Optical Performance of Nikon F-Mount Lenses

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2.671 Measurement and Instrumentation

Abstract

In photographic systems, lenses are one of the most important pieces of the system towards determining whole-system performance. Recently, lens resolution has been superseded by sensor resolution as Moore's law drives the transistors and pixels smaller and smaller, making lens resolution the limiting factor as modern photographic lenses struggle to resolve the 5 m pixels of modern sensors. Lens performance is typically not reported in enough detail - notably, most lens data does not include data for multiple apertures, but aperture can have a huge effect on lens resolution. In order to study lens performance, a specialized super-resolution sensor was used to directly measure lens's optical characteristics by resolving the step function of the lens and deriving the transfer function. So far, lens performance has been ascertained for one lens and matches published values, while also providing a far more complete view of the lens' performance characteristics through a full transfer function determination at every aperture, showing that this novel method can be applied successfully towards lens performance testing.

1 Introduction

Lens performance is not perfect - lens designers need to make choices when considering the design, including complexity, cost optimization, weight, size, material properties, and tolerances. All of these can lead to lenses with sub-optimal performance, and in fact, designing a perfect lens is essentially impossible. Many manufacturers, including Nikon, publish some sort of lens data. This is typically presented in an MTF (Modulation Transfer Function) chart. Unfortunately, these MTFs typically present a very limited view of lens performance, usually only specifying performance at one (usually unspecified) aperture, and two spatial frequencies (typically 10 and 30 lp/mm), while we really desire the lens performance at all apertures and showing the performance at spatial frequencies that are useful for modern sensors (at least 50 lp/mm). Knowing performance at all apertures is especially important, because two different factors can affect performance at different apertures - manufacturing and design flaws, which dominate at wide apertures, and diffraction limit, which dominates at small apertures.

In order to fill in the missing information regarding the full range of aperture values and extending the performance information out to the spatial resolutions that match modern sensors, new measurement methods must be employed - rather than simply imaging resolution targets, we can image a "step function" and examine the transfer function through a bit of math - the theory behind this will be covered in more detail in the background section.

2 Background

2.1 Lens Basics

Lenses are composed of different elements - individual pieces of glass that are arranged very precisely to achieve the total lens performance. In Figure 1 (Nikon), the elements are white. Lenses also contain an aperture, which serves to decrease the amount of light that is let through a lens, by forcing it through a smaller or larger hole. This is illustrated in Figure 2 (PixeLarge).

Fig. 1: Lens diagram for Nikon 50mm f/1.8D lens. (Nikon)

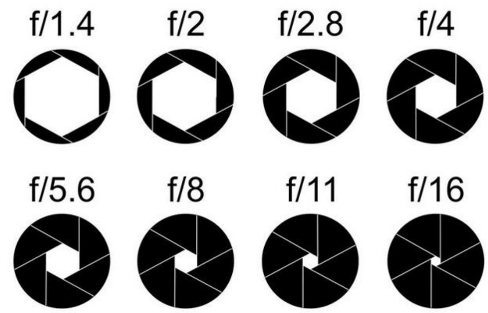

Fig. 2: Various aperture sizes, showing relationship between photographic aperture and opening diameter. (PixeLarge)

The MTF shows the gain of selected spatial frequencies and orientations across the radial axis of the lens, measured as mm across a standard sensor size (which sits a standard distance from the back of the lens). An example MTF for the Nikon 50mm f/1.8D is shown in Figure 3 (Nikon). A graphic detailing the difference between sagital and meridonial traces is in Figure 4 (Nikon). We see that the gain at 30 lp/mm is about 0.6, and decreases as we move away from the center of the lens. Though this data is useful, it only presents data at two specific spatial frequencies and does not present data at different apertures. In particular, many MTF's are specified at 30 lp/mm, while modern sensors can resolve better than 50 lp/mm of spatial resolution, leaving us unsure of how much the lens is handicapping the system. In general, lenses can be thought of as optical low-pass filters, given spatial frequencies, so knowing the performance at 30 lp/mm, we can only extrapolate that the performance at 50 lp/mm will be worse. Unfortunately, it is not really possible to guess the shape of the transfer function based off of two points.

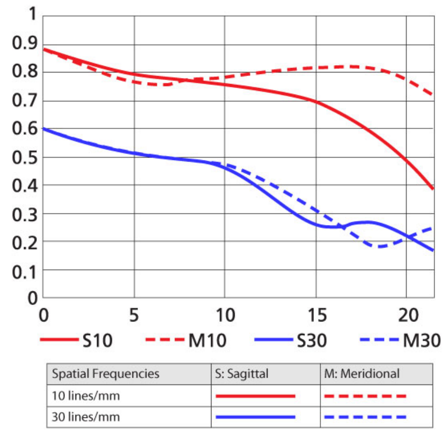

Fig. 3: Nikon's published MTF for the Nikon 50mm f/1.8D lens. Note that only 10 and 30 lp/mm are represented, and aperture is not specified. (Nikon)

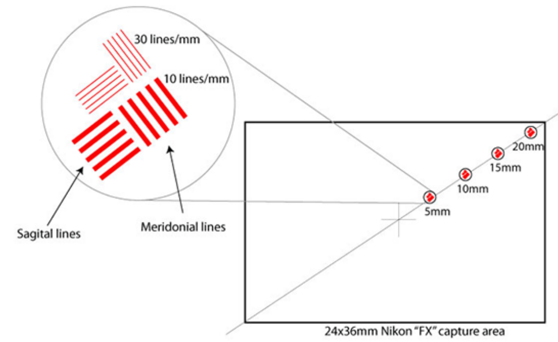

Fig. 4: Diagram illustrating the difference between sagital and meridonial lines in the MTF chart. (Nikon)

Finally, the effect of aperture on lens performance must be mentioned. At smaller apertures (higher numerical apertures), depth of field improves, but the diffraction limit is reached. The diffraction limit is the highest resolution that any optical system can achieve, given by the aperture and wavelength of light. This fundamental limit can only be surpassed by specialized techniques such as interferometric microscopy, near-field microscopy, and other specialized microscopy techniques. The diffraction limit is given as

$$d = \frac{\lambda}{2NA} \tag{1}$$

Where d is the radius of the smallest circle a point of light can be focused to, λ is the wavelength of light, and NA is the numeric aperture, where the photographic aperture is $1/(2 * NA)$. The diffraction limit sets a gold standard for lenses - the perfect lens will be diffraction limited at all apertures. In reality, most lenses are diffraction limited at apertures smaller than about f/4 through f/16, depending on the lens.

This brings us to the crux of this research - measuring a lens' ultimate resolving power, and determining at what aperture this occurs.

2.2 Theoretical Background

In order to understand how to measure a lens' ultimate resolving power, we must first discuss the Point Spread Function (PSF), Line Spread Function (LSF), Edge Spread Function (ESF), and Optical Transfer Function (OTF). The MTF is the absolute value of the complex-valued OTF, and does not include information on phase shift that is contained within the OTF. The PSF is the response to a 2-dimensional impulse - a point of light. As with all systems, the Fourier Transform of the system's impulse response is the system's transfer function. In this case, taking a 2D Fourier Transform of the PSF gives the OTF, from which the absolute value can be taken to obtain the MTF. However, getting a point source of light small enough to be considered a "point" is difficult - at a focused distance of 1m, this point would have to be about 200 μm across. Instead, it is easier to image a black square next to a white square - a step function input, whose response is the ESF. From there, you can take the derivative of the ESF to obtain the LSF, the 1-dimensional analog of the PSF. As such, the Fourier Transform can be taken to reveal the 1-dimensional OTF. If the lens can be assumed to be radially symmetric, which is an assumption we will make, this is just a slice from the symmetric 2D OTF, and can thus be used to compute the 2D OTF. This series of relationships is summarized in Figure 5 (Schowengerdt [2000]).

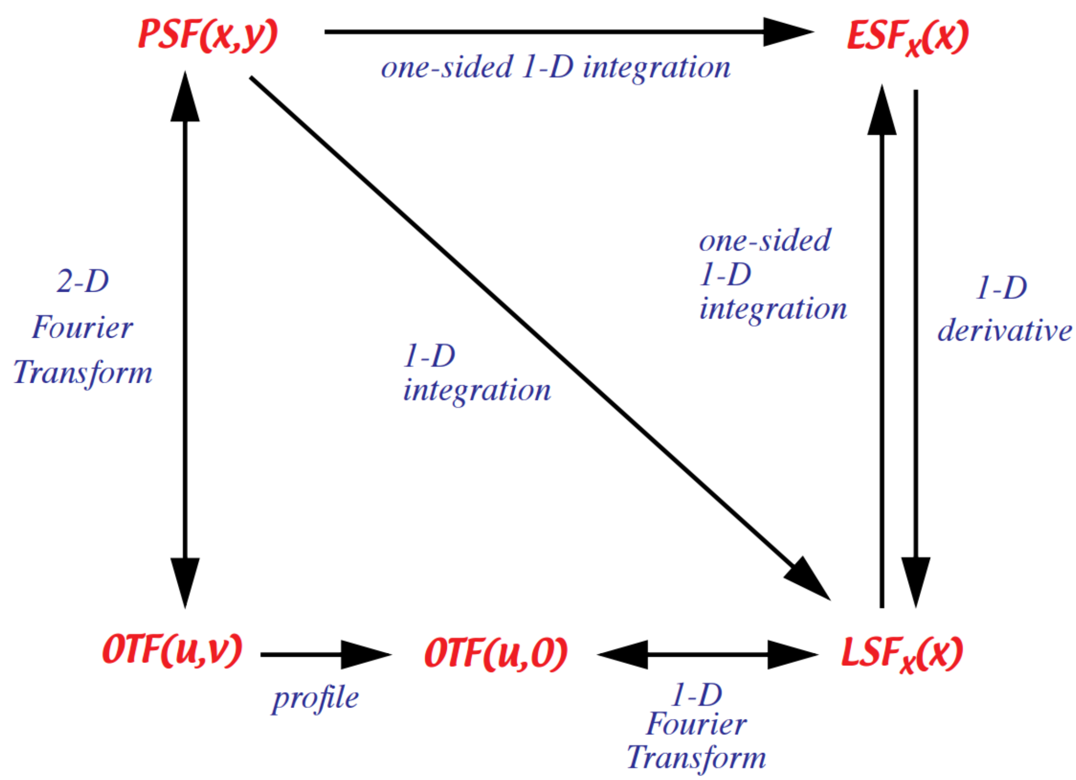

Fig. 5: Diagram describing the relationships between various functions and responses relevant to lens performance. In this research, we will measure the ESF directly, and compute the OTF from this. (Schowengerdt [2000])

As briefly mentioned, directly measuring the PSF is impossible, but measuring the ESF is easy - we simply need a black square and a white square with a sharp boundary, which is a standard test target for photographic systems. From there, taking the first derivative, then the Fourier Transform yields the 1D OTF. Then, taking the absolute value yields the MTF.

2.2.1 Airy Disk

The prototypical PSF of an optical system is the Airy Disk, which is described by the equation

$$I(\theta) = I_0 \left(\frac{2J_1(ka\sin\theta)}{ka\sin\theta} \right)^2 \tag{2}$$

Where $I(\theta)$ is the intensity at θ, the angle of observation from the optical axis. I_0 is the intensity at $\theta = 0$. J_1 is the Bessel Function of the first kind of order one, $k = 2\pi/\lambda$ is the wavenumber, and a is the radius of the aperture. In particular, $ka\sin\theta = \frac{\pi q}{\lambda N}$, where q is the radial distance from the optical axis and N is the photographic aperture. The shape of the Airy Disk is shown in Figure 6.

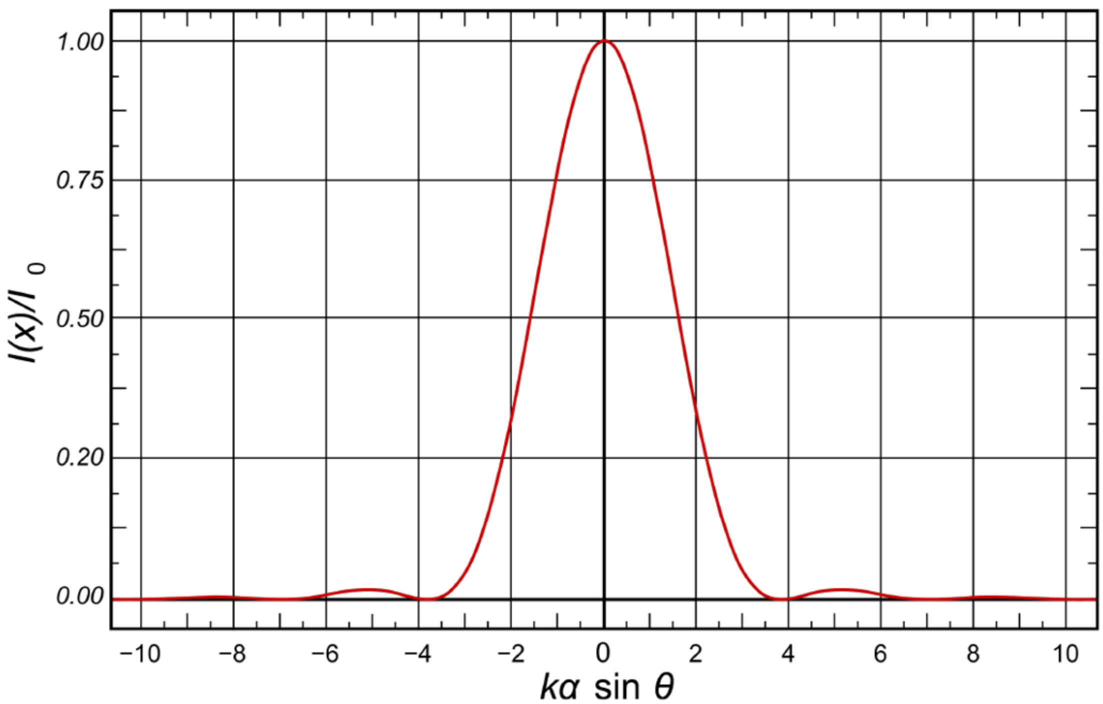

Fig. 6: Airy Disk, with normalized intensity.

3 ESF Measurement

Our basic goals in this experiment are to measure the ESF of a lens, while maintaining enough resolution for detailed analysis. Therefore, we made us of a special pixel-shifting camera, the Vieworks VN-29-MC, which is a 29MP 35mm monochrome machine vision camera featuring 5.47 μm pixels. This camera is special and particularly well-suited to lens-measurement applications because the sensor is mounted on a piezo-drive stage, which can be moved laterally and vertically with a published resolution of 1 nm, allowing interpolation of virtual pixels down to a theoretical resolution of 1 nm. This resolution is well beyond the theoretical best resolution of any photographic lens. In order to measure the ESF, we selected a common focusing target, a grid of white and black squares (from which a single edge transition was selected), which was illuminated with a 100W white LED to eliminate sensor noise. The exposure time was tuned to avoid saturating the sensor while providing maximum dynamic range. In order to allow for precise focusing, the lens was mounted on focusing bellows. In order to achieve sufficient resolution while decreasing experimental time, a 1823 nm shift was selected, for 3 frames total per test point. This was selected on the basis of the smallest diameter we might see, 1.8 μm, based on the Airy disk diameter for an f/1.8 lens with green light. If we had noticed resolution suffering as the lens performs better than expected, we could have decreased the shift further, though this did not turn out to be necessary. In Figure 7 is an example output from the camera in the final setup.

Fig. 7: Sample output from the test setup. Most important is the white/black edge transition, which is a spatial "step function", from which we can measure the ESF directly, and indirectly compute the MTF.

3.1 Pixel-Shift Validation

In order to validate the pixel-shifting capabilities of the camera, a high-contrast, irregular object (in this case, a scrap aluminum billet with irregular surface finish) was imaged twice - once with a pixel shift of 0 nm, once with a pixel shift of +5470 nm (1 pixel). Then, the 2-dimensional cross-correlation was taken between these two images. As expected, a peak was observed at a 1-pixel offset, confirming that the sensor shifted the correct amount.

4 Results and Discussion

From the raw data, we first interleave the three images, effectively tripling the resolution, and achieving an effective pixel pitch of 1.82μm. We extract the ESF by vertically averaging a small region of the edge, then normalizing. Shown in Figure 8 is an example of the ESF obtained from this technique. There are 15 "micropixels" between an intensity of 0.9 and 0.1 at f/22. This indicates that we have increased our resolution to a sufficient threshold to resolve the transition from white to black.

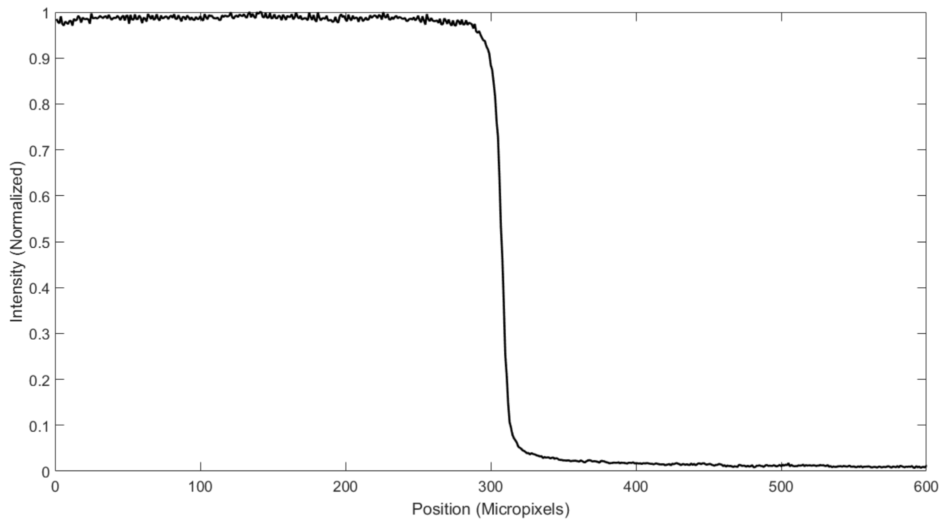

Fig. 8: The edge spread function of a Nikon 50mm f/1.8D at f/22, measured by averaging columns of pixels around the white/black transition mentioned in Figure 7. Notably, our camera has enough resolution through micropixel stepping to resolve the S-curve nature of the step response.

After obtaining the ESF, we can take a numerical derivative to obtain the LSF, as shown in Figure 9. Notice that the noise is much higher on the "high" side, which is due to photon noise - the noise due to different numbers of photons hitting the system follow a Gaussian distribution, centered around the true value, where the standard deviation increases with the mean. Thus, the white side has higher noise.

Finally, after obtaining the LSF, we run a Fast Fourier Transform (FFT) to obtain the OTF, then take the absolute value to obtain the MTF, as shown in Figure 10. To validate our method, compare the value at 30 lp/mm to Nikon's published data. At 30 lp/mm, Nikon's published data indicates a gain of 0.6 in the center of the image, decreasing slightly from there. Our test location is fairly close to the center of the image - the region of interest was 684 pixels from the center of the image vertically and 601 pixels away from the center of the image horizontally, for a total real world distance of 4.98mm. Reading off Nikon's MTF chart, we therefore expect a gain of about 0.51. Indeed, we calculate a gain of 0.473 ± 0.074 at 30 lp/mm. The two results match, confirming our experimental setup produces reasonable results.

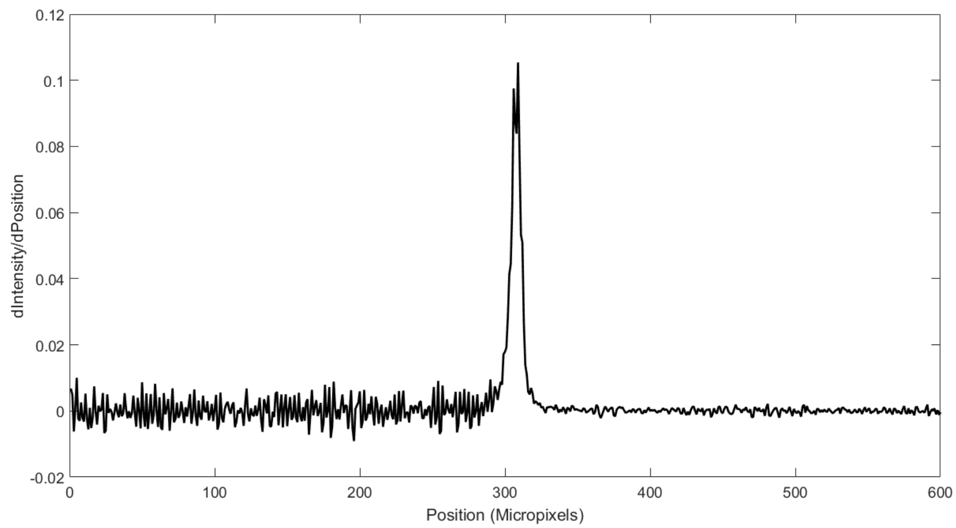

Fig. 9: The line spread function of a Nikon 50mm f/1.8D at f/22. The plot has been inverted, equivalent to reversing the transition from black to white instead of white to black.

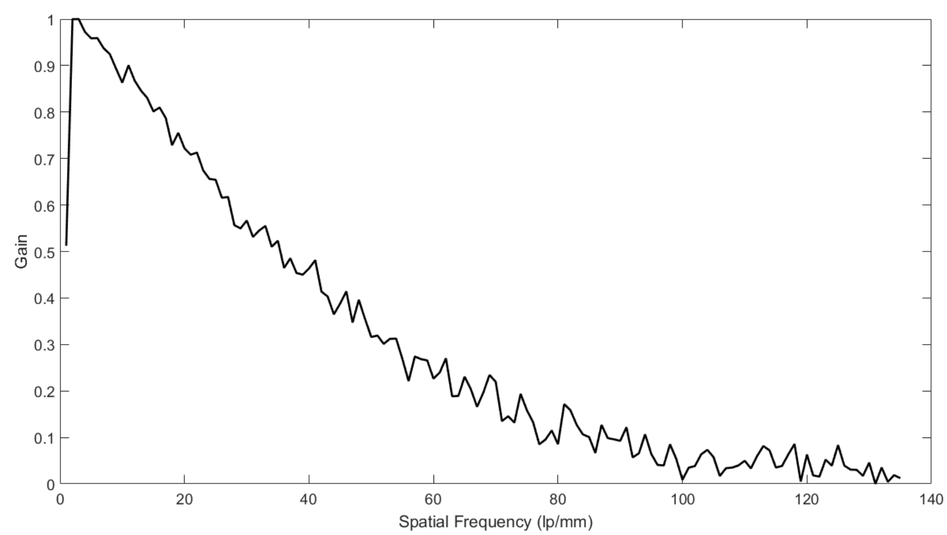

Fig. 10: The MTF of a Nikon 50mm f/1.8D at f/2.

Finally, we arrive at the data we're interested in - how aperture affects the MTF. As mentioned previously, there are two factors at play - manufacturing and design flaws limiting performance, which will dominate at the wide apertures, and diffraction limit, which will dominate at the small apertures. In Figure 11, we can see the gain at 30 lp/mm for each aperture, and see clearly that lens performance is optimal at f/4. At wider apertures, the lens performs significantly worse than the diffraction limits, and at smaller apertures, it is mostly controlled by the diffraction limit. A full comparison of the MTF for all apertures is presented in Figure 12.

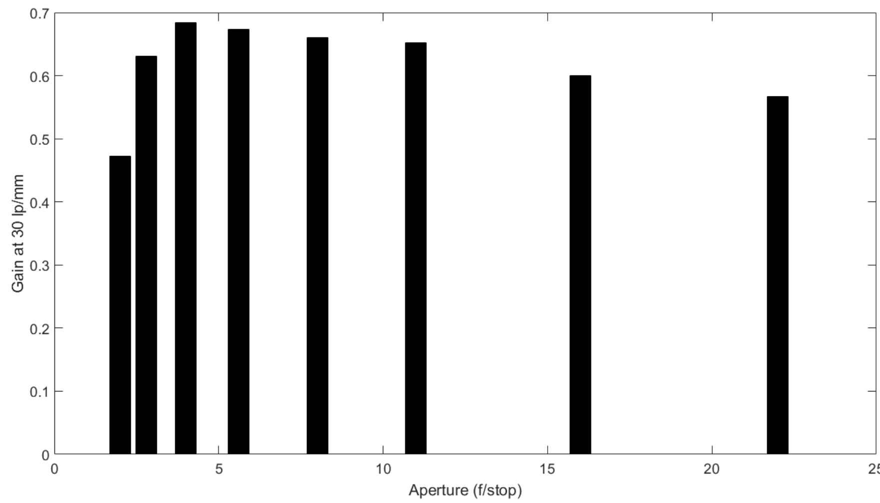

Fig. 11: Comparison of gain at 30 lp/mm for all apertures of the Nikon 50mm f/1.8D. We can clearly see that at f/2 and f/2.8, manufacturing or design flaws clearly limit lens performance, while the steady decline in performance from f/4 through f/22 is the result of diffraction limiting. The information gleaned from this - namely that f/4 is the best-performing aperture, can not typically be found in lens specifications.

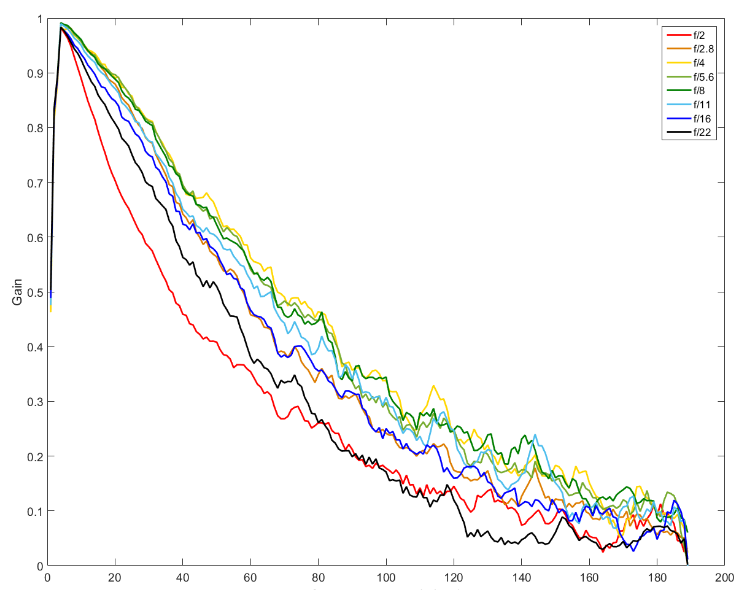

Fig. 12: MTF comparison for all whole apertures of the Nikon 50mm f/1.8D. Here we can see that all apertures exhibit similar decline in performance at higher spatial resolutions, and can compare different apertures at each spatial resolution. f/4 clearly remains the best-performing aperture for most of the frequency range, while f/2 is the worst for most of the frequency range.

5 Conclusions

A new method for computing the MTF of lenses has been tested and works as desired, making use of a pixel-shifting camera to achieve extremely high resolution capable of testing the resolution limits of modern lenses. This method can give the full MTF at all spatial frequencies, which is superior to the published MTF curves, which give an incomplete view of lens performance. This data matches published data to within 10%, which is almost certainly within sample-to-sample variation of the lens tested. In particular, the measured gain at 30 lp/mm and an offset of 5mm was 0.473 ± 0.074, while the published gain was 0.51.

In future work, we hope to confirm the results by testing against different lenses, testing different radial distances from the optical axis, and characterizing the performance further, including the effects of focus on lens performance. We also would like to characterize sample-to-sample variation among lenses, especially to quantify (if it exists) a relationship between lens price and sample-to-sample variance.

Acknowledgements

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