UNDERSTANDING LENS DESIGN LIMITATIONS

DIFFRACTION LIMIT

Every lens has an absolute upper performance limit dictated by the laws of physics. This limitation is controlled by the working f/# of the lens and the wavelength(s) of light that pass through the lens. Known as the **Diffraction Limit**, this limitation is given in line pairs/mm and determines the theoretical maximum resolving power of the lens. Even a perfect lens that is not limited by design will be diffraction limited. This limit is the point where two Airy patterns are no longer distinguishable from each other. To calculate the diffraction limit, a simple formula that relates it to the f/# of the lens and the wavelength of light can be used *(Equation 1). Learn more about f/# in our Imaging Optics Catalog.*

After the diffraction limit is reached, the lens becomes incapable of resolving greater frequencies. The diffraction limit detailed in *Table 1* shows contrast at 0% for given frequencies. These numbers may appear rather high, but are strictly theoretical – a number of other practical factors must also be considered. First, as a general rule, imaging sensors cannot reproduce information at or near 0% contrast. Due to inherent noise, contrast generally needs to be above 10% to be reliably detected on standard imaging sensors. To avoid imaging complications, it is recommended to target 20% contrast or higher at the application's critical lp/mm resolution. Additionally, lens aberrations and variations associated with manufacturing tolerances also reduce performance. **Modulation Transfer Function (MTF)** curves are used to determine whether a lens will effectively utilize a sensors capabilities and fulfill the desired application's requirements.

$$\text{Diffraction Limit} = \frac{1000\ \mu\text{m/mm}}{f/\#\ \text{x wavelength (in } \mu\text{m)}}$$

Equation 1

f/#	0% Contrast Limit (lp/mm) @ 0.520 µm
1.4	1374
2	962
2.8	687
4	481
5.6	343
8	240
11	175
16	120

Table 1: The diffraction limit calculated at different f/#s for 520 nm light (green light)

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MODULATION TRANSFER FUNCTION (MTF) AND MTF CURVES

MTF curves show resolution and contrast information simultaneously allowing a lens to be evaluated based on the requirements for a specific application and can be used to compare the performance of multiple lenses. Used correctly, MTF curves can help determine if an application is actually feasible.

Figure 1 is an example of an MTF curve for a 12 mm lens used on the Sony IXC 625 sensor, which has a sensor format of ⅔" and 3.45 μm pixels. The curve shows lens contrast over a frequency range from 0 lp/mm to 150 lp/mm (sensor's limiting resolution is 145 lp/mm). Additionally, this lens has its f/# set at 2.8 and is set at a PMAG of 0.05X, which yields a FOV of approximately 170 mm for 20X the horizontal dimensions of the sensor. This FOV/PMAG will be used for all examples in this section. White light is used for the simulated light source.

This curve provides a variety of information. The first thing to note is that the diffraction limit is represented by the black line. The black line indicates that the maximum theoretically possible contrast that can be achieved is almost 70% at the 150 lp/mm frequency, and that no lens design, no matter how good, can perform higher than this. Additionally, there are three colored lines: blue, green, and red. These lines correspond to how this lens performs across the sensor in the center (blue), the 0.7X position at 70% of the full field on the sensor (green), and the corner of the sensor (red), respectively. It is clearly shown that at lower and higher frequencies contrast reproduction is not the same across the entire sensor and, thus, not the same over the FOV.

Additionally, it can be seen that there are two green and two red lines. These lines represent the tangential and sagittal contrast components associated with detail reproduction that is not in the center of the FOV. Due to aberrational effects, a lens will produce spots that are not completely round and will therefore have different sizes in the horizontal and vertical orientation. This size variation leads to spots blending together more quickly in one direction than the other, and produces different contrast levels in different axes at the same frequency. It is very import to consider the implications of the lower of these two values when evaluating a lens for a given application. It is generally advantageous to maximize the contrast level across the entire sensor to gain the highest levels of performance in a system.

Figure 1

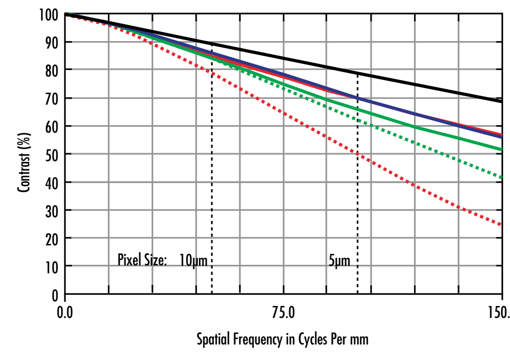

Figure 1: MTF curve for a 12 mm lens used on the Sony IXC 625 sensor

COMPARING LENS DESIGNS AND CONFIGURATIONS

Example 1: Comparison of two different lens designs with the same focal length (fl), 12 mm, at f/2.8

Figure 2 examines two different lenses of the same focal length that have the same FOV, sensor, and f/#. These lenses will produce systems that are the same size but differ in performance. In analysis, the horizontal light blue line at 30% contrast on *Figure 2a* demonstrates that at least 30% contrast is achievable essentially everywhere within the FOV, which will allow for the entire capability of the sensor to be well-utilized. For *Figure 2b*, nearly half the field is below 30% contrast. This means that better image quality will only be achievable at half of the sensor. Also to note, the orange box on both curves represents the intercept frequency of the lower performance lens in *Figure 2b* with 70% contrast. When that same box is placed on *Figure 2a*, tremendous performance difference can be seen even at lower frequencies between the two lenses.

The difference between these lenses is the cost associated with overcoming both design constraints and fabrication variations; *Figure 2a* is associated with a much more complex design and tighter manufacturing tolerances. *Figure 2a* will excel in both lower resolution and demanding resolution applications where relatively short working distances for larger field of view are required. *Figure 2b* will work best where more pixels are needed to enhance the fidelity of image processing algorithms and where lower cost is required. Both lenses have situations where they are the correct choice, depending on the application.

Figure 2a

Figure 2b

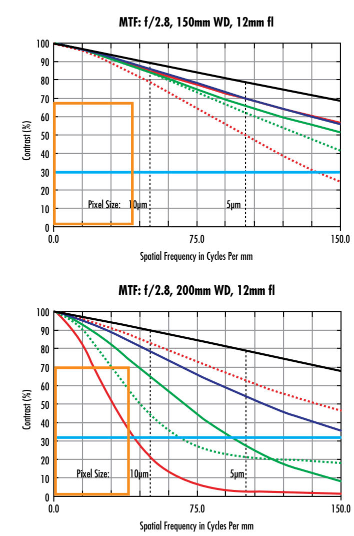

Figure 2: MTF curves for two lens designs (a and b) with the same focal length, f/#, and system parameters

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Example 2: Two different high resolution lens designs with different focal lengths: 12 mm and 16 mm at f/2.8

Figure 3 examines two different high resolution lenses with focal lengths of 12 mm and 16 mm that have the same FOV, sensor, and f/#. By looking at the lens's contrast at the Nyquist limit of *Figure 3b* (light blue line), a distinct performance increase can be seen when compared to *Figure 3a*. While the absolute difference is only about 10 - 12% contrast, the relative difference is closer to 33% considering the change from approximately 30% contrast to 42%. Another orange box has been placed on this graph, this time where *Figure 3a* hits 70% contrast. Note that the difference at this level is not as extreme as in the previous example. The tradeoff between these lenses is that the working distance for the lens in *Figure 3b* has an increase of about 33% but with a decent increase in performance. *This follows the general guidelines outlined in our Imaging Optics Catalog.*

Figure 3a

Figure 3b

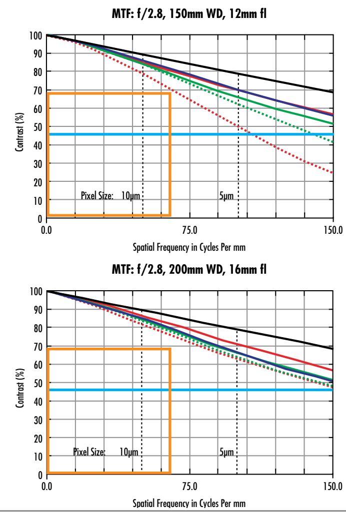


Figure 3:
Two different high resolution lens designs with different focal lengths at the same f/# and system parameters

Example 3: Comparison of MTF for different f/#s of the same 35 mm lens design

Figure 4 features the MTF for a 35 mm lens design using white light at f/4 *(a)* and f/2 *(b)*. The yellow line shows the diffraction-limited contrast at the Nyquist limit for *Figure 4a* on both graphs while the blue line denotes the lowest actual performance at the Nyquist limit of the same lens at f/4 in *Figure 4a*. While the theoretical limit of *Figure 4b* is far higher, the performance is much lower. This is an example of how a higher f/# can reduce the aberrational effects, greatly increasing performance of a lens, even though the theoretical performance limit is greatly reduced. The primary tradeoff besides resoultion is less light throughput at the higher f/#.

Figure 4a

Figure 4b

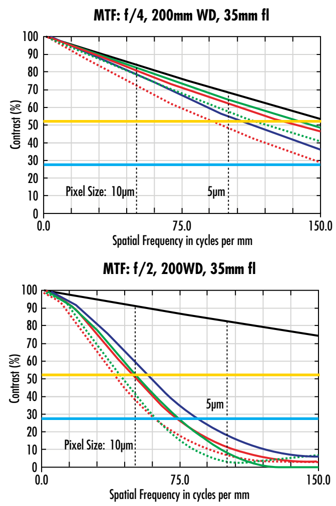


Figure 4:
MTF curves for a 35 mm lens at the same WD and different f/#s: f/4 (a) and f/2 (b)

Example 4: The Effect of Changing Working Distance on MTF

For *Figure 5*, working distances of 200 mm *(a)* and 450 mm *(b)* are examined for the same 35 mm lens design at f/2. A large performance difference can be seen, which is directly related to the ability to balance aberrational content in lens design over a range of working distances. Changing working distance, even with refocusing, will lead to variations or reductions in performance as the lens moves away from its designed range. These effects are most profound at lower f/#s. *More details on these effects can be found in our Imaging Optics Catalog.*

Figure 5a

Figure 5b

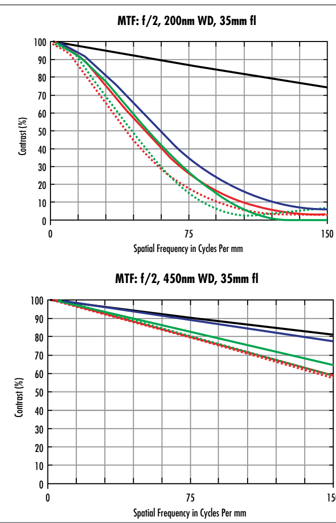
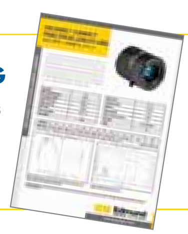


Figure 5:
MTF curves for a 35 mm focal length lens at f/2 with different working distances

Visit **WWW.EDMUNDOPTICS.EU/IMAGING** to **download comprehensive datasheets** for all TECHSPEC® imaging lenses which feature these MTF curves.



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WAVELENGTH EFFECTS ON PERFORMANCE

Different wavelengths bend at different angles as light passes through a medium (glass, water, air, etc.). This is commonly observed when sunlight passes through a prism and creates a rainbow effect; shorter wavelengths are bent more than longer ones. This same effect creates problems when trying to resolve details and gain information in imaging systems. To avoid this issue, imaging and machine vision systems commonly use monochromatic illumination, which involves only single wavelengths or narrow bands of the spectrum. Monochromatic illumination, e.g. from a 660 nm LED, practically eliminates what are known as chromatic aberrations in an imaging system.

Chromatic Aberrations

Chromatic aberrations exist in two fundamental forms: lateral color shift *(Figure 6)* and chromatic focal shift *(Figure 7)*.

Figure 6

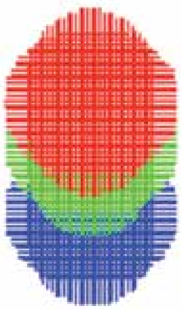

Figure 6: Lateral Color Shift

Lateral color shift, *Figure 6*, can be seen as you move from the center of the image towards the edge of the image. In the center, the spots for different wavelengths of light are concentric. Moving towards the corner of the image, wavelengths tend to separate and produce a rainbow effect. As a result of this color separation, a given point on the object is imaged over a larger area, resulting in reduced contrast. On sensors with smaller pixels, this result is even more pronounced, as the blurring spreads over more pixels. *In depth details on lateral color can be found in our Imaging Optics Catalog.*

Chromatic focal shift, *Figure 7*, relates to the ability of a lens to focus all wavelengths at the same distance away from the lens. Different wavelengths will have different planes of best focus. This shift in focus with respect to wavelength results in reduced contrast, since the different wavelengths create different size spots at the image plane where the camera sensor is located. In the image plane of *Figure 7* a small spot size in the red wavelengths, a larger spot size in green, and the largest spot size in blue is shown. Not all colors will be in focus all at once. *Advanced details can be found in our Imaging Optics Catalog.*

Figure 7

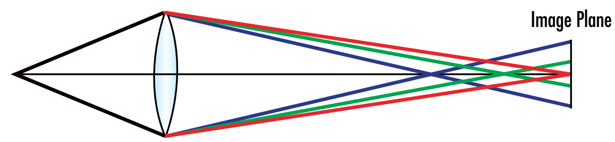

Figure 7: Chromatic Focal Shift

Choosing the Optimal Wavelength

Monochromatic illumination enhances contrast by eliminating both chromatic focal shift and lateral chromatic aberration. It is readily available in the form of LED illumination, lasers, and through the use of filters. However, different wavelengths can have different MTF effects in a system. The diffraction limit defines the smallest theoretical spot which can be created by a perfect lens, as defined by the Airy Disk diameter, which has a wavelength (λ) dependence. *See our Imaging Optics Catalog for more details on the Airy Disk and diffraction limit.* Using the *Equation 2*, one can analyze the change in spot size for both different wavelengths and different f/#s.

$$\text{Minimum spot size (Airy Disk diameter) in } \mu m = 2.44 \times \lambda\ (\mu m) \times f/\#$$

Equation 2

Table 2 features the calculated Airy disk diameter for wavelengths ranging from Violet (405 nm) to Near-Infrared (880 nm) at various f/#s. This data clearly shows that lens systems have better theoretical resolution and performance when they are utilized with shorter wavelengths. The benefits to understanding this are multi-fold. First, shorter wavelengths allow for better utilization of the sensor's pixels regardless of size due to the smaller achievable spot size. This is especially pronounced on sensors with very small pixels. Second, it allows for more flexibility to use higher f/#s, which will allow for greater depth of field. For example, a red LED could be used at f/2.8 to generate a spot size of 4.51 μm or a blue LED could be used to generate almost the same spot size at f/4. If both options yield acceptable levels of performance at best focus, the system set at f/4 using blue light will produce better depth of field, which could be a critical requirement. *Advanced details may be found in our Imaging Optics Catalog.*

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

Table 2: Theoretical Airy Disk diameter spot size (in μm) for various wavelengths and f/#s

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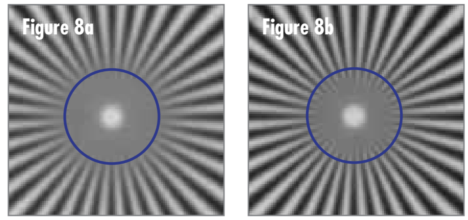
Example 1: Improvement with Wavelength

Both images in *Figure 8* are taken with the same lenses and camera producing the same field of view, thus presenting the same spatial resolution on the object in lp/mm. The camera utilizes 3.45 μm pixels. The illumination used in *Figure 8a* is set at 660 nm and *Figure 8b* at 470 nm. The high resolution lens was set to higher f/# to greatly reduce any aberrational effects. This allows diffraction to be the primary limitation in the system. The blue circles are representative of the limiting resolution at in *Figure 8a*. Note that *Figure 8b* has a significant increase in resolvable detail (approximately 50% finer detail). Even at the lower frequencies (wider lines), there is a higher level of contrast with 470 nm illumination in *Figure 8b*.



Each image is from the center of the field of view of a multi element star target. The elements of a star target allow for the visualization of changing resolution produced by a lens and camera system in all directions. Higher resolutions are observed closer to the center of the star where the lines become narrower, producing higher frequencies.

Figure 8: Images of a star target taken with the same lens, at the same f/#, with the same sensor. The wavelength is varied from 660 nm *(a)* to 470 nm *(b)*

Example 2: White Light vs. Monochromatic MTF

In *Figure 9*, the same lens is used at the same working distance and f/#. *Figure 9a* is using white light, and *Figure 9b* is using 470 nm illumination. In *Figure 3.9a*, all of the performance is at 50% or below at the Nyquist limit. For *Figure 9b*, all of the performance at the Nyquist limit is higher than *Figure 9a*. Additionally, performance in the center of the system in *Figure 9b* is above the diffraction limit of *Figure 9a*. The reason for this increase in performance is twofold: using monochromatic light eliminates chromatic aberrations in the system which generally allows for much smaller spots to be created, and 470 nm illumination is one of the shortest wavelengths of light that is used in visible range imaging. As detailed in the sections on diffraction limit and Airy Disk, shorter wavelengths allow for higher levels of resolution.

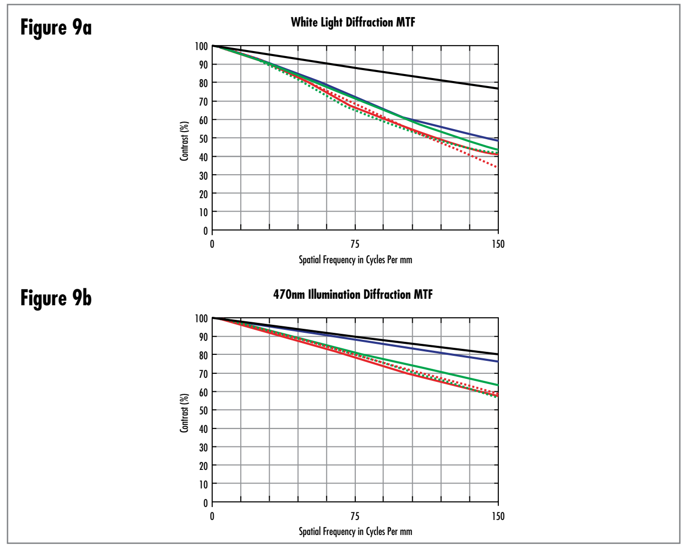


Figure 9: MTF curves for the same lens at f/2 using a different wavelengths; white light *(a)* and 470 nm *(b)*

Wavelength Considerations

A few issues can arise with changing wavelength that need to be understood. From a lens design perspective, the further into the blue portion of the spectrum, as wavelengths become shorter, the more a lens design can struggle regardless of how narrow the waveband that is used. Essentially, glass materials tend to not perform well at shorter wavelengths. Designs do exist in this region of the spectrum, but they are often limited in their capabilities, and the exotic materials that may be required to build the lens can be costly. The best theoretical performance seen in *Table 2* is at the violet wavelength of 405 nm, but most system designs cannot perform well in this area. It's very important to evaluate what a lens can realistically do at such short wavelengths using lens performance curves.

Example 3: Theoretical Limitations

Figure 10 compares a 35 mm lens at f/2 with blue (470 nm) and violet (405 nm) wavelengths *(10a and 10b respectively)*. While *Figure 10a* has a lower diffraction limit, it also shows that the 470 nm wavelength yields higher performance at all field positions. The effect here is increased when the lens is used at the extremes of its design capabilities for f/# and WD *(detailed in our Imaging Optics Catalog)*.

Another wavelength issue that can greatly affect performance is related to chromatic focal shift. As the application's wavelength range increases, the lens's ability to maintain high levels of performance will be compromised. *More details on the phenomenon in our Imaging Optics Catalog.*

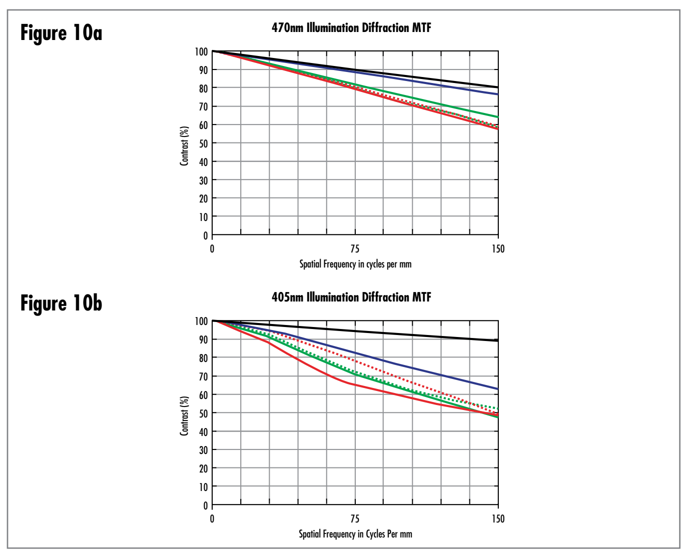


Figure 10: MTF curves for a 35 mm lens at f/2 with 470 nm *(a)* and 405 nm *(b)* wavelength illumination

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