Pixel Sizes and Optics

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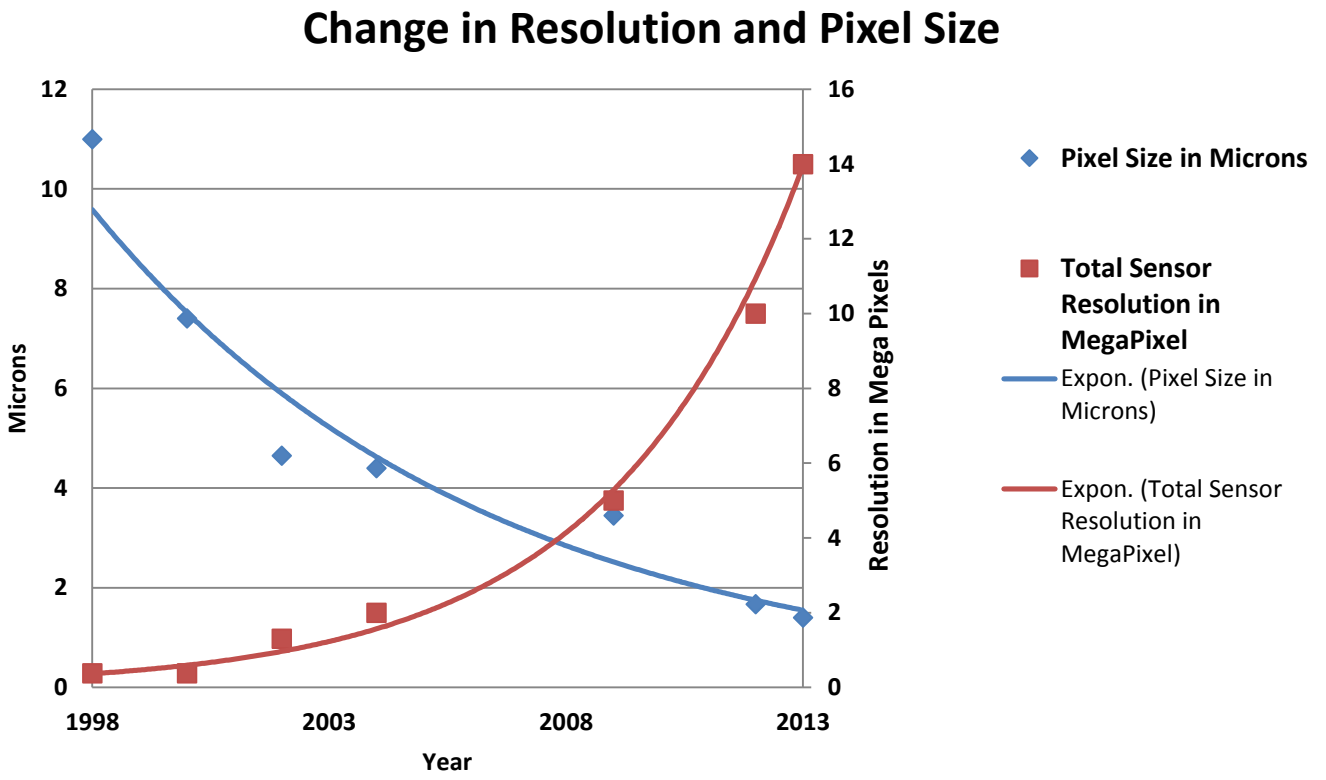
AUTOMATE • 2017

Agenda

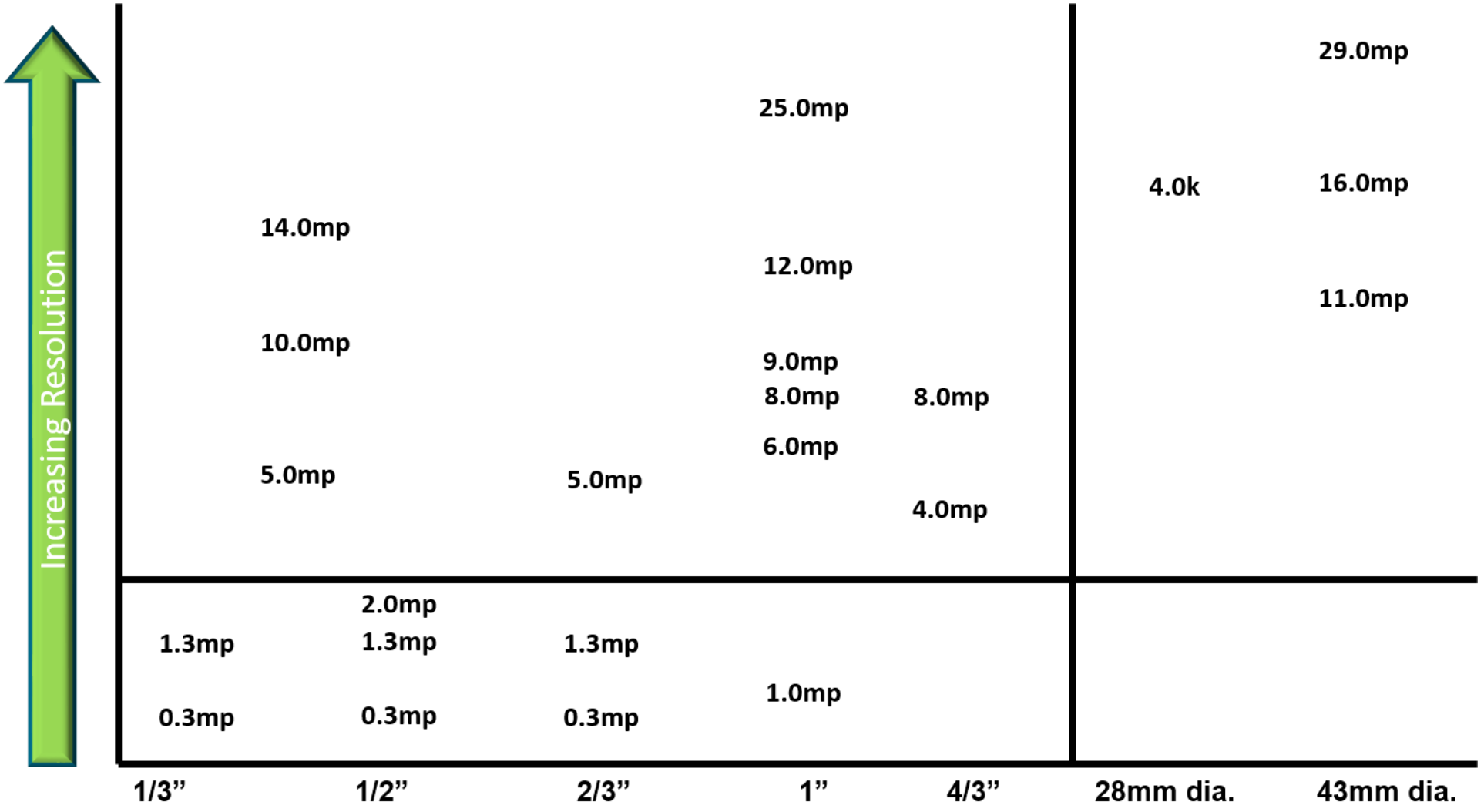
- Sensor technology development
- Review of resolution and contrast
- Review of Modulation Transfer Function (MTF)
- Real-world lens performance
- Optimizing lens performance on small pixels

Sensor Technology Development

- Understanding sensor development aids in foreseeing optical development
- As pixel sizes decrease, resolutions increase
- Applications split into two different areas: large and small cost high resolutions
- The optics to handle these application areas are different



Sensor Technology Development



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Sensor Technology Development

Pixel Size	MegaPixel	Horizontal	Vertical	Dimension Horizontal	Dimension Vertical	Diagonal
3.69	4	2000	2000	7.38	7.38	10.44
3.69	8	2828	2828	10.44	10.44	14.76
3.69	12	3464	3464	12.78	12.78	18.08
3.69	16	4000	4000	14.76	14.76	20.87
3.69	20	4472	4472	16.50	16.50	23.34
3.69	25	5000	5000	18.45	18.45	26.09
3.69	30	5477	5477	20.21	20.21	28.58
3.69	35	5916	5916	21.83	21.83	30.87
3.69	40	6325	6325	23.34	23.34	33.00
3.69	45	6708	6708	24.75	24.75	35.01
3.69	50	7071	7071	26.09	26.09	36.90
3.69	55	7416	7416	27.37	27.37	38.70
3.69	60	7746	7746	28.58	28.58	40.42
3.69	65	8062	8062	29.75	29.75	42.07
3.69	70	8367	8367	30.87	30.87	43.66
3.69	75	8660	8660	31.96	31.96	45.19

Sensor Technology Development

Pixel Size	MegaPixel	Horizontal	Vertical	Dimension Horizontal	Dimension Vertical	Diagonal
2.8	4	2000	2000	5.60	5.60	7.92
2.8	8	2828	2828	7.92	7.92	11.20
2.8	12	3464	3464	9.70	9.70	13.72
2.8	16	4000	4000	11.20	11.20	15.84
2.8	20	4472	4472	12.52	12.52	17.71
2.8	25	5000	5000	14.00	14.00	19.80
2.8	30	5477	5477	15.34	15.34	21.69
2.8	35	5916	5916	16.57	16.57	23.43
2.8	40	6325	6325	17.71	17.71	25.04
2.8	45	6708	6708	18.78	18.78	26.56
2.8	50	7071	7071	19.80	19.80	28.00
2.8	55	7416	7416	20.77	20.77	29.37
2.8	60	7746	7746	21.69	21.69	30.67
2.8	65	8062	8062	22.57	22.57	31.92
2.8	70	8367	8367	23.43	23.43	33.13
2.8	75	8660	8660	24.25	24.25	34.29

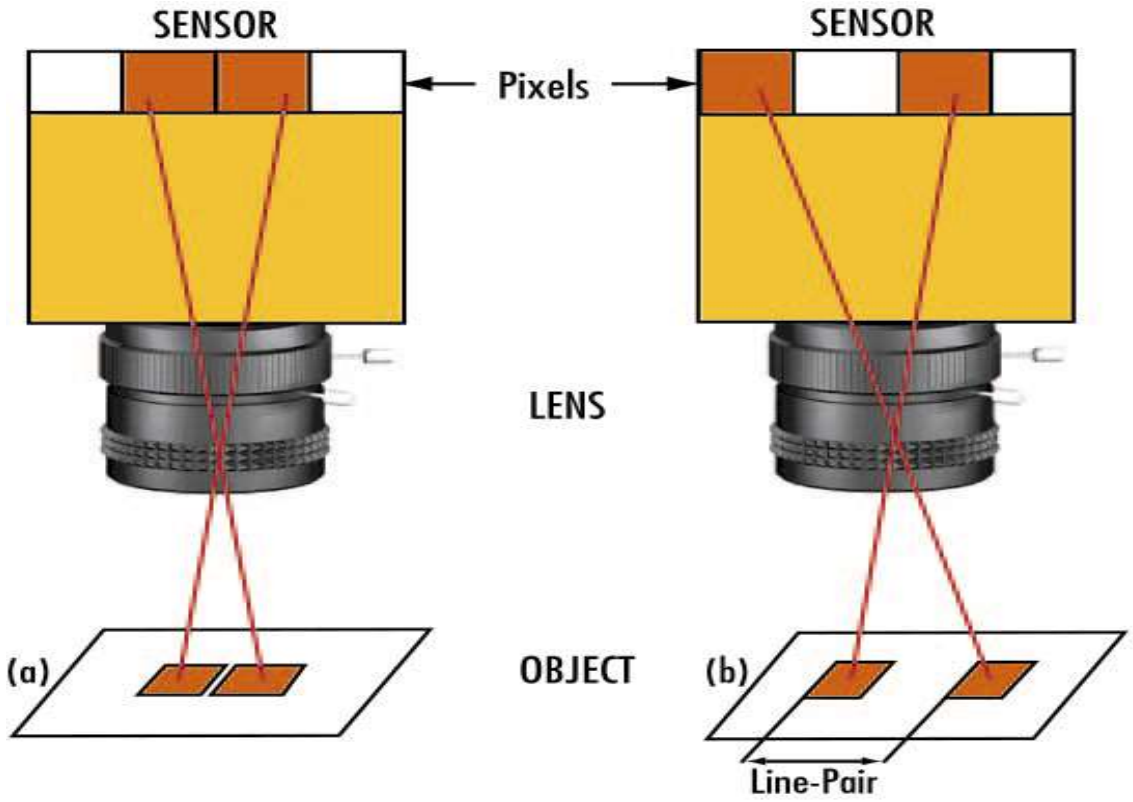
Sensor Technology Development

Pixel Size	MegaPixel	Horizontal	Vertical	Dimension Horizontal	Dimension Vertical	Diagonal
2.2	4	2000	2000	4.40	4.40	6.22
2.2	8	2828	2828	6.22	6.22	8.80
2.2	12	3464	3464	7.62	7.62	10.78
2.2	16	4000	4000	8.80	8.80	12.45
2.2	20	4472	4472	9.84	9.84	13.91
2.2	25	5000	5000	11.00	11.00	15.56
2.2	30	5477	5477	12.05	12.05	17.04
2.2	35	5916	5916	13.02	13.02	18.41
2.2	40	6325	6325	13.91	13.91	19.68
2.2	45	6708	6708	14.76	14.76	20.87
2.2	50	7071	7071	15.56	15.56	22.00
2.2	55	7416	7416	16.32	16.32	23.07
2.2	60	7746	7746	17.04	17.04	24.10
2.2	65	8062	8062	17.74	17.74	25.08
2.2	70	8367	8367	18.41	18.41	26.03
2.2	75	8660	8660	19.05	19.05	26.94

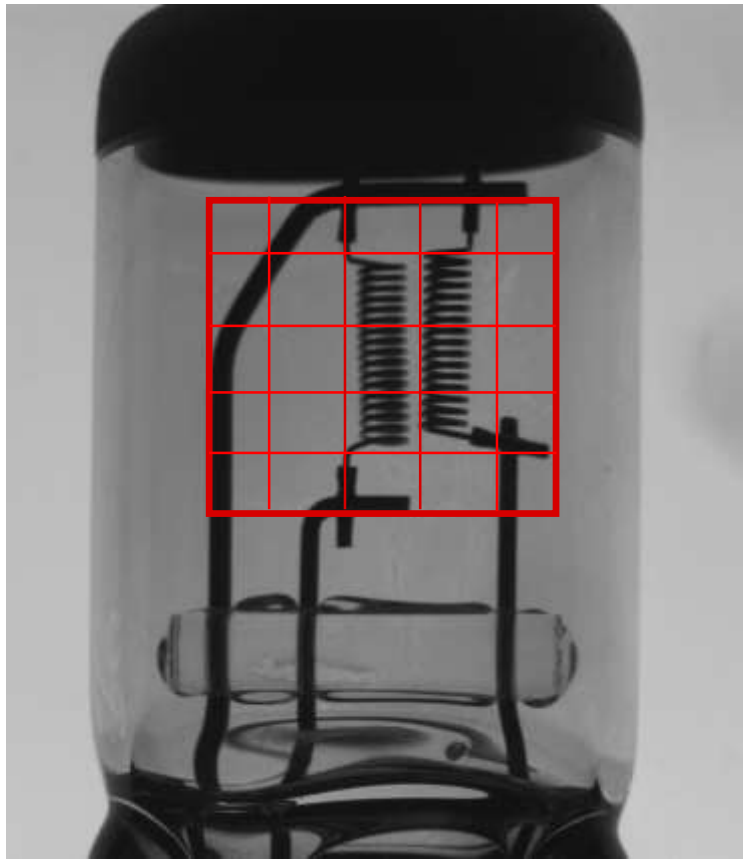
Resolution Definition

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

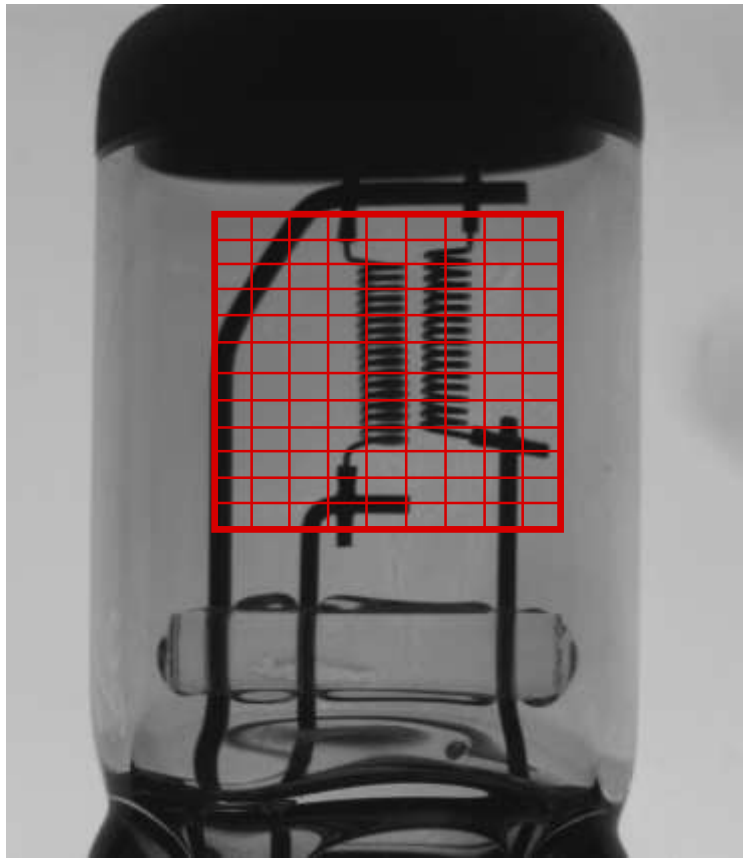
- In the example to the right, in order for the objects to be resolved, there must be at least one pixel of space between them



Example of Increasing Resolution



640 x 480 Pixel
(0.3 MegaPixels)



1600 x 1200 Pixel
(2 MegaPixels)

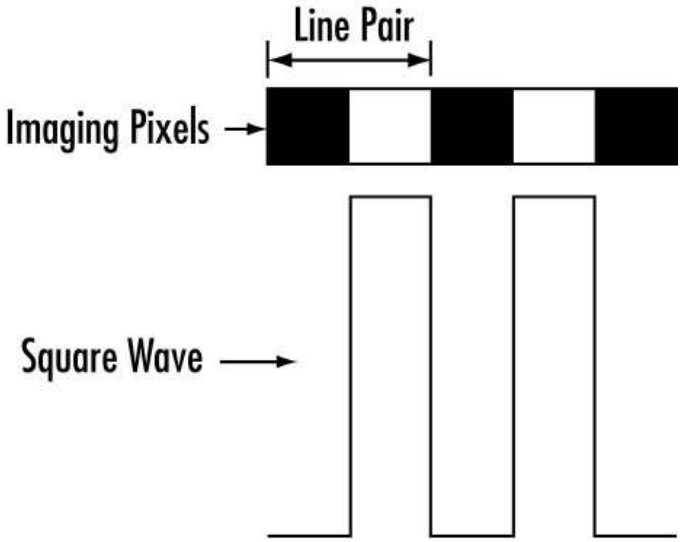
Resolution Definition in Optics

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

- Typically represented in line pairs per mm (lp/mm)

- $\xi(lp/mm) = \frac{1000^{\mu m}/_{mm}}{^{2}/_{lp} * pixel\ size\ (\mu m)}$

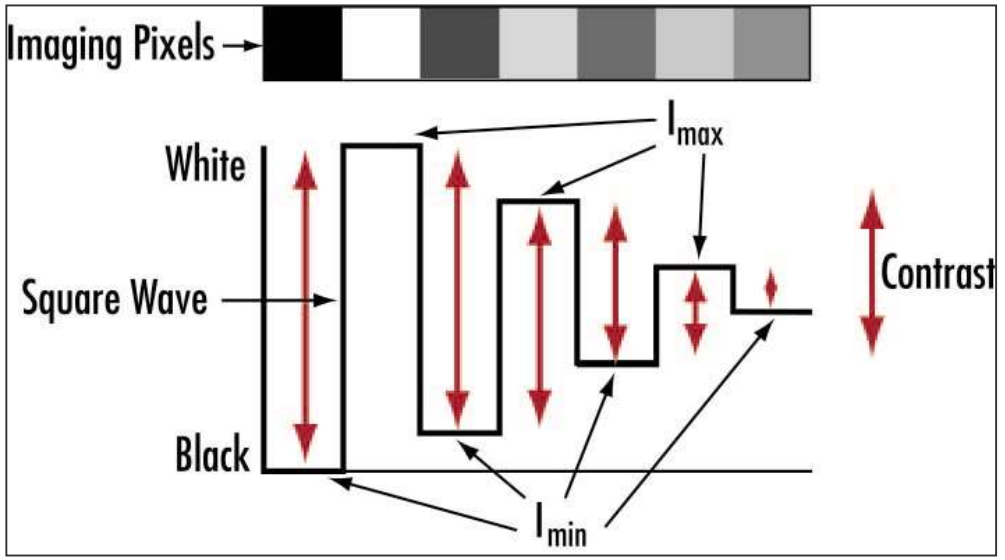
$$= \frac{500}{pixel\ size\ (\mu m)}$$



Typical simplification of an object as line pairs formed by square waves

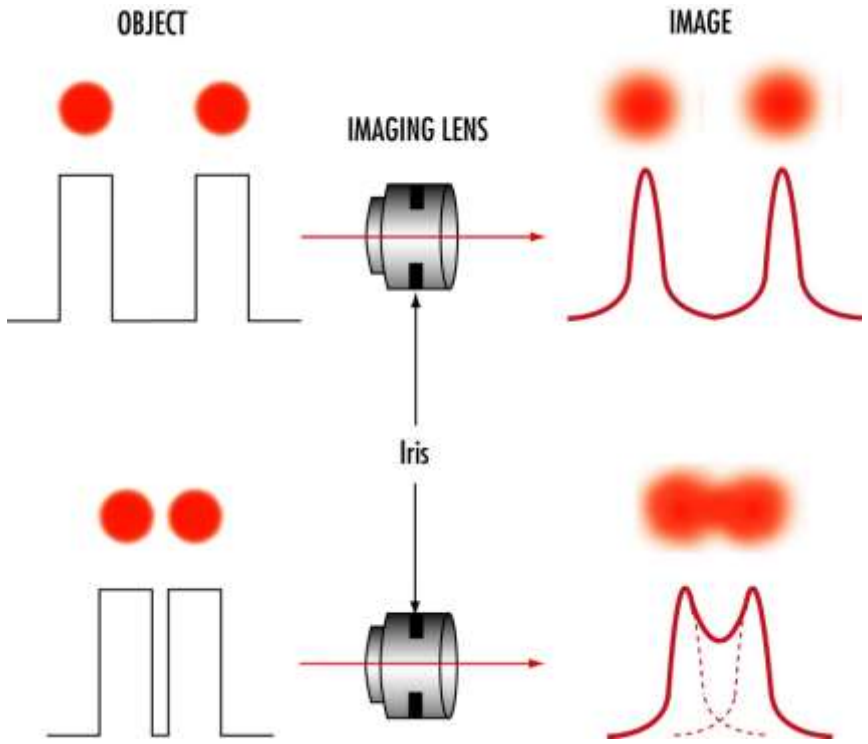
Contrast

- Contrast describes the separation in intensity between blacks and whites
- $Contast\ (\%) = \left|\frac{I_{max}-I_{min}}{I_{max}+I_{min}}\right| * 100$
- The greater the difference in intensity between a black and white line, the better the contrast
- Perfect black and perfect white are impossible to attain unless there are errors in the system



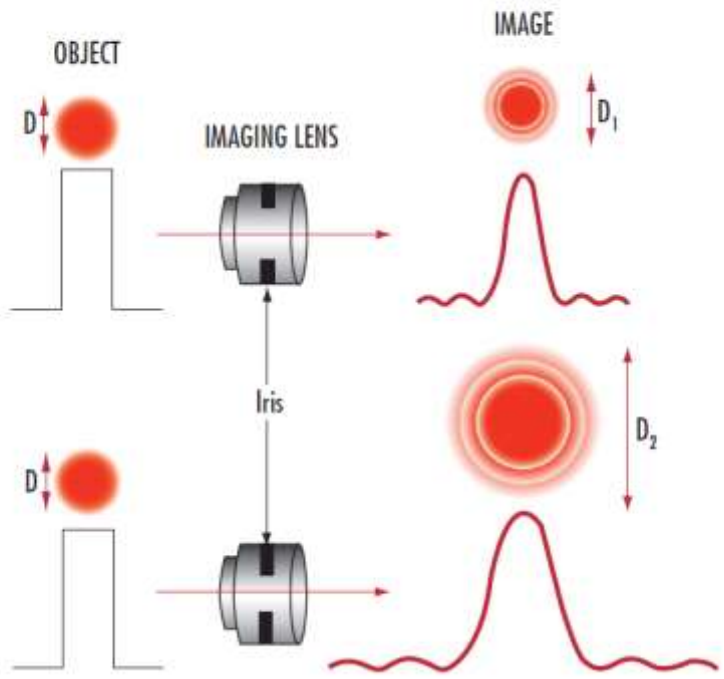
Link Between Resolution and Contrast

- Resolution and contrast are closely linked
- Contrast is defined at a specific resolution
  - Typically, as resolution increases, contrast decreases
- The typical limiting contrast of 20% is often used to define the limiting resolution level
  - For the human eye a contrast of 1-2% is often used to define resolution

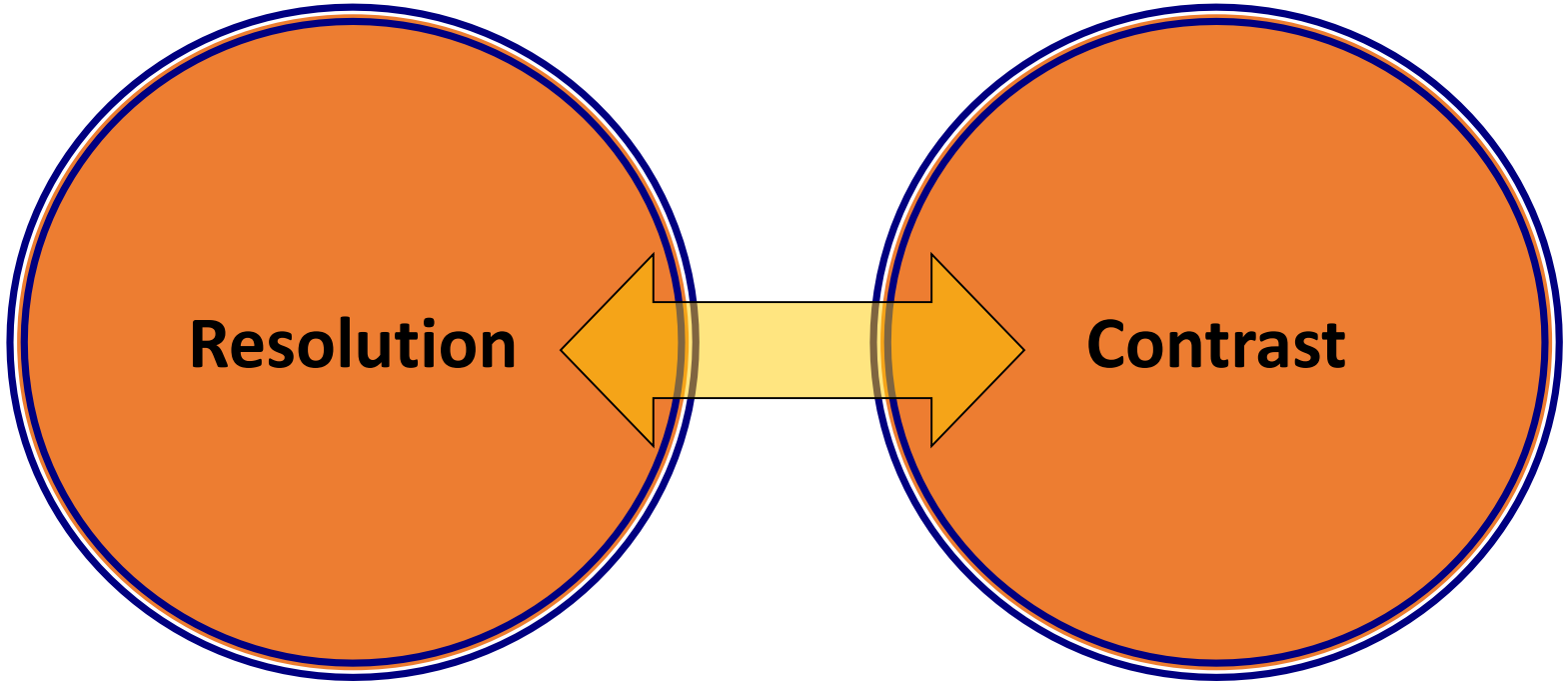


What Affects Contrast Reproduction in Lenses?

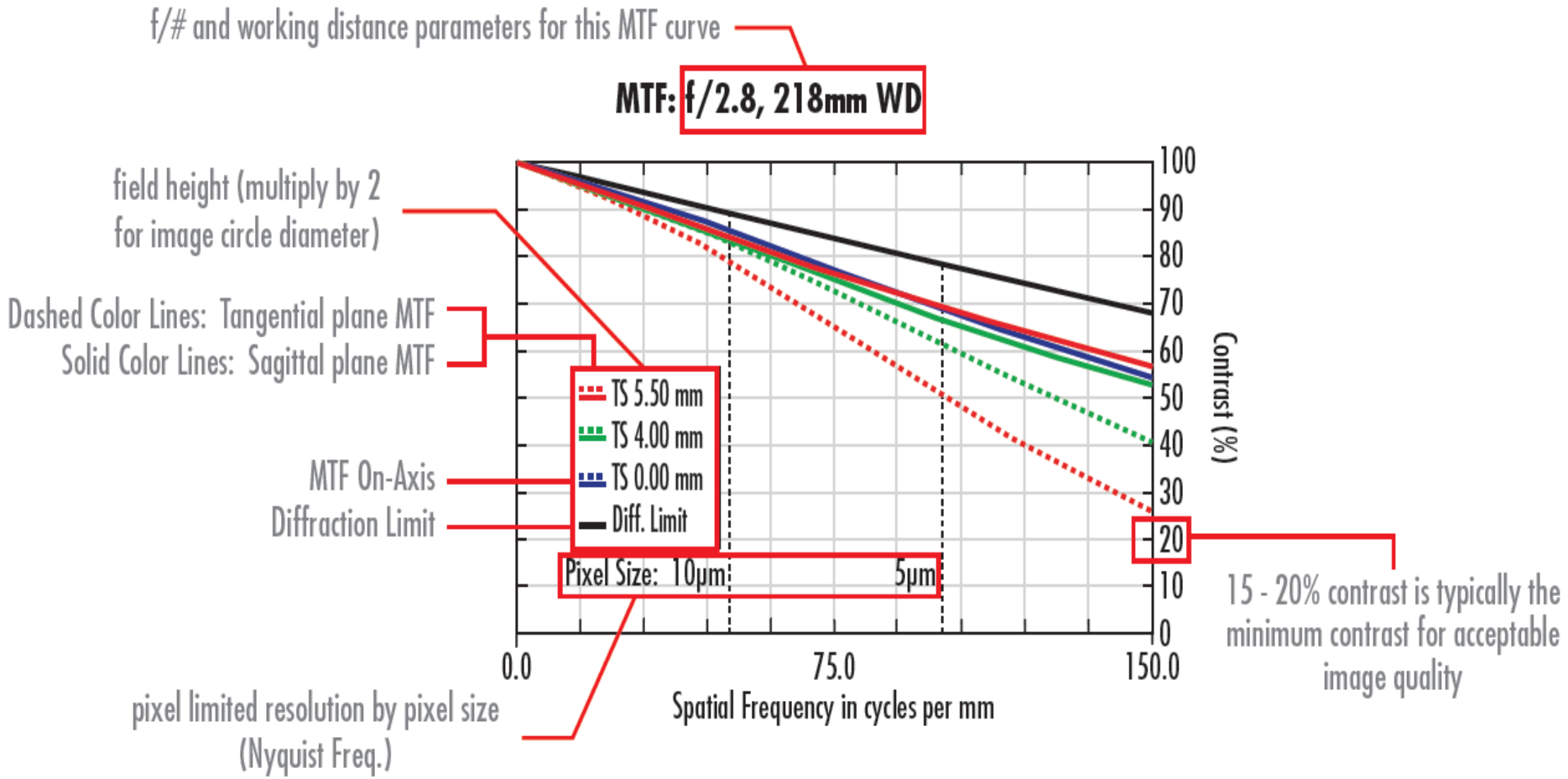
- Two major factors: Aberrations and contrast
- This talk will focus primarily on diffraction effects
- $D = 2.44\lambda\left({}^{f}/_{\#}\right)_{W}$
  - Where λ is the wavelength of light
  - ${}^{f}/_{\#}$ is the f-number of the lens



Modulation Transfer Function



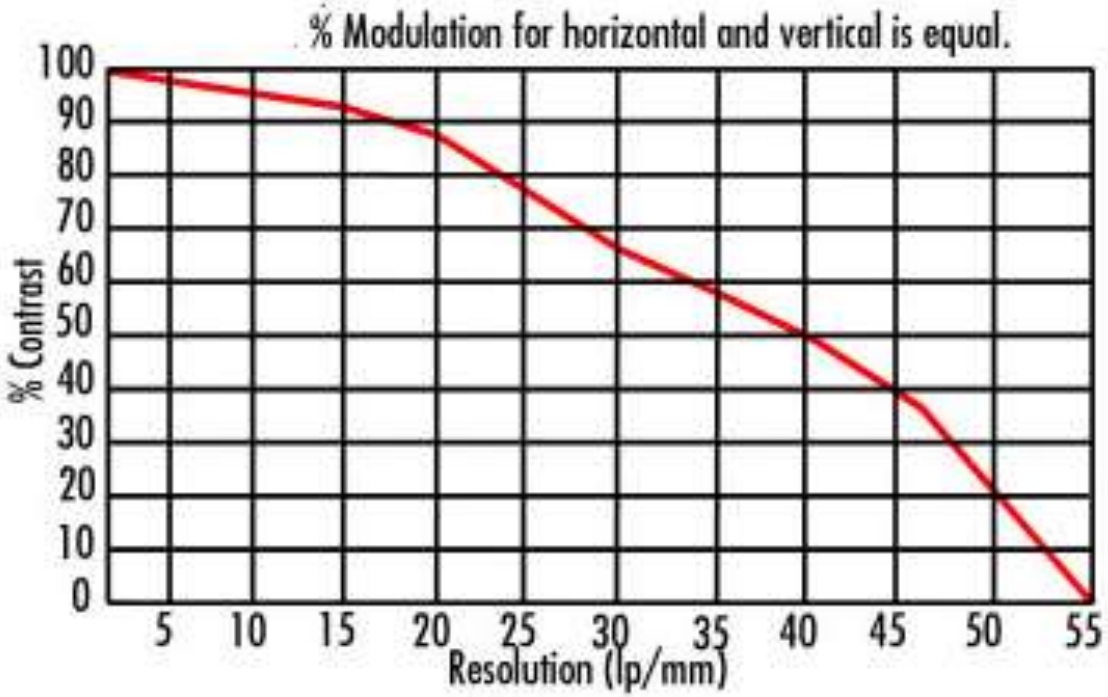
Modulation Transfer Function



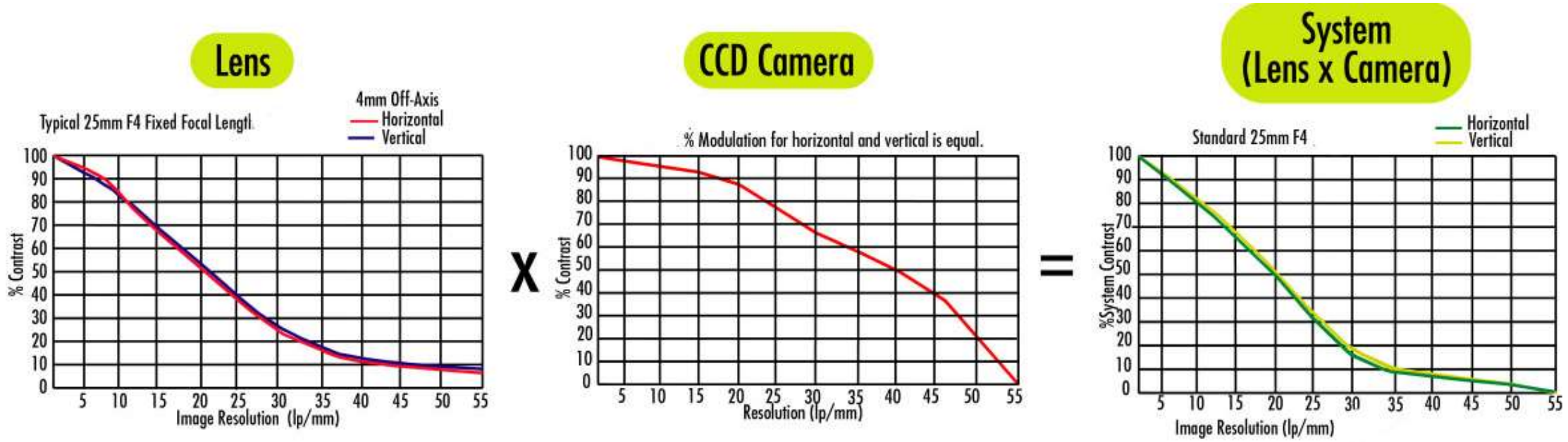
What Else Has an MTF?

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

- The image to the right shows an MTF curve for a CCD sensor

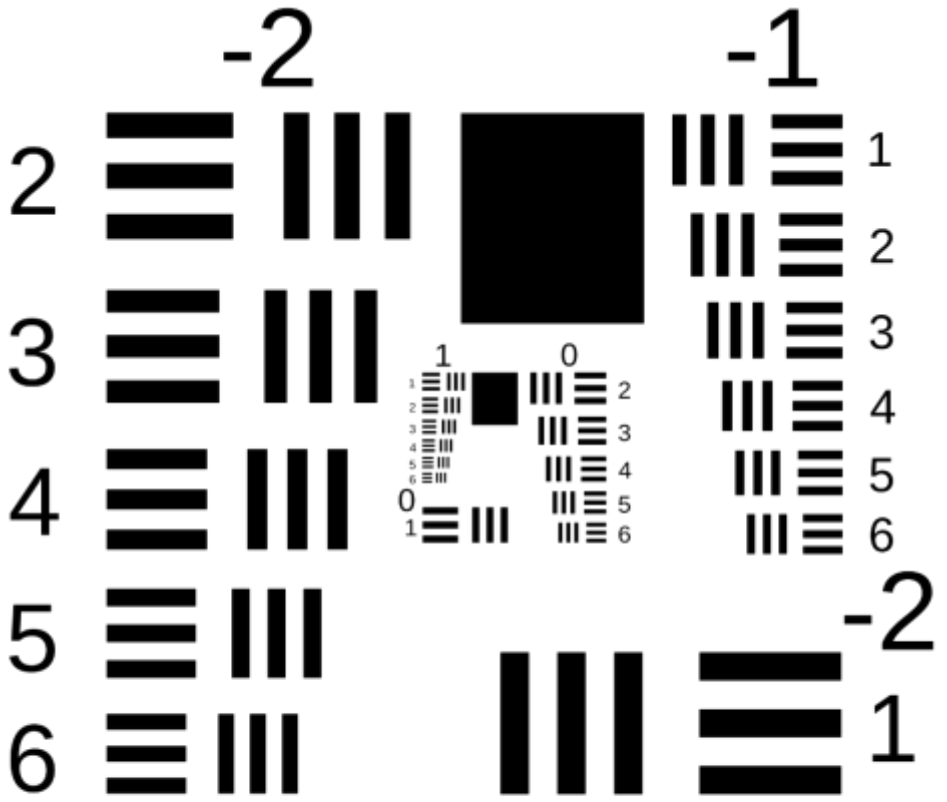


MTFs are Multiplicitive



How Is Resolution/Contrast Tested?

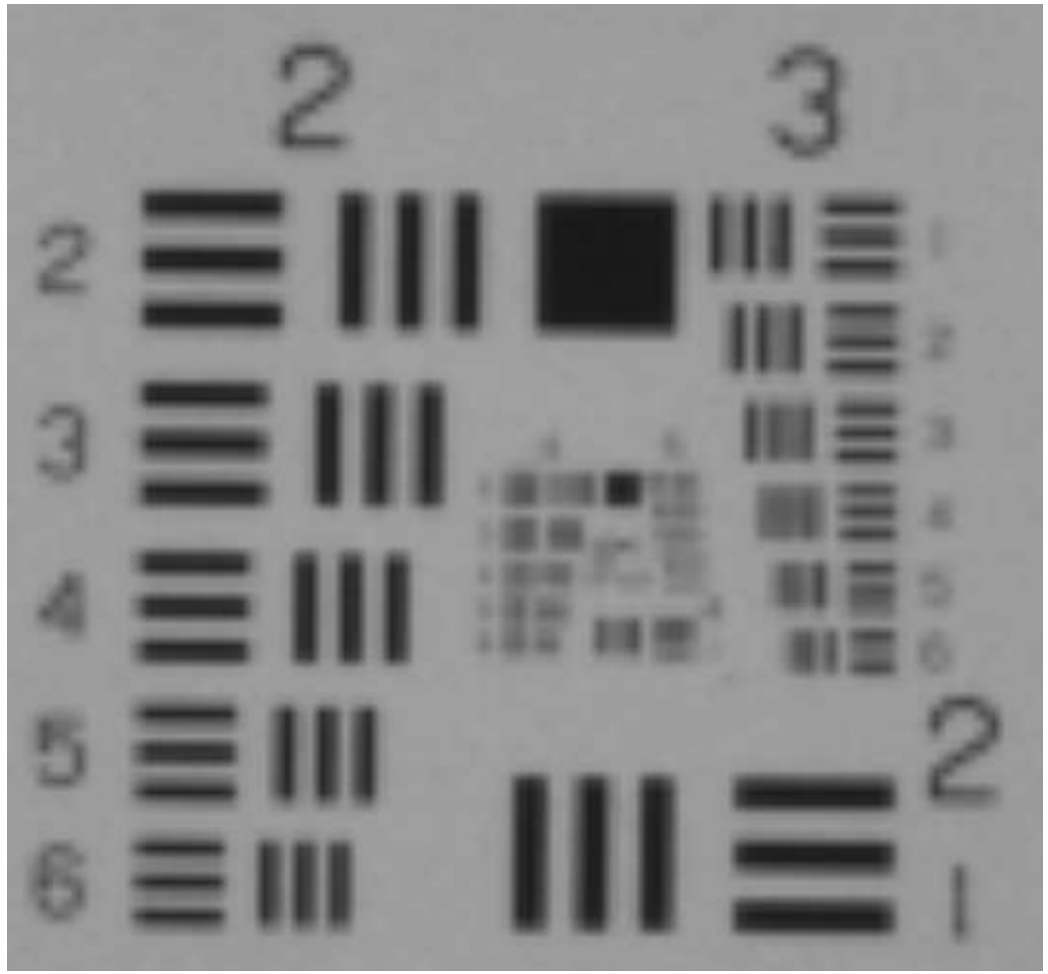
- The following examples all use a USAF 1951 target during testing
- Each group has six elements, each representing a different frequency
- Going from one group to the next increases element frequency by a factor of 2
  - For example, G3E1 is 8 lp/mm, where G4E1 is 16 lp/mm



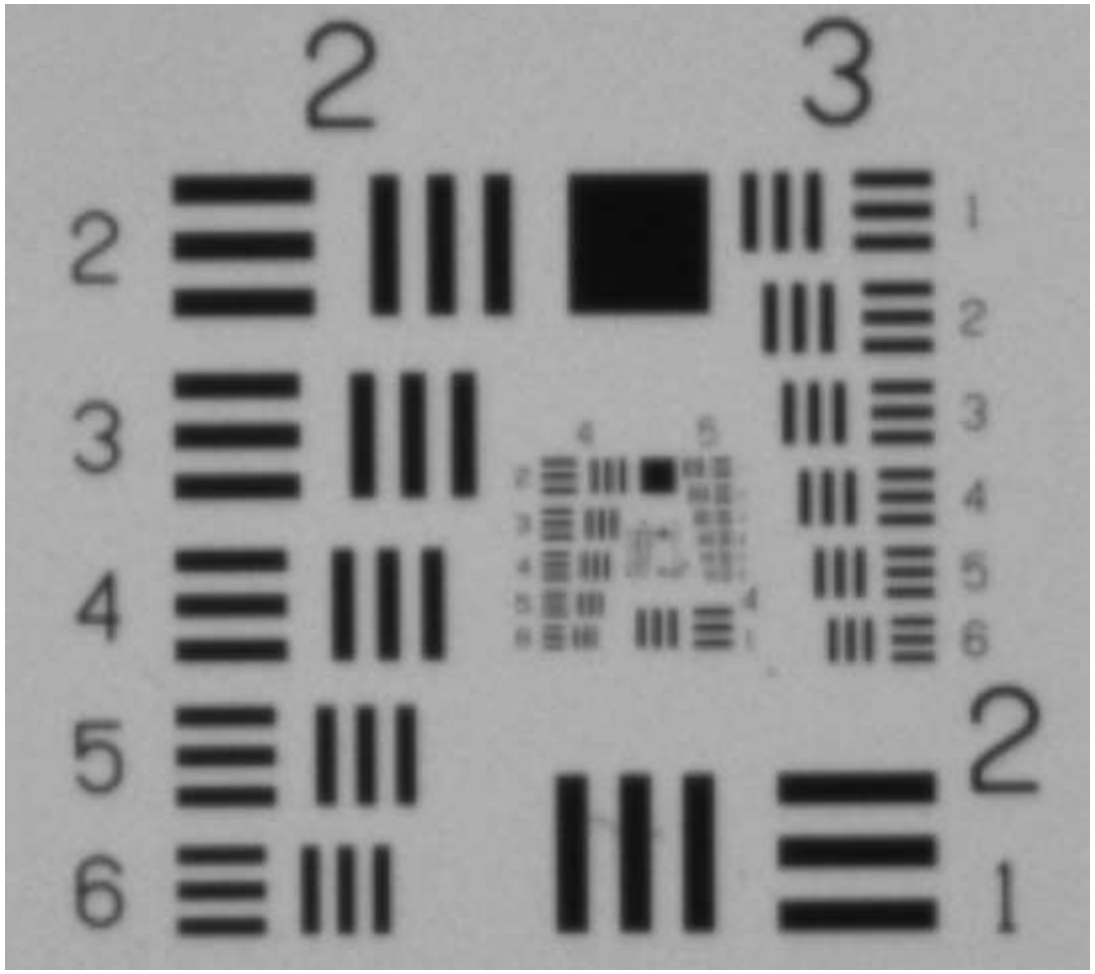
Source: Wikipedia.org

Real World Performance

4 MP, 7.4 micron pixel



5 MP, 3.45 micron pixel



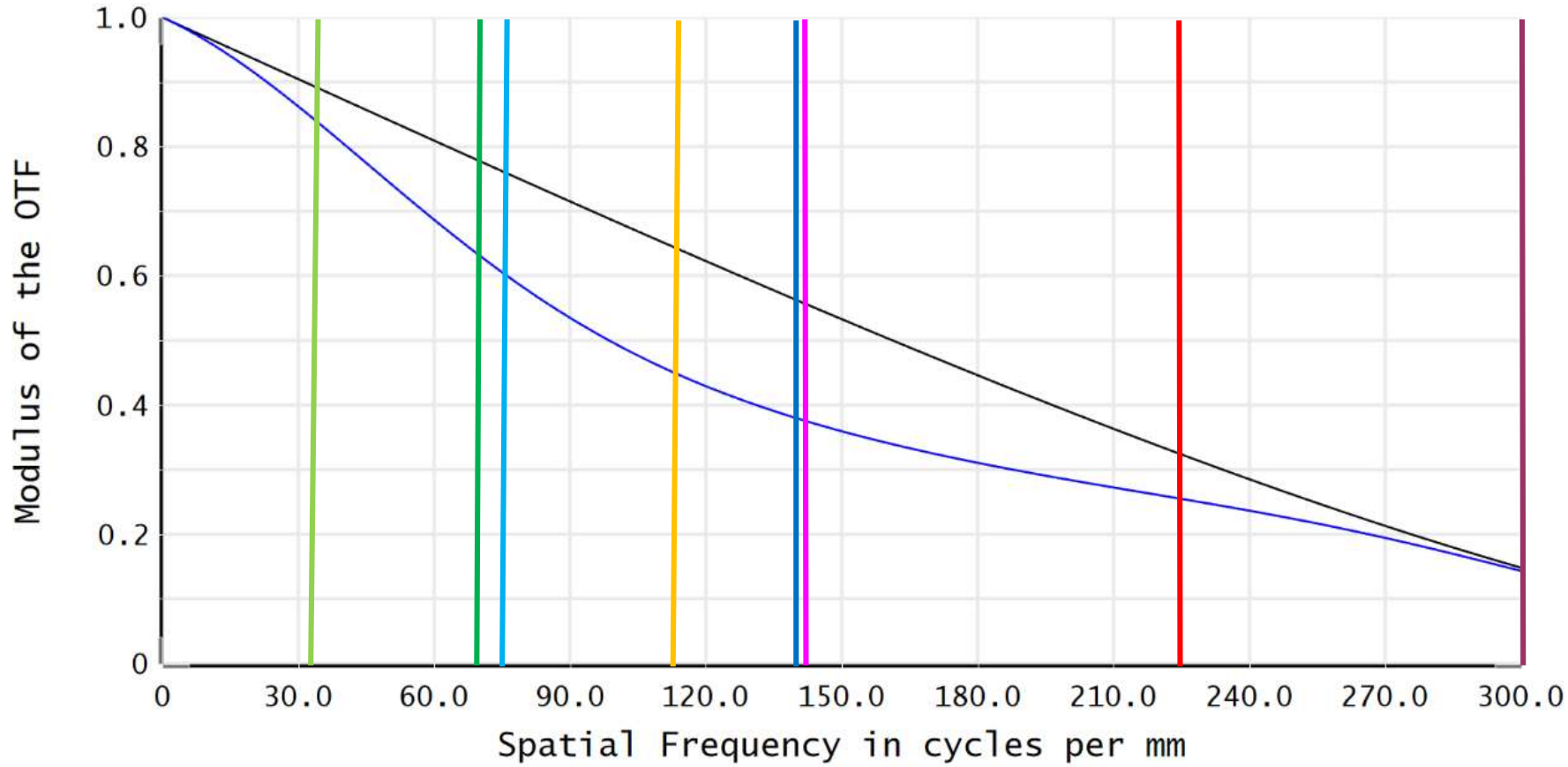
Real World Lens Performance

10 MP 1/2.3 Inch
1.67 micron pixel
300 lp/mm
150 lp/mm

5 MP 1/2.5 Inch
2.2 micron pixel
227 lp/mm
113 lp/mm

5 MP 2/3 Inch
3.45 micron pixel
145 lp/mm
72 lp/mm

4 MP 1.2 Inch
7.4 micron pixel
67 lp/mm
33 lp/mm

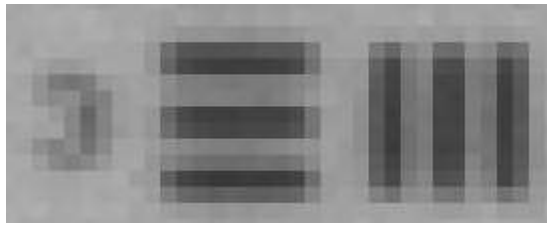


Analysis on 50mm fl. at f/4, 300mm working distance (mag 0.177X)
Waveband: RGB white LED

Real World Lens Performance

5 MP 1/2.5 Inch
2.2 micron pixel

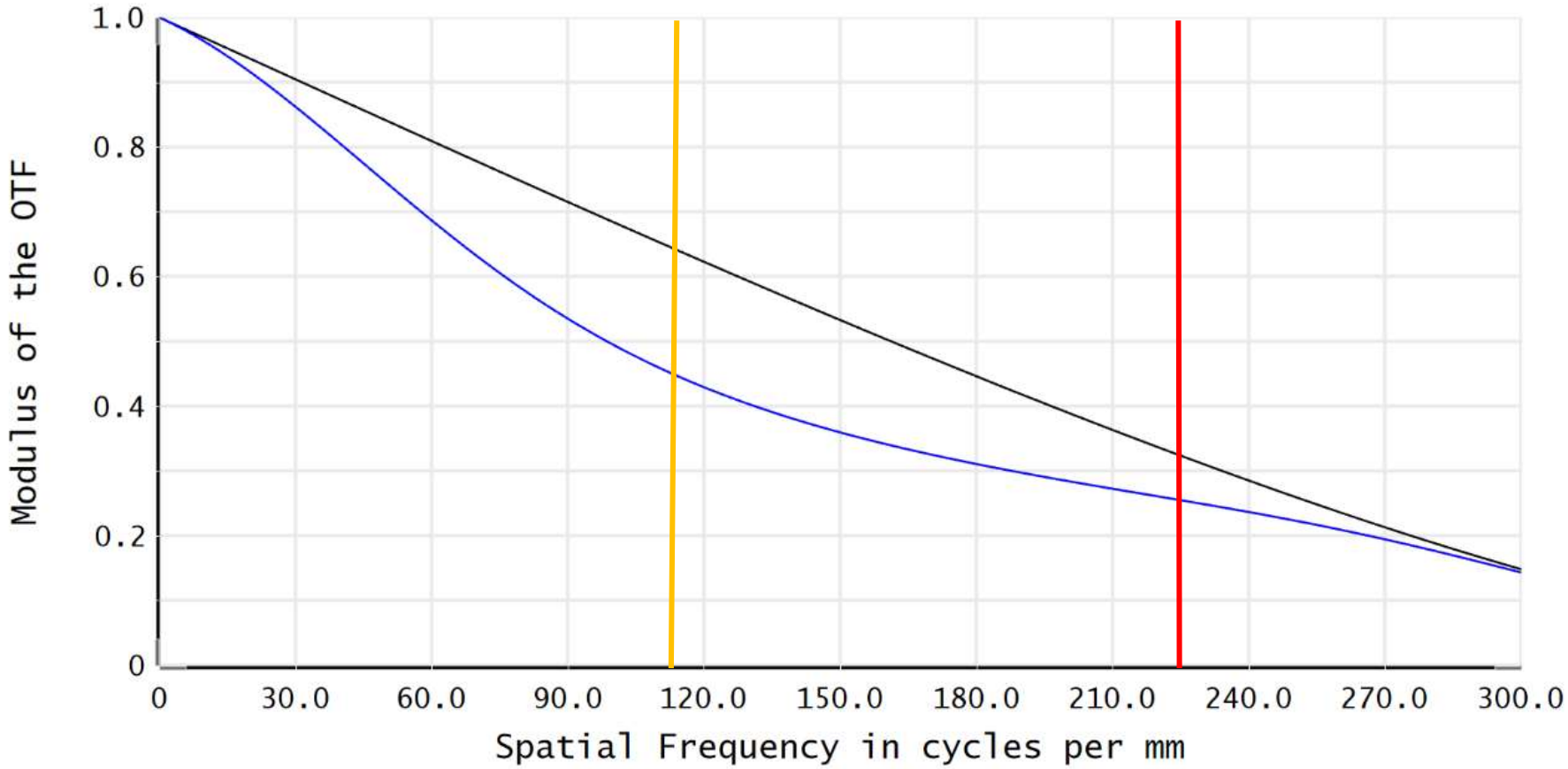
113 lp/mm



Contrast 24.8%

227 lp/mm

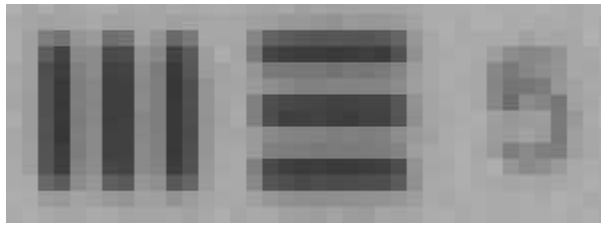
Contrast 8.8%



Real World Lens Performance

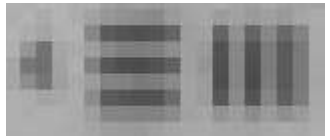
5 MP 2/3 Inch
3.45 micron pixel

72 lp/mm

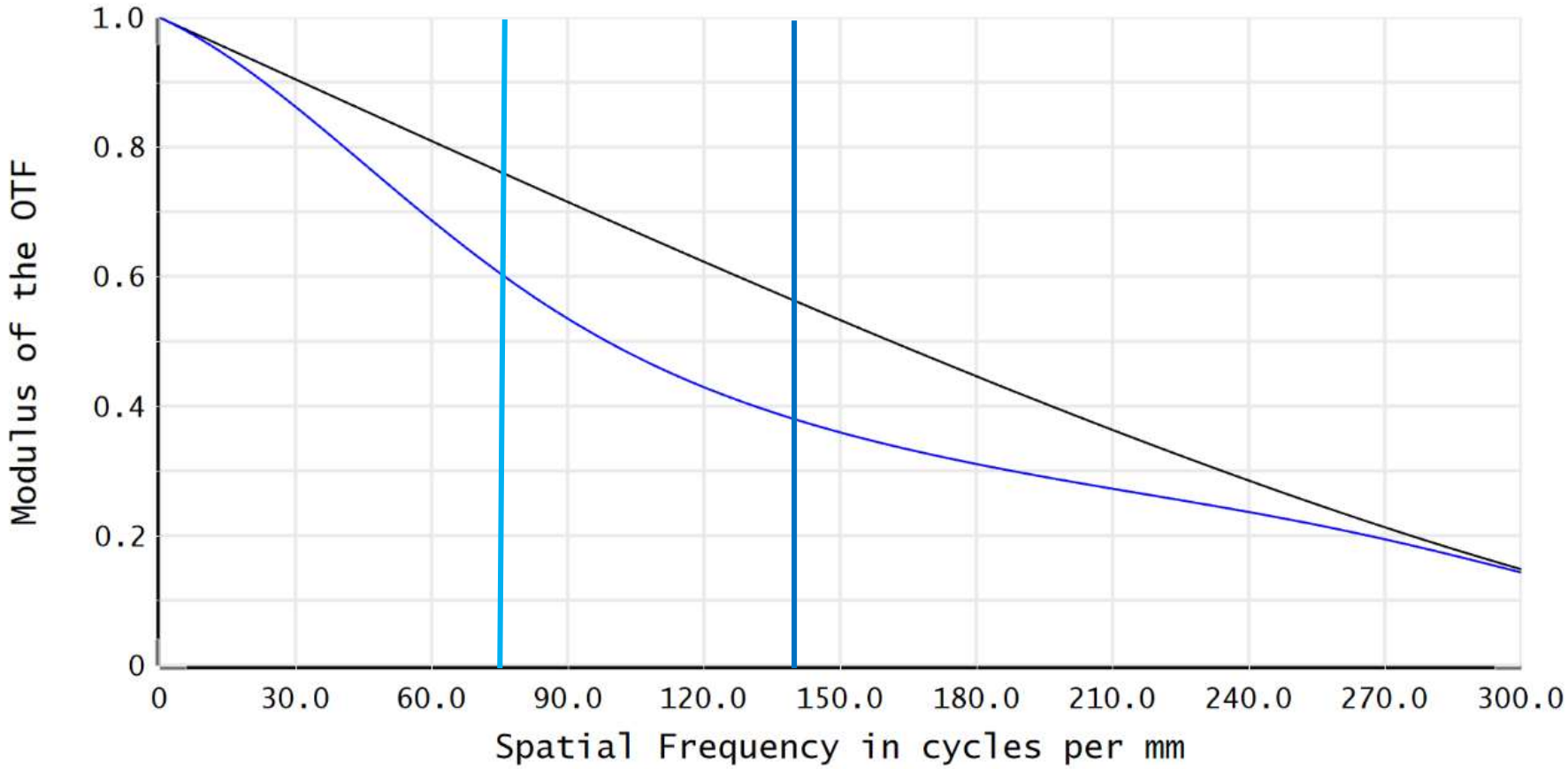


Contrast: 48%

145 lp/mm



Contrast: 24.6%



Real World Lens Performance

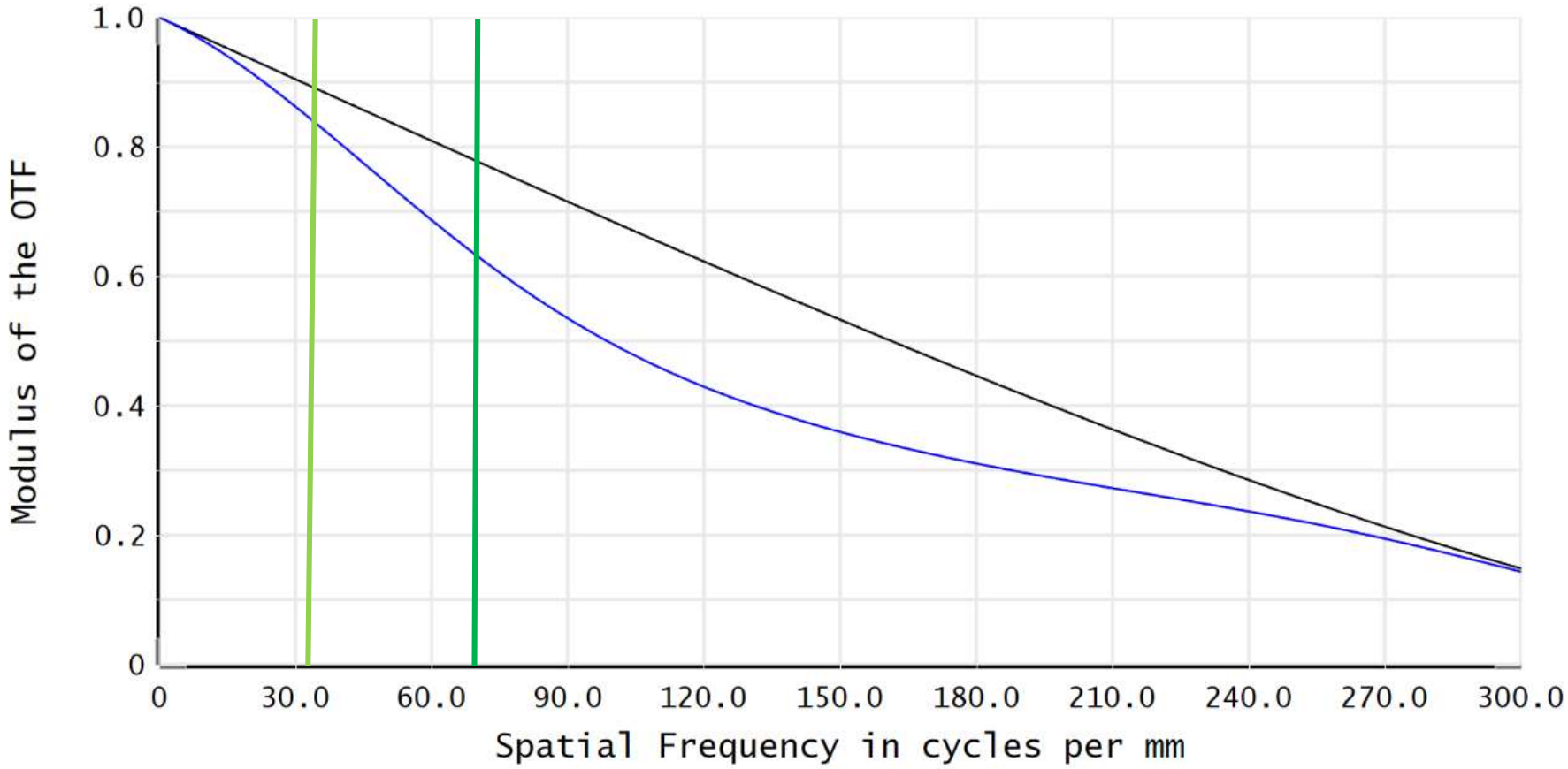
4 MP 1.2 Inch
7.4 micron pixel

33 lp/mm

Contrast: 55.3%

67 lp/mm

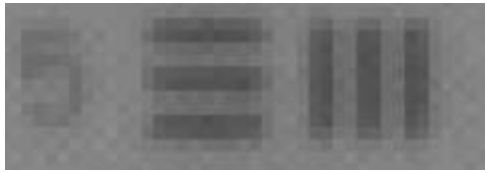
Contrast: 33.6%



Real World Lens Performance

10 MP 1/2.3 Inch
7.4 micron pixel

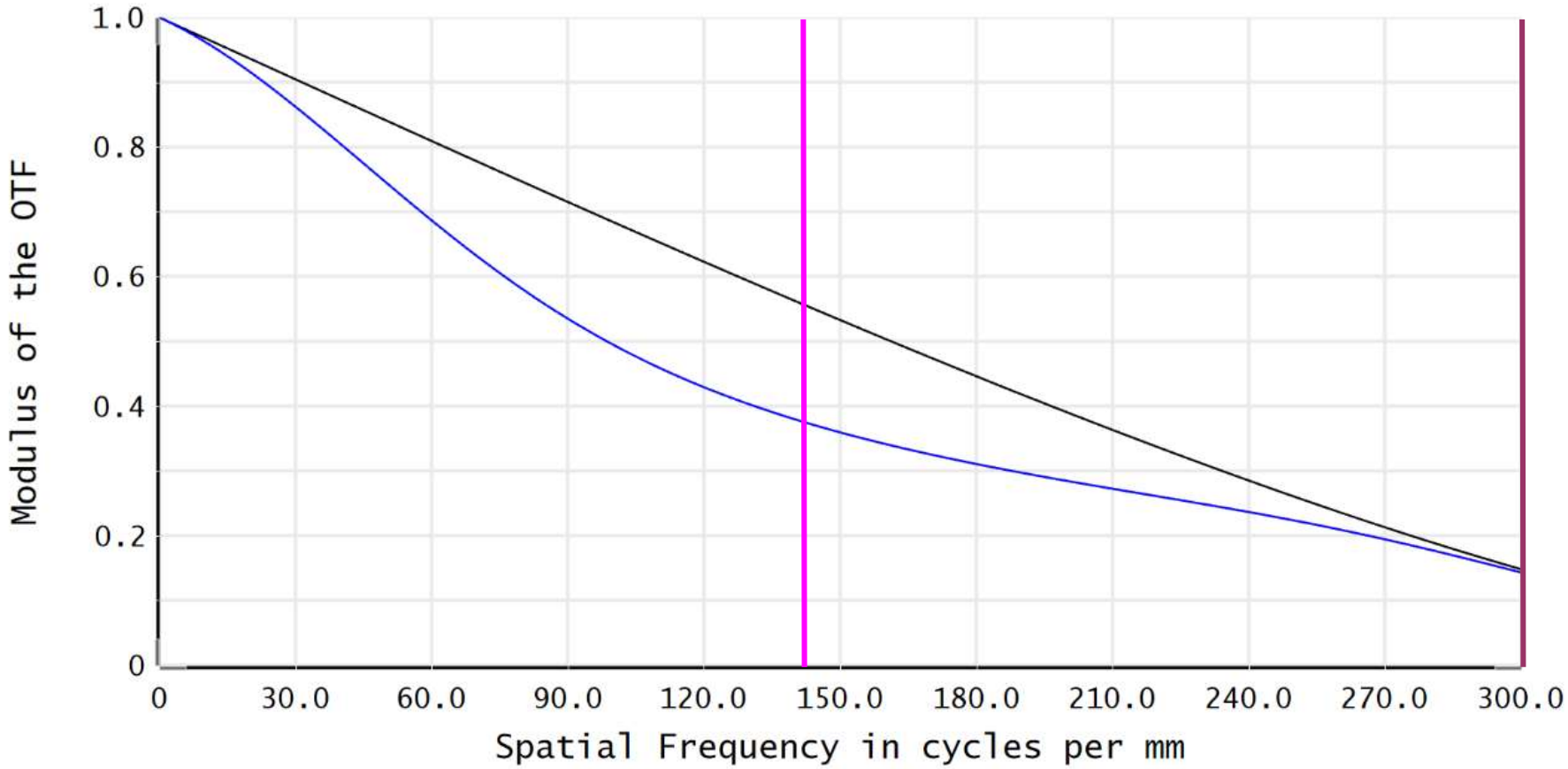
150 lp/mm



Contrast: 11.5%

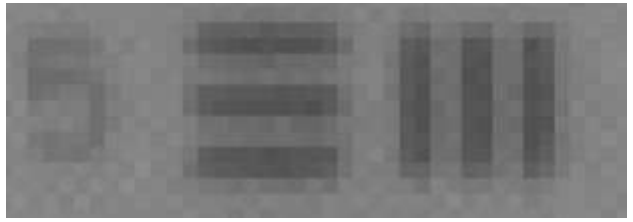
300 lp/mm

Contrast: 3.0%



Real World Lens Performance

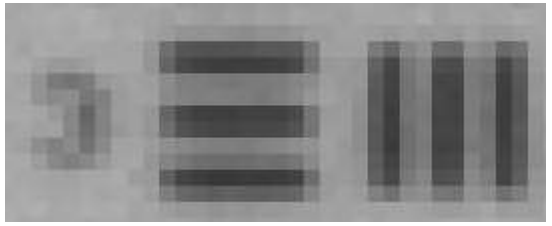
10 MP 1/2.3 Inch
1.67 micron pixel



11.5% Contrast

3.0% Contrast

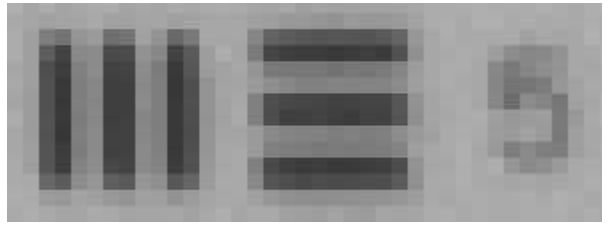
5 MP 1/2.5 Inch
2.2 micron pixel



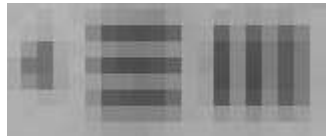
30.3% Contrast

8.8 % Contrast

5 MP 2/3 Inch
3.45 micron pixel

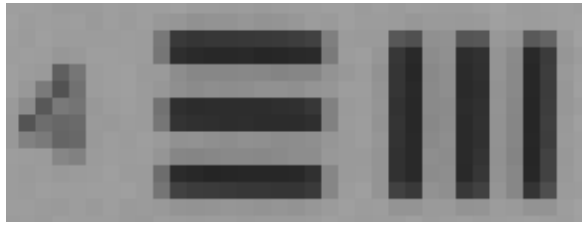


48.0% Contrast



24.6% Contrast

4 MP 1.2 Inch
7.4 micron pixel

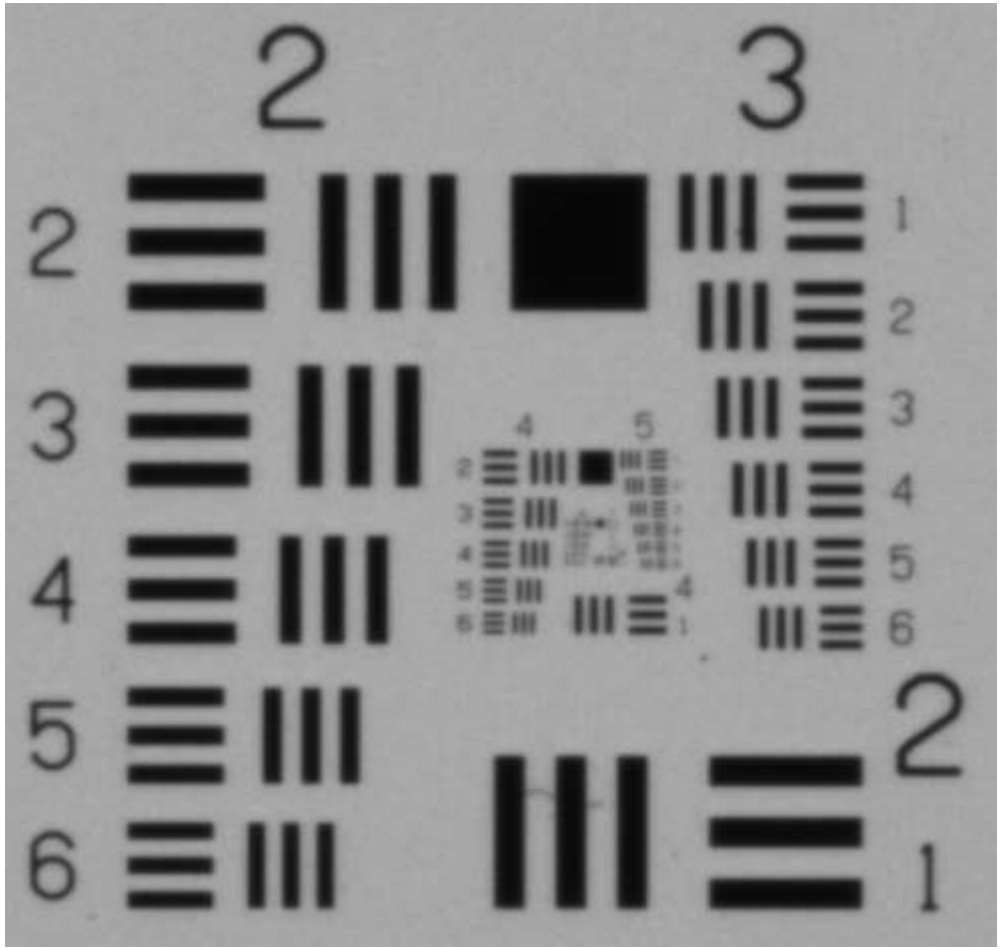


55.3% Contrast

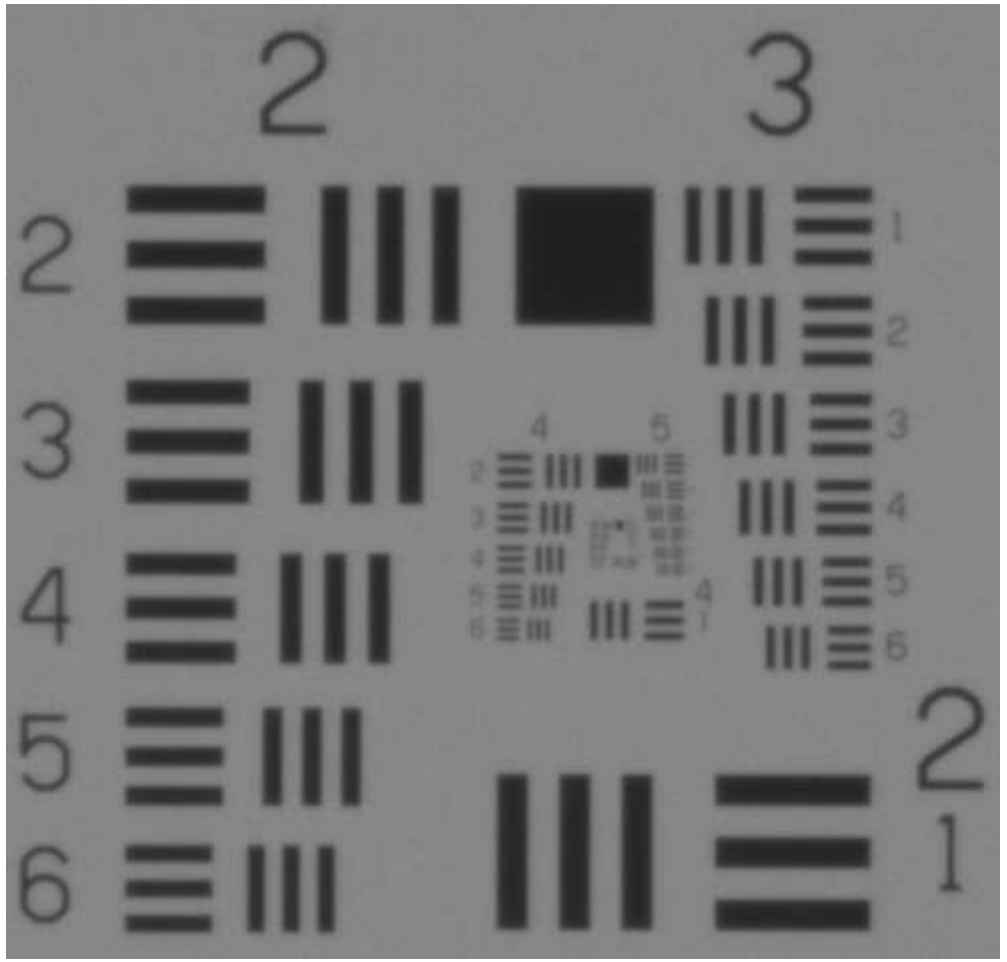
33.6% Contrast

Real World Performance

5 MP, 2.2 micron pixel



10 MP, 1.67 micron pixel

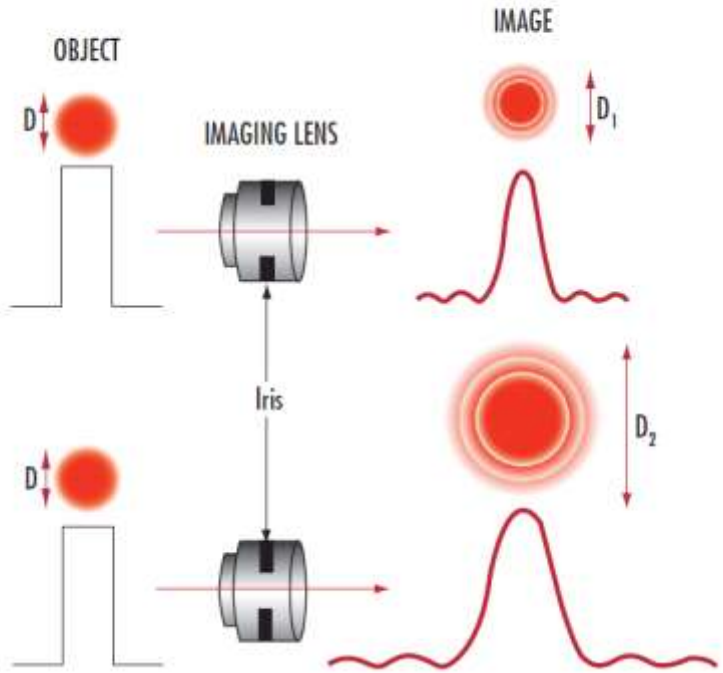


Impact of f/# on Performance

The smallest achievable spot of a lens = $2.44\lambda\left({}^{f}/_{\#}\right)_{W}$

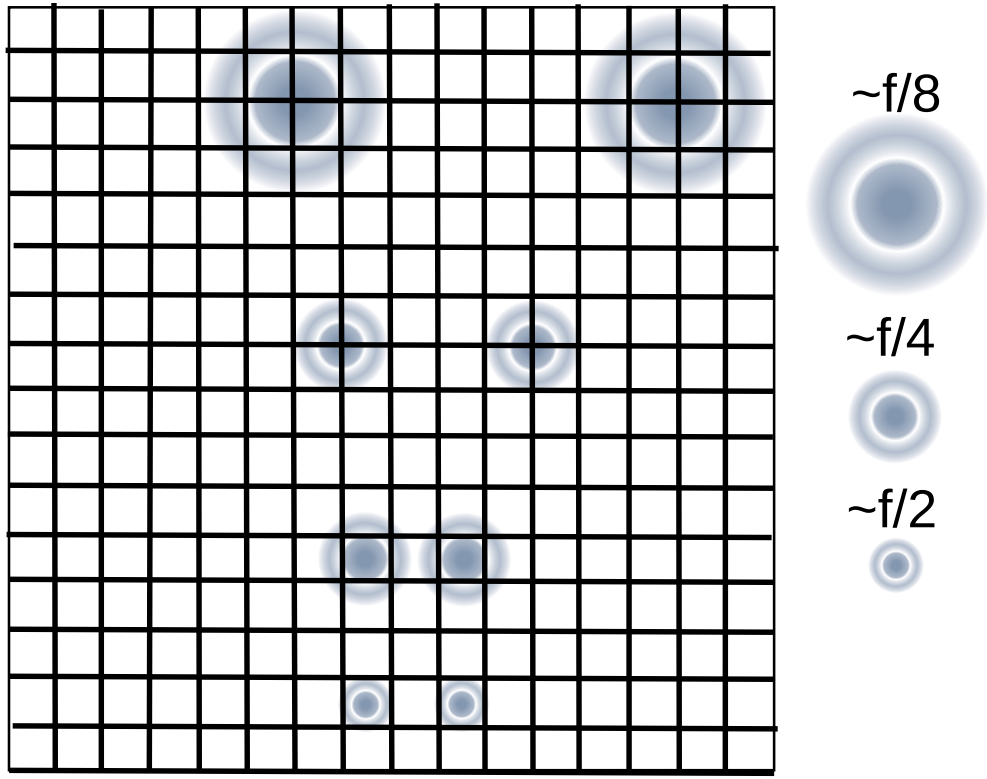
f/#	Lens Aperture Diameter (mm)	Aperture Opening Area (mm^2)
1	25.0	490.6
1.4	17.9	250.3
2	12.5	122.7
2.8	8.9	62.6
4	6.3	30.7
5.6	4.5	15.6
8	3.1	7.7

f/#	Airy Disk Diameter (μm) at a Wavelength of 520nm
1.4	1.78
2	2.54
2.8	3.55
4	5.08
5.6	7.11
8	10.15
11	13.96
16	20.30

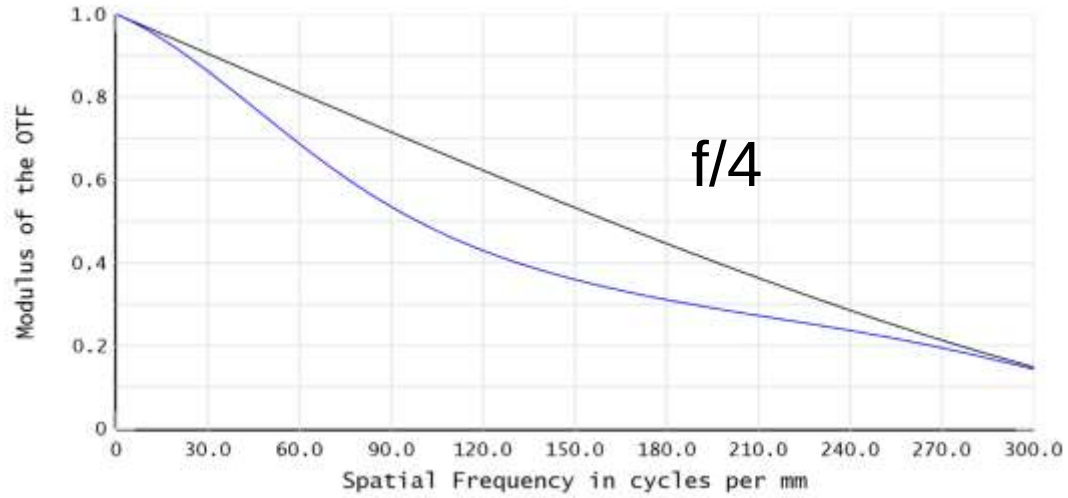


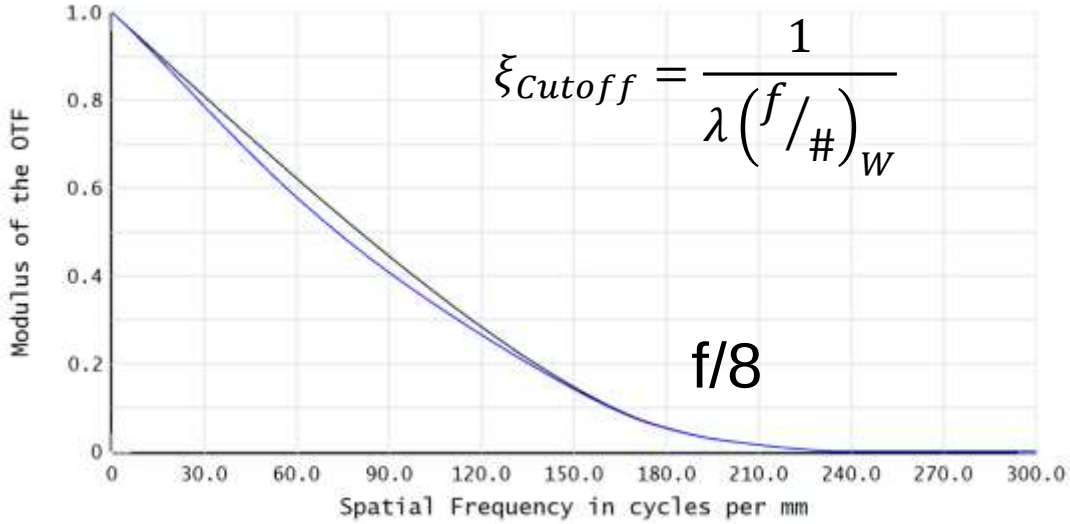
Impact of f/# on Performance

$$D = 2.44\lambda\left({}^{f}/_{\#}\right)_{W}$$



2.2 micron pixels

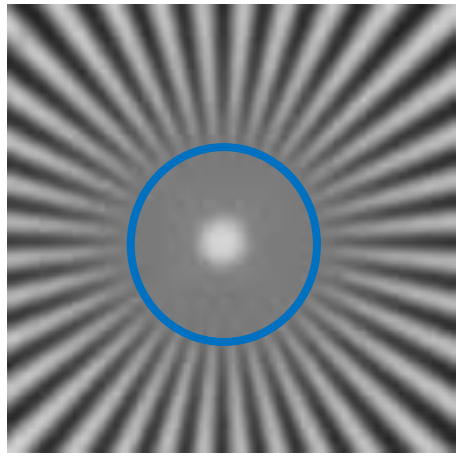




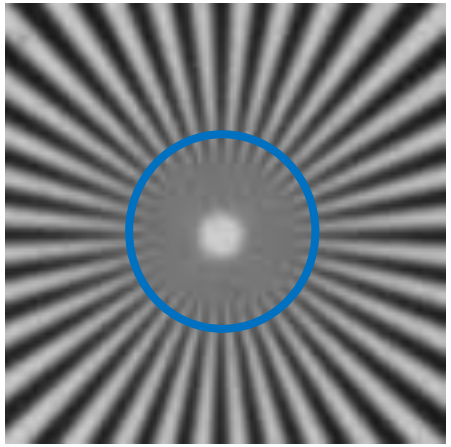
$$\xi_{Cutoff} = \frac{1}{\lambda\left({}^{f}/_{\#}\right)_{W}}$$

Impact of Wavelength on Performance

Color	Wavelength (nm)	Aperture (f/#)				
		f/1.4	f/2.8	f/4	f/8	f/16
NIR (Near-Infrared)	880	3.01	6.01	8.59	17.18	34.36
Red	660	2.25	4.51	6.44	12.88	25.77
Green	520	1.78	3.55	5.08	10.15	20.30
Blue	470	1.61	3.21	4.59	9.17	18.35
Violet	405	1.38	2.77	3.95	7.91	15.81

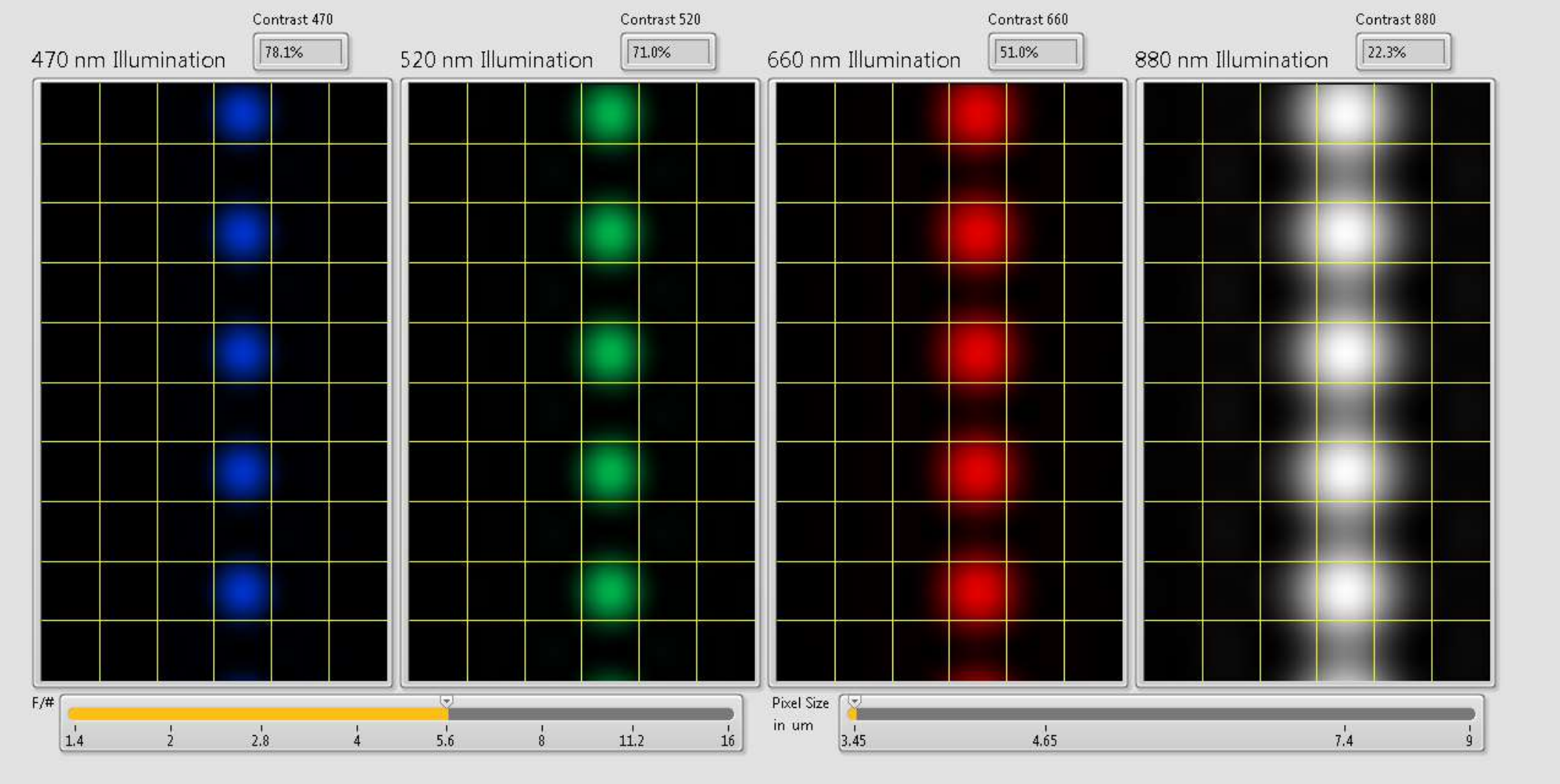


660nm Light

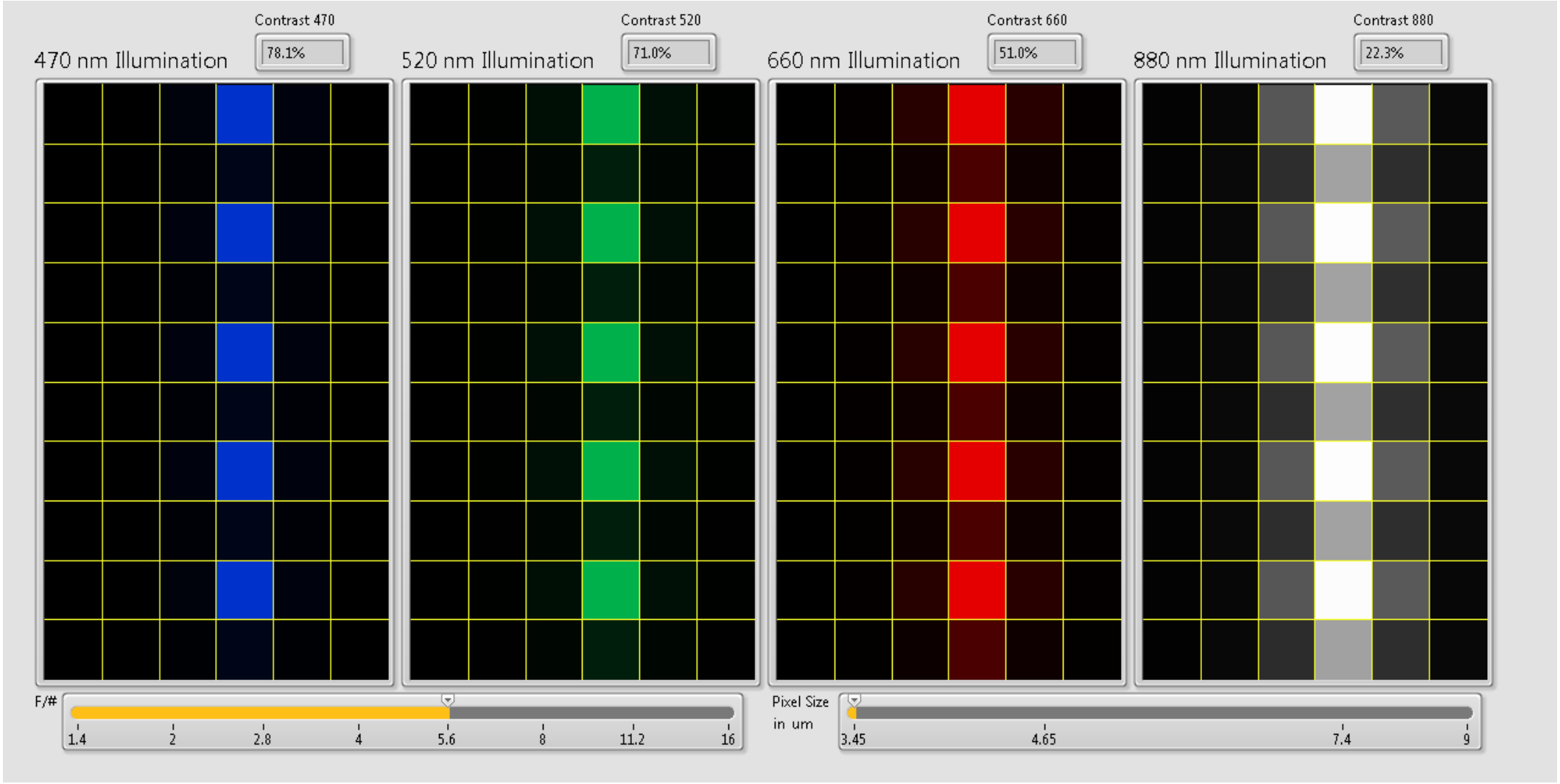


470nm Light

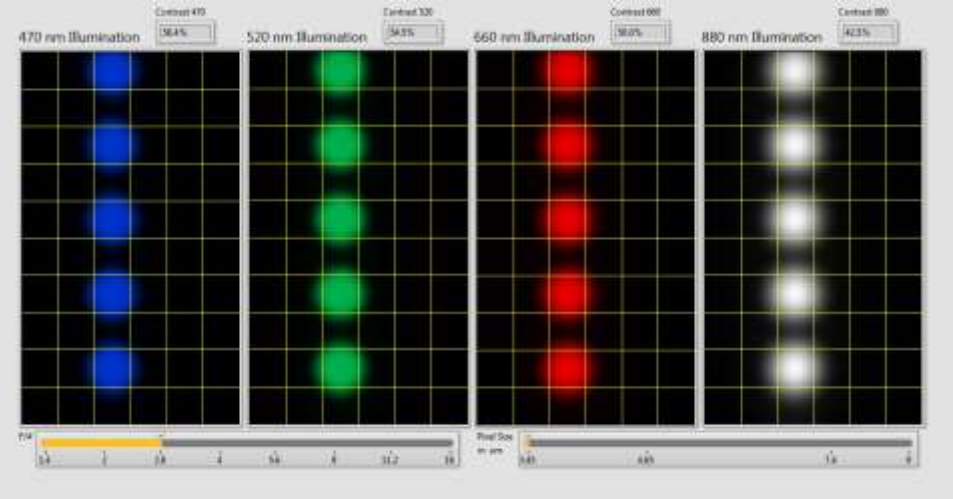
Impact of Wavelength on Performance

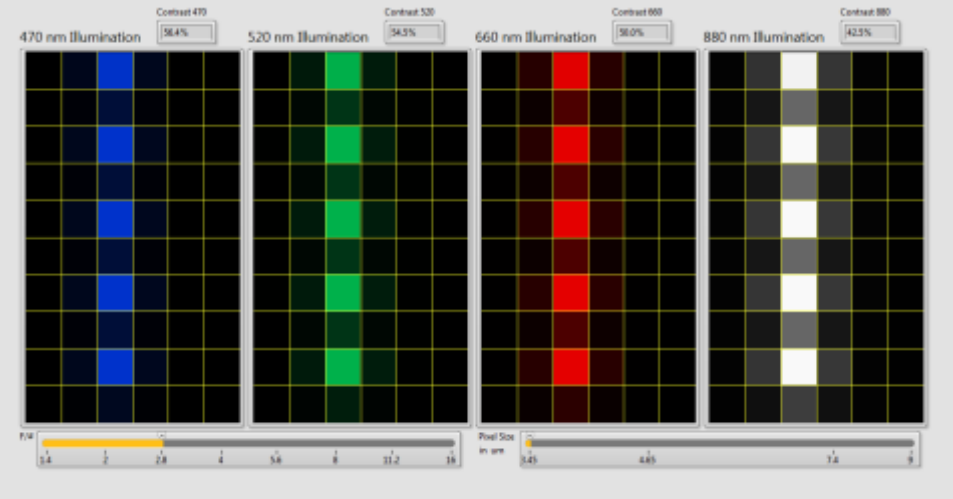


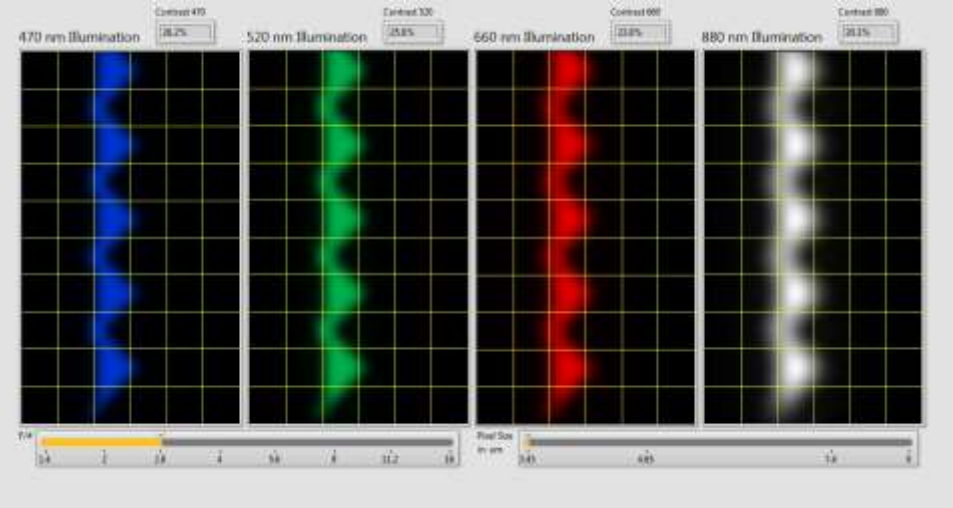
Impact of Wavelength on Performance

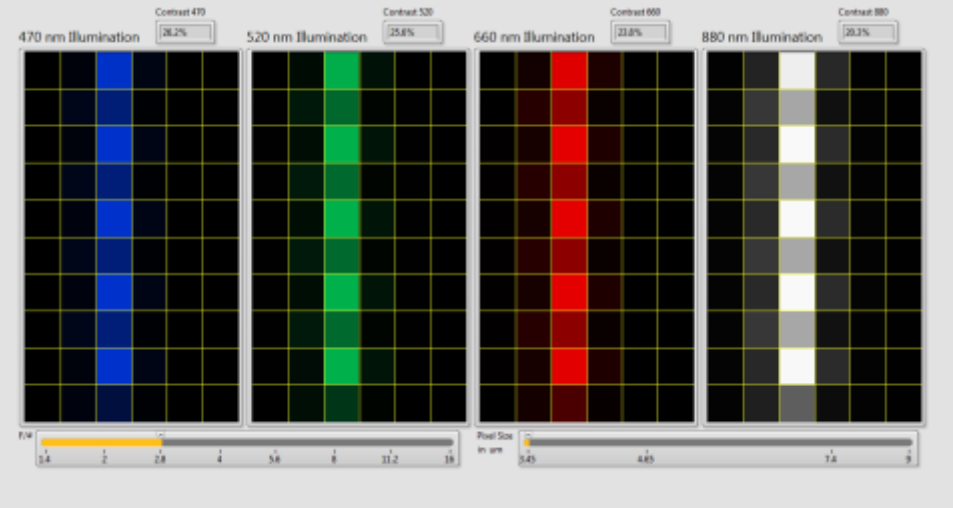


Wavelength and f/# Coupled

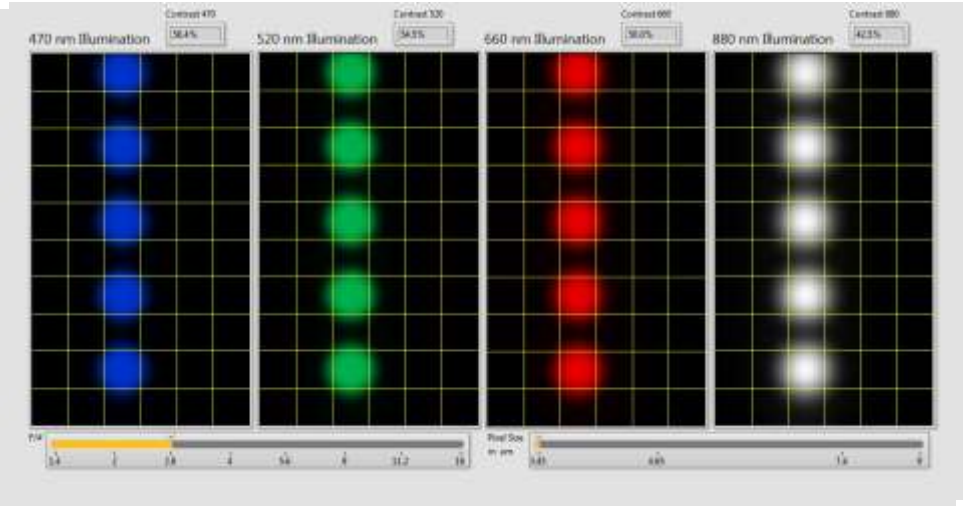


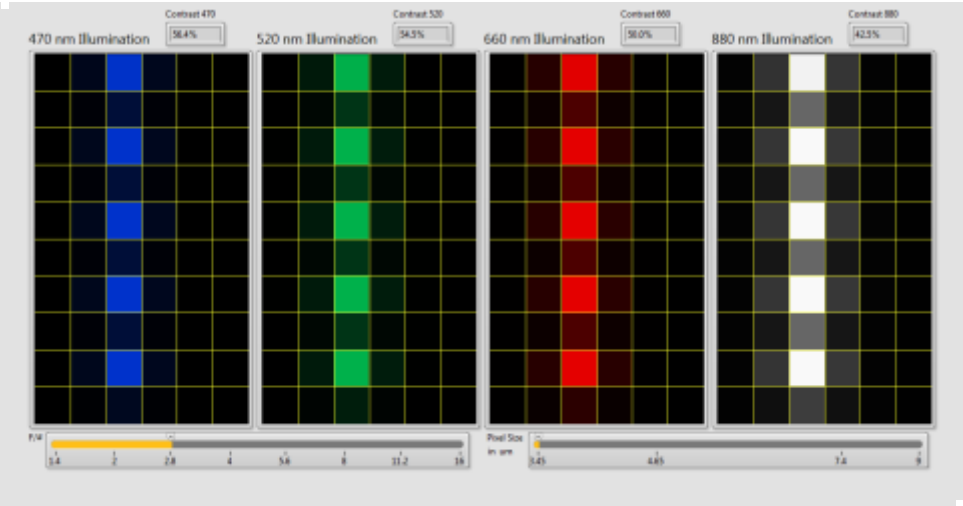


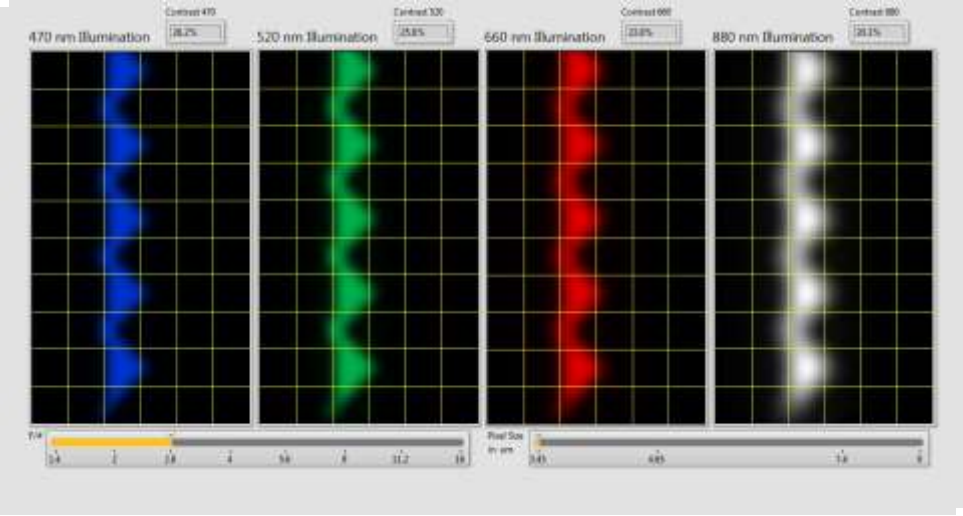


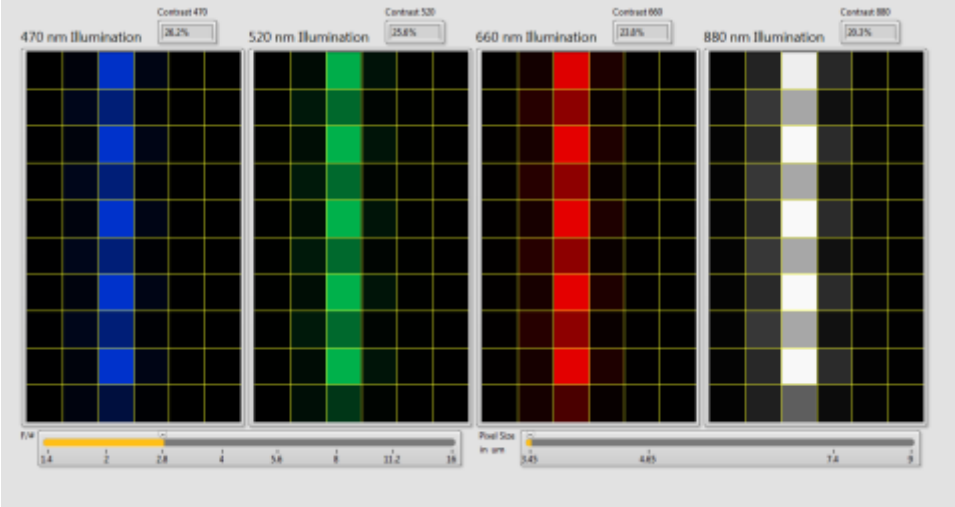


Wavelength and f/# Coupled

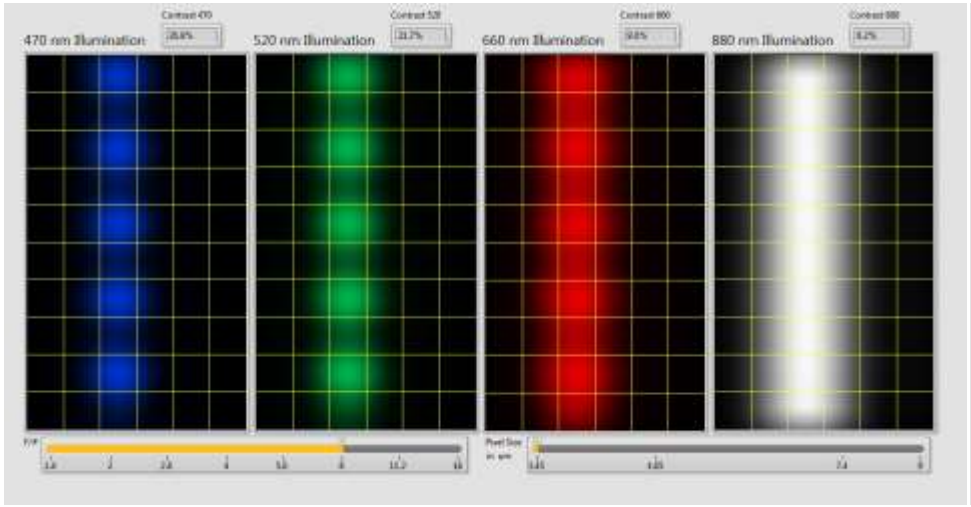


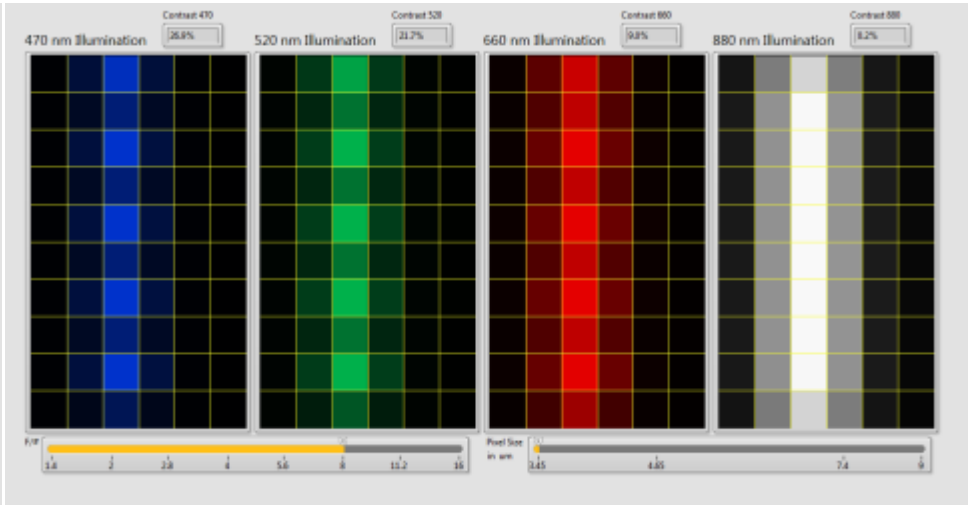


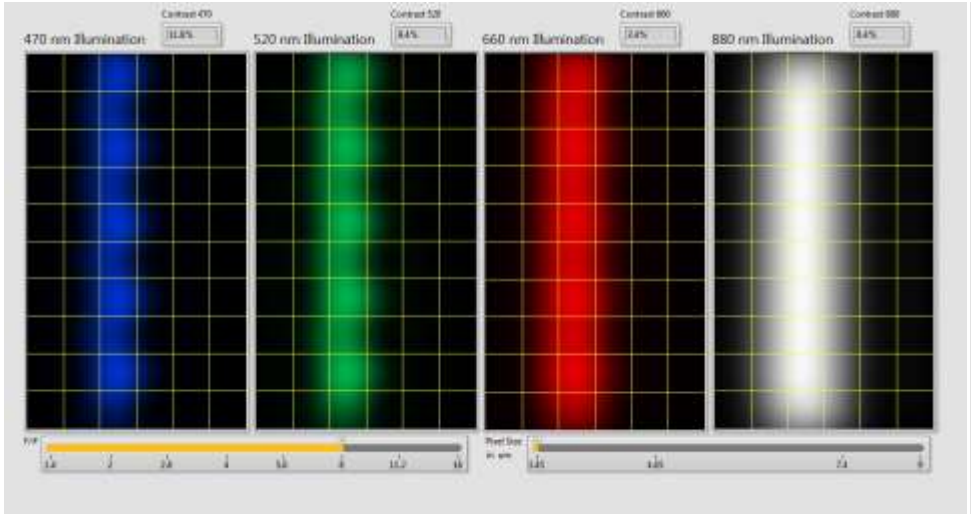


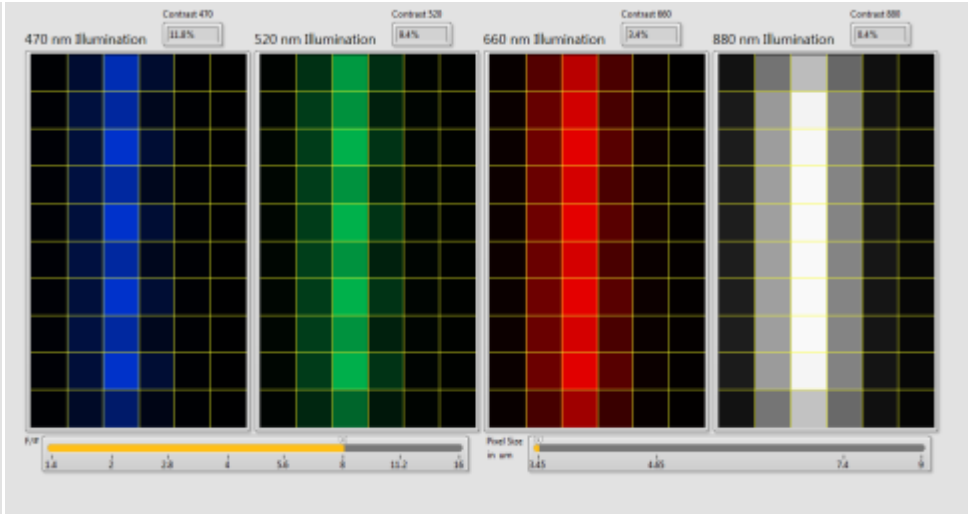


Wavelength and f/# Coupled

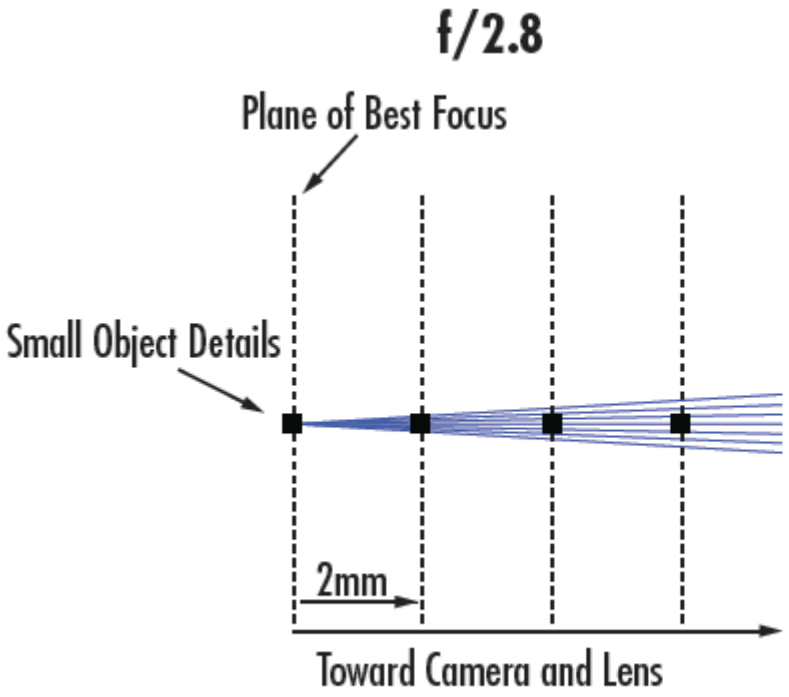


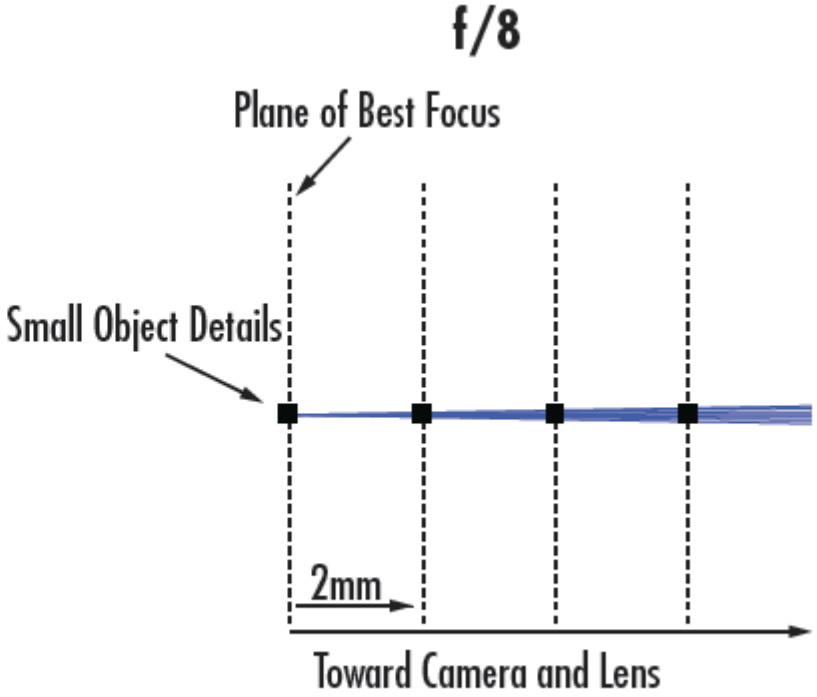




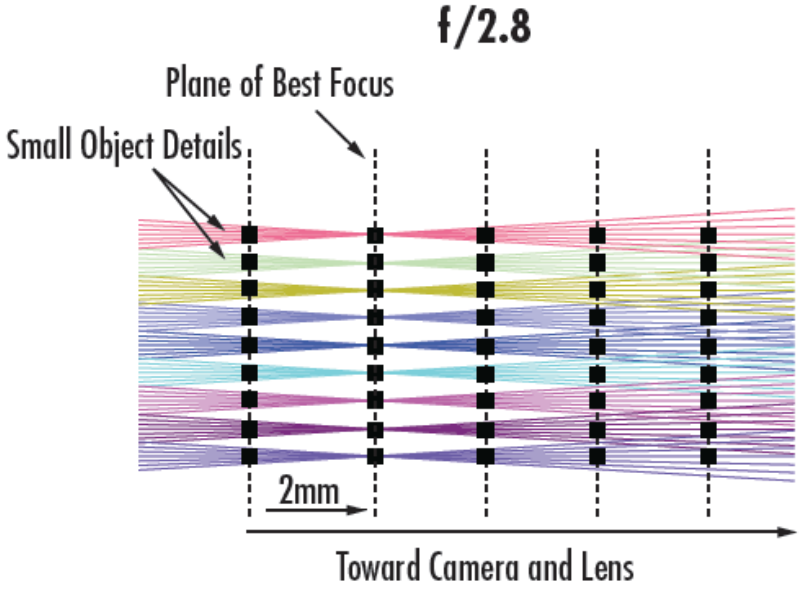


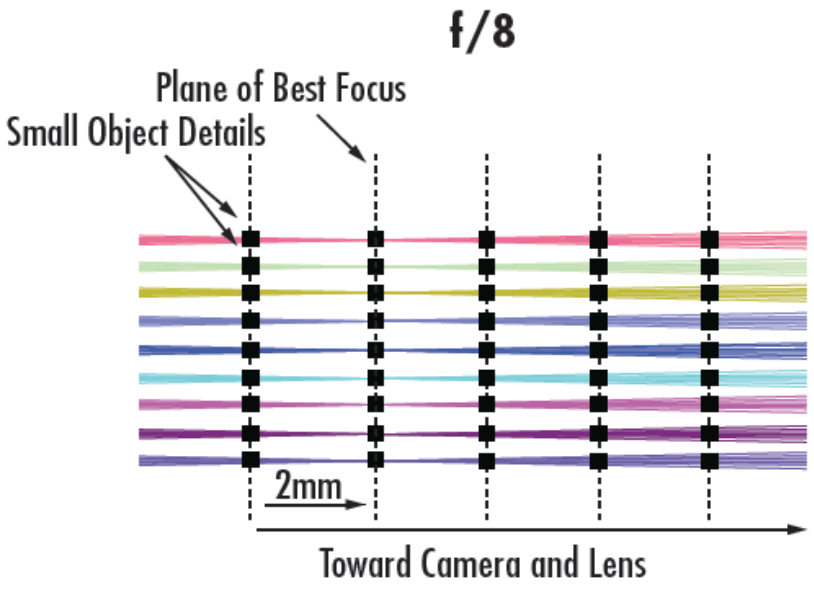
Resolution and DOF Compromise

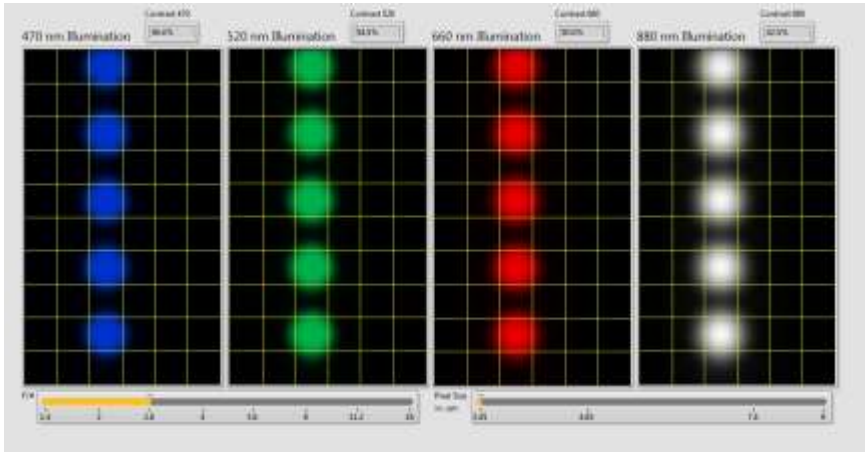


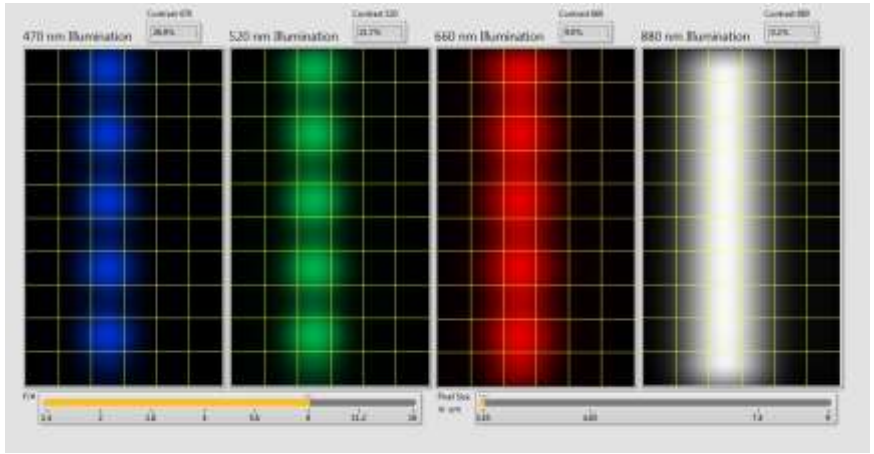


Resolution and DOF Compromise









Thank you for your time!

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