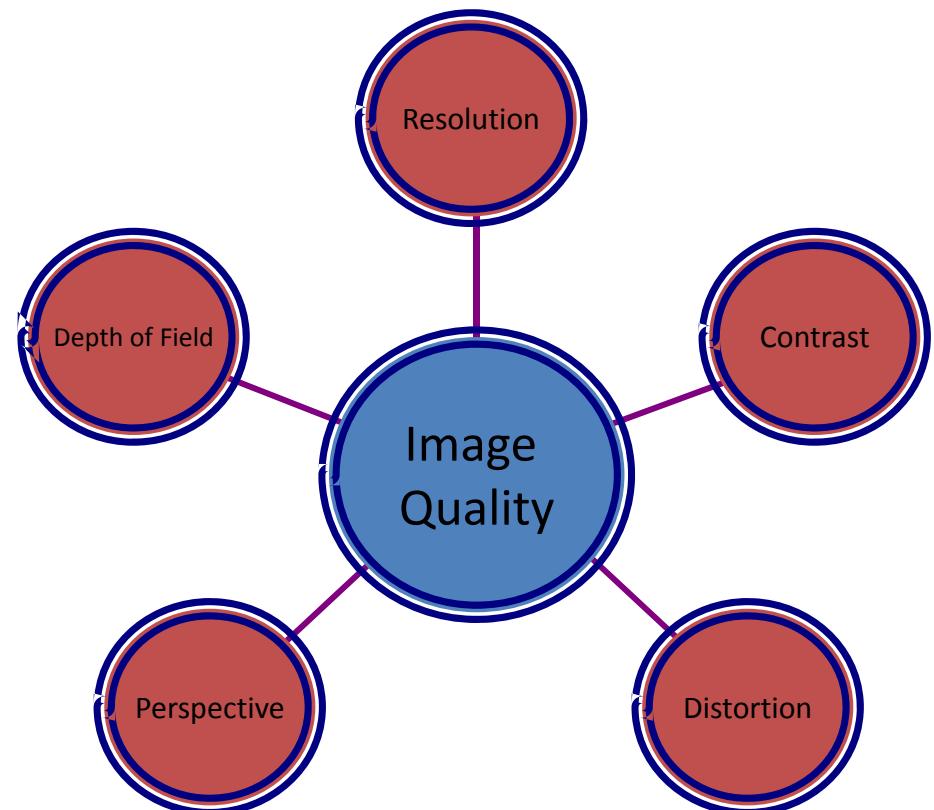
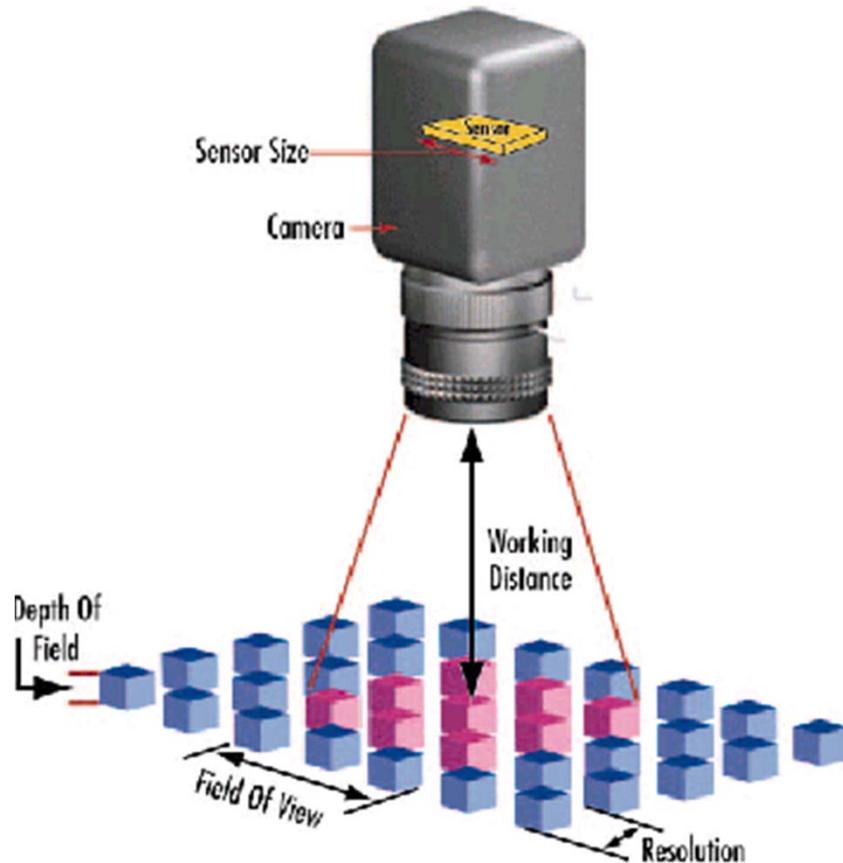
Telecentric Lens



Close ups



Review of Basics



Finally, Do your Homework!

Optics can process images at the speed of light. Give it the time it deserves!

Specify what you need as a system not just components.

Expect a lot from optical suppliers. They should know much more than just lens design.



Suggested Texts For Further Information On Image Quality

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

Shannon, The Art and Science of Optical Design, Massachusetts, Cambridge University, 1997

Optikos Corp., How to measure MTF PDF file

http://www.optikos.com/classes/pdfs/how_to_measure_mtf.pdf



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