 

# Limits of Resolution. 3. Diffraction and Photosite Size

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## Summary

Resolution limits (lp/mm) for a perfect lens as a function of aperture and sensor photosite size are determined by simulation. Results are shown for 20, 50, and 80% line-pair contrast ratios. Smaller photosites always increase resolution and contrast (within the range of sizes and aperture values simulated), although marginal gains are small if diffraction blur is appreciably larger than photosite size. If diffraction blur diameter is reduced to less than photosite size, resolution can improve substantially, particularly when line-pair contrast is high. With respect to "total" resolution (LW/PH), the usual rules of "camera equivalence" are obeyed. The result is that, with perfect lenses, larger sensors can achieve higher total resolution than smaller ones only if they have more photosites (or if depth of field is sacrificed). Resolution limits for a perfect lens are compared to published test results for the Nikkor 85mm f/1.4G on a Nikon D3x, and for the Zeiss Otus 55mm f/1.4 on a Nikon D800E. Test results for the two lens/camera combinations are inconsistent with each other and with simulations, even at smaller apertures where diffraction rather than lens performance is assumed to limit resolution. Reasons for the inconsistencies are discussed. Given that resolution limits depend upon both diffraction blur *and* photosite size, it is generally not useful to erect a dichotomy between "diffraction-limited" and "sensor-limited" resolution.

**Key words:** resolution limits, sampling frequency, diffraction, sensor pixel size, photosite size, perfect lens, line-pairs, simulation, Nikkor 85mm f/1.4G, Zeiss Otus 55mm f/1.4, Airy disk, camera equivalence, diffraction-limited resolution, sensor-limited resolution, LensRentals.com, Photozone

## 1. Introduction

In the first paper of this series,[1] I showed how the sampling frequency imposed by a camera sensor affects the appearance of black and white line-pairs in a digital image. Although a sampling frequency of two photosites per pair is sufficient to *resolve* the line-pairs, the contrast of the original pattern is reduced by one-half, on average. In order to recover the original contrast, a sampling frequency of four photosites per line-pair is necessary. That paper considered only un-blurred line-pairs. The second paper in this series illustrates the effect of diffraction on the contrast of line-pairs.[2] A diffraction blur diameter greater than about 115% of

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[1] Service, Phil. 2014. Limits of Resolution. 1. Sampling Frequency.

[2] Service, Phil. 2014. Limits of Resolution. 2. Diffraction.

the line-pair width is sufficient to obscure the pattern. The present paper simulates the combined effects of diffraction and sampling frequency on the recorded image. As a result, we will obtain the resolution limits for "perfect" lenses as a function of aperture and photosite size.

### 1.1. Terminology

As in the previous papers, it will be useful to define a few terms at the outset. The *lens image* is the image that is formed by the lens. The lens image is an effectively continuous, analog representation of the external world — *object field* — in front of the lens. The *sensor* image is the digitized image recorded by the sensor. It is absolutely crucial to understand that this is a *sample* of the lens image. Blur affects the lens image, *not* the sampling process. Therefore, there is not a simple relationship between blur circle diameter and photosite pitch — a fact that seems generally not to be understood. *Resolution* in the present context means line-pairs per millimeter (lp/mm). *Total resolution* is the total number of line-pairs in an image of a given height (LP/PH). In general, a *contrast ratio* will be associated with a resolution measure. The contrast ratio is the maximum difference in lightness values of alternating light and dark lines, divided by their sum. A *perfect lens* is a lens with no optical aberrations. In the absence of diffraction, it would produce an image with no blur. A perfect lens is assumed in everything that follows, and diffraction is the only source of lens image blur. *Nyquist rate resolution* is the maximum resolution (lp/mm) achievable with a given sensor. A minimum of two rows or columns of photosites is required to record a line-pair. Thus, if photosite spacing is 4 µm, then 8 µm (= 0.008 mm) are required to sample one line-pair. The Nyquist rate resolution is then 1/0.008 = 125 lp/mm.

## 2. The Model

Simulations were carried out with C-language programs written as OS X command line tools. The programs were based on the one used for the previous paper in this series.[3] Each simulation is a two-step process: the first step simulates the diffraction-blurred lens image; the second step *samples* the blurred lens image by overlaying a grid of photosites. It is important to understand that the blurring produced by diffraction, and the sampling process imposed by the sensor are distinct and independent phenomena — although both affect the contrast of the "final" sensor image. Photosite "size" and "spacing" (or "pitch") are used synonymously. That is, borders between adjacent photosites are assumed to have negligible width. Any complications arising from a color filter array, a feature of almost every camera sensor, are ignored. For simulation of diffraction, the wavelength of light is taken to be 550 nm, and the diameter of the diffraction blur circle is calculated as 70% of the Airy disk.[3] In the absence of diffraction, each black line in the lens image would receive no light; and each white line would receive just enough light to fully saturate photosites in the absence of sampling effects. Finally, I assume no sharpening; or exposure, white level, or black level adjustments: all of which can affect line-pair contrast in a processed image.

[3] Service, Phil. 2014. Limits of Resolution. 2. Diffraction

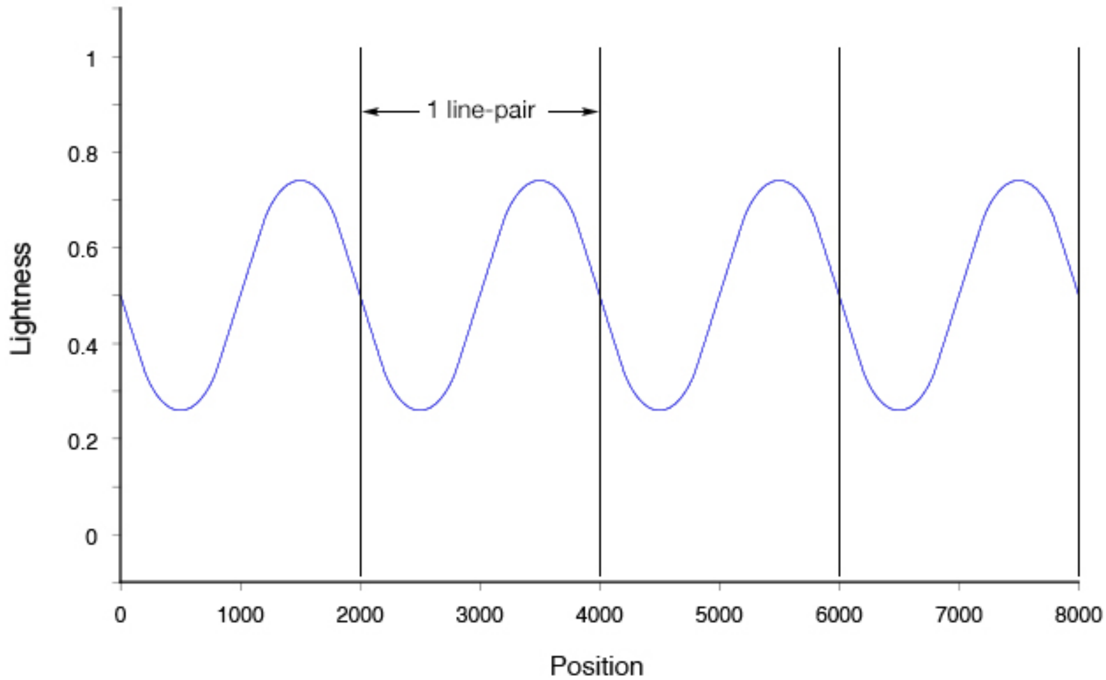


Fig. 1. Representation of a line-pair pattern simulated with a diffraction blur diameter equal to 80% of the line-pair width. Contrast ratio is 48%. See text for additional explanation. Units on horizontal axis are dimensionless.

### 2.1. Simulations with Fixed Line-pair Resolution

As in the previous paper, a fixed lens-image spatial resolution is simulated. Fig. 1 is a graphical representation of the pattern — before sensor sampling — in the case where the diameter of the diffraction blur circle is 80% of the width of a line-pair. The contrast ratio is about 48%. The graph shows lightness on the vertical axis as a function of position within a sequence of four line-pairs (horizontal axis). The theoretical limits of lightness are 0 (black) to 1 (white). The units of distance on the horizontal axis are dimensionless. The line-pair frequency is 1 per 2000 units. The borders of the line-pairs are indicated. Dimensionless units make it convenient to obtain general results that are based on the relative sizes of line-pairs, blur circles, and photosites.

Sampling by the sensor is simulated by subdividing the curve in Fig. 1 into segments that represent the photosites, the borders of which are indicated by the vertical red lines in Fig. 2. The sampling frequency illustrated is four photosites per line-pair. The lightness value recorded by a photosite is simply the average of the curve in the interval between a pair of red lines. In the case of the sampling illustrated in Fig. 2, the “photosites” are 500 units wide. Thus each photosite lightness will be an average of 500 successive points on the curve. There is one further issue that needs to be taken into account: the position of the sensor relative to the line-pair pattern will in general be haphazard. In, other words, the red lines in Fig. 2 could be shifted to the left or right, which would change the lightness values recorded by each photosite. For the example illustrated, there are 2,000 unique alignments of the photosite photosite grid relative to the line-pair pattern. Different alignments will produce different contrast ratios in the sensor

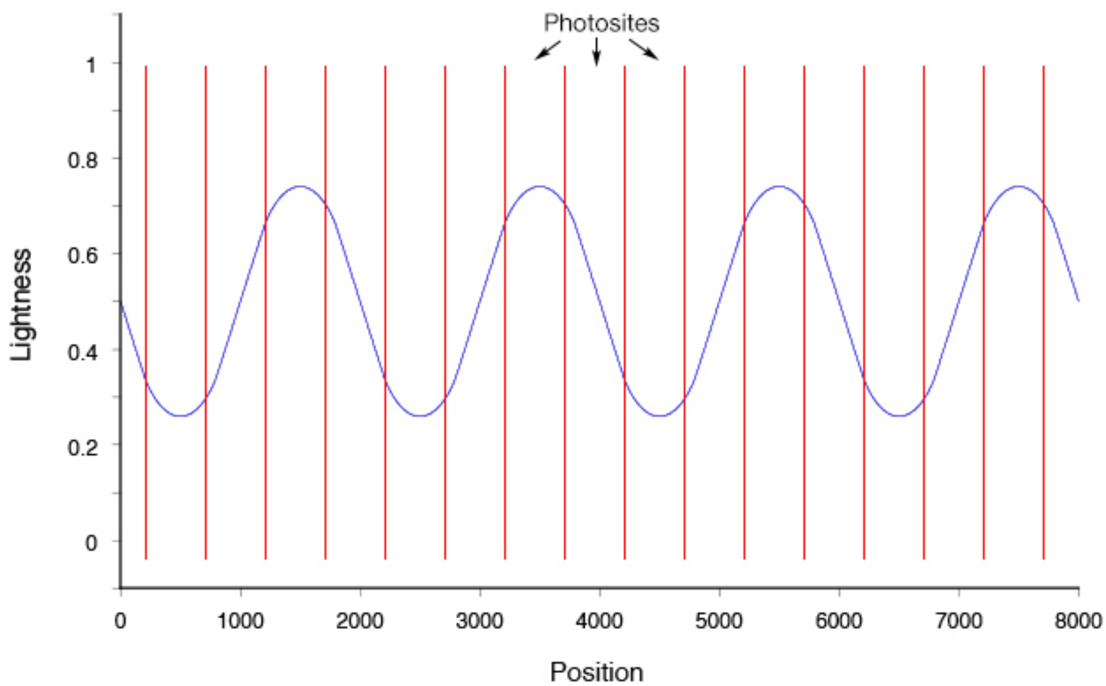


Fig. 2. The blurred line-pair pattern of Fig. 1 with superimposed photosite sampling indicated by vertical red lines. See text for additional explanation.

image. I found the maximum and minimum contrast patterns, and the average sensor image contrast over all alignments.[4] Simulations were carried out for diffraction blur sizes ranging from 20 – 100% of the line-pair width, and for sampling frequencies of 2 – 8 photosites per line-pair.

### 2.2. Simulations with Specified Photosite Size and Aperture Value

Although the simulations described in Section 2.1 provide useful general insight into the combined effects of diffraction and sampling frequency, they do not permit easy determination of the contrast-specific resolution limits (lp/mm) that can be achieved with particular aperture values and particular physical photosite sizes. Therefore, a second series of simulations was carried out by similar procedures except that absolute photosite size and diffraction blur diameter were both specified (in microns). For each combination of photosite and diffraction size, line-pair spacing was systematically varied to find the frequencies that gave sensor images with 20, 50, or 80% contrast ratios. For example, we will find that for a perfect lens at f/4 and using a sensor with 4 μm photosites, the resolution limit with 50% contrast in the sensor image is approximately 120 lp/mm.

[4] Because of symmetry, the actual number of possible alignments that must be evaluated is equal to half the width of a line-pair, which in this case means 1,000 different positions of the photosite grid.

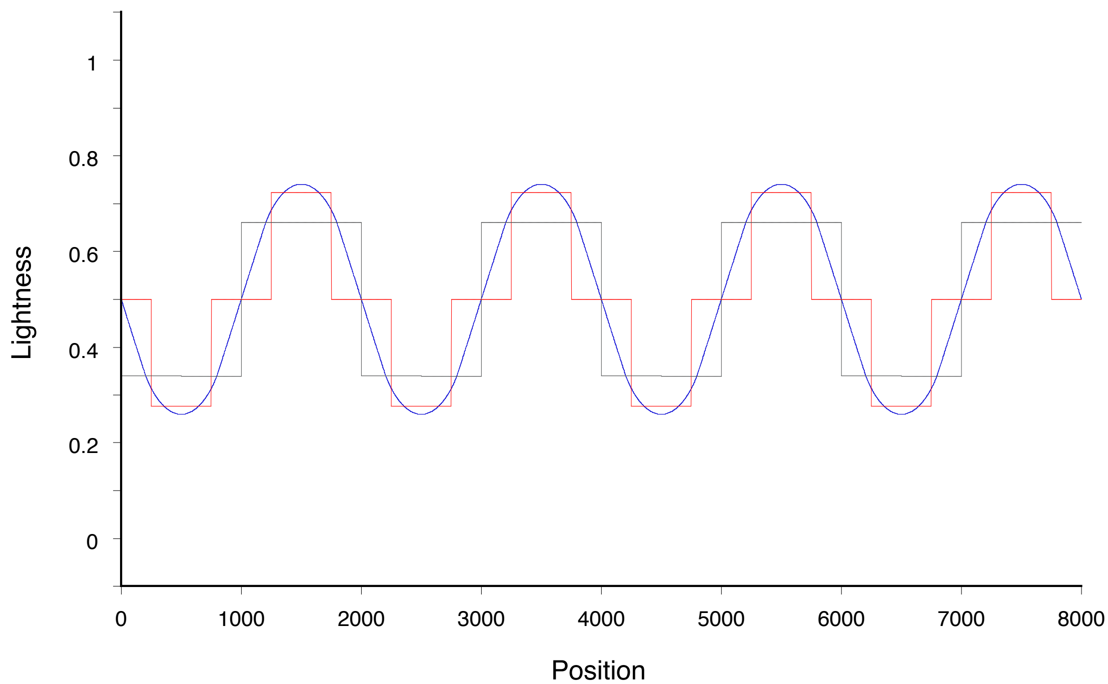


Fig. 3. Lightness values of a grid of photosites superimposed on the blurred lens image of a sequence of four line-pairs. The sampling frequency is four photosites per line-pair. Blue curve: lens image. Red line: photosite lightness values for the maximum contrast photosite alignment. Gray line: photosite lightness values for the minimum contrast case.

**Table 1. Line-pair Contrast Ratio as a Function of Relative Diffraction Blur and Sampling Rate**

| Diffraction Blur Diameter, % of line-pair width | Lens Image Contrast Ratio, % | Sampling Rate, photosites/line-pair | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 20 | 100 / 60* | 48 | 85 | 96 | 99 | 100 | 100 | 100 |
| 40 | 100 / 20* | 42 | 72 | 84 | 91 | 95 | 97 | 98 |
| 60 | 84 | 32 | 55 | 64 | 70 | 74 | 76 | 78 |
| 80 | 48 | 20 | 35 | 40 | 43 | 45 | 46 | 46 |
| 100 | 22 | 9 | 16 | 19 | 20 | 21 | 21 | 21 |

* The second number is the proportion of each line that is either completely black or completely white (lightness = 0 or 1, respectively).

# 3. Results

## 3.1. Simulations with Fixed Line-pair Resolution

Fig. 3 illustrates the effect of sensor sampling as depicted in Fig. 2. In this particular example, the diffraction blur circle is 80% of the line-pair width, and the sampling frequency is four photosites per line-pair. Note that the sampling process converts the smooth curve of the lens image into a step function of photosite lightnesses in the sensor image. The average photosite contrast ratio over all possible alignments of photosites and line-pairs is 40.4%. The red line in Fig. 3 depicts the photosite lightnesses for the maximum contrast alignment (44.6%), and the gray line shows the photosite lightnesses for the minimum contrast case (32.1%). Although the gray line appears to show only two photosites per line pair, in fact the minimum contrast alignment results in alternating *pairs* of photosites with the same lightness values — two light followed by two dark, and so on.

Results for additional blur sizes and sampling frequencies are given in Table 1. As expected, sensor image contrast improves with smaller blur diameter and higher sampling frequency. This analysis shows that 50% is the limiting mean contrast ratio for Nyquist rate sampling (two photosites per line-pair): in agreement with earlier analyses of un-blurred line-pairs.[5] The red entries in Table 1 indicate combinations in which the blur diameter is *smaller* than the photosite size — a point to which I shall return in the Discussion.

### 3.2. Simulations with Specified Photosite Size and Aperture Value

Results for 50%, 80%, and 20% sensor-image contrast are shown in Tables 2 – 4. They follow predictable patterns. Resolution (lp/mm) increases at wider apertures and with smaller photosites. Resolution is also inversely related to contrast. Nyquist rate resolution is readily achieved at 20% contrast ratio, especially if photosites are relatively large (Table 4).

**Table 2. 50% Contrast Ratio Resolution Limits for a Perfect Lens, lp/mm‡**

| Aperture | Diffraction Blur Diameter, μm | Photosite Size, μm | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1.4 | 1.32 | 455 | 245 | 165 | 124 | 100 | 83 | 71 | 63 |
| 2 | 1.88 | 369 | 239 | 164 | 124 | 100 | 83 | 71 | 63 |
| 2.8 | 2.63 | 281 | 227 | 161 | 123 | 99 | 83 | 71 | 62 |
| 4 | 3.76 | 200 | 184 | 154 | 120 | 97 | 82 | 70 | 62 |
| 5.6 | 5.26 | 148 | 141 | 128 | 114 | 94 | 80 | 70 | 62 |
| 8 | 7.52 | 104 | 101 | 98 | 92 | 85 | 76 | 67 | 60 |
| 11 | 10.33 | 76 | 75 | 74 | 71 | 66 | 65 | 62 | 57 |
| Nyquist Rate Resolution | | 500 | 250 | 167 | 125 | 100 | 83 | 71 | 63 |

‡ Red entries represent combinations in which the blur diameter is smaller than the photosite size.

5 Service, Phil. 2014. Limits of Resolution. 1. Sampling Frequency.

**Table 3. 80% Contrast Ratio Resolution Limits for a Perfect Lens, lp/mm‡**

| Aperture | Diffraction Blur Diameter, μm | Photosite Size, μm | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1.4 | 1.32 | 322 | 220 | 152 | 115 | 93 | 77 | 66 | 58 |
| 2 | 1.88 | 271 | 195 | 148 | 114 | 92 | 77 | 66 | 58 |
| 2.8 | 2.63 | 211 | 160 | 131 | 110 | 90 | 76 | 66 | 57 |
| 4 | 3.76 | 157 | 135 | 108 | 97 | 85 | 74 | 64 | 57 |
| 5.6 | 5.26 | 115 | 105 | 94 | 80 | 75 | 66 | 61 | 55 |
| 8 | 7.52 | 82 | 78 | 73 | 68 | 62 | 54 | 53 | 49 |
| 11 | 10.33 | 60 | 59 | 55 | 54 | 49 | 47 | 45 | 40 |
| Nyquist Rate Resolution | | 500 | 250 | 167 | 125 | 100 | 83 | 71 | 63 |

‡ Red entries represent combinations in which the blur diameter is smaller than the photosite size.

**Table 4. 20% Contrast Ratio Resolution Limits for a Perfect Lens, lp/mm‡**

| Aperture | Diffraction Blur Diameter, μm | Photosite Size, μm | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1.4 | 1.32 | 500* | 250* | 167* | 125* | 100* | 83* | 71* | 63* |
| 2 | 1.88 | 475 | 250* | 167* | 125* | 100* | 83* | 71* | 63* |
| 2.8 | 2.63 | 371 | 250* | 167* | 125* | 100* | 83* | 71* | 63* |
| 4 | 3.76 | 266 | 237 | 167* | 125* | 100* | 83* | 71* | 63* |
| 5.6 | 5.26 | 191 | 186 | 162 | 125* | 100* | 83* | 71* | 63* |
| 8 | 7.52 | 134 | 132 | 129 | 119 | 100* | 83* | 71* | 63* |
| 11 | 10.33 | 98 | 97 | 96 | 95 | 91 | 81 | 71* | 63* |
| Nyquist Rate Resolution | | 500 | 250 | 167 | 125 | 100 | 83 | 71 | 63 |

‡ Red entries represent combinations in which the blur diameter is smaller than the photosite size.
* Contrast ratio greater than 20% at Nyquist rate resolution.

# 4. Discussion

## 4.1. More Photosites Are Always Better for Resolution and Fine-scale Contrast

The main and not surprising conclusion to be drawn from these simulations is abundantly clear. If spatial resolution (lp/mm) and fine-scale contrast are the only considerations, higher sampling rates — that is, more, smaller photosites — are always better.[6] That can be seen in in the case where line-pair frequency is held constant: contrast ratios increase with higher sampling rate as one moves from left to right along any row of Table 1. In the cases where contrast ratios remain constant (Tables 2 – 4), smaller photosites result in greater spatial resolution. For example, in Table 2, for any given aperture, resolution increases as photosite size decreases (moving from right to left along a row). It is, of course, possible to reach a state of diminishing returns. In Table 1, the marginal gains in contrast become progressively smaller as sampling rate increases above five photosites per line-pair. Similarly, particularly for smaller apertures (larger f-numbers), marginal gains in spatial resolution also decline as photosites become very small (for example, Table 2, moving right to left along the row for f/11). Whether more sensor megapixels make a perceptible difference in displayed images is an entirely separate issue. That depends mainly on the physical dimensions of the displayed image, and whether the image is printed or shown on a monitor. Smaller photosites also have implications for noise and dynamic range, but again that is a different issue.

The second, and most definitely not surprising conclusion is that larger apertures are associated with higher spatial resolution and greater contrast *in the case of perfect lenses.* For photographers seeking maximum image detail, it is perhaps disappointing that most lenses designed for m4/3 and larger sensors perform sub-optimally at apertures larger than about f/4.

### 4.2. Case Studies with Lens Test Data

How do the theoretical resolution limits obtained here compare with test results of real lenses on real cameras? At the outset, I emphasize that such comparisons are fraught with difficulty. We need resolution numbers associated with a specified modulation transfer function (MTF) value. However, it is not at all clear that test results for MTF50, for example, are directly comparable to simulation results for 50% contrast. In the case studies that I am using, lens resolutions were obtained with the Imatest package. I have never used Imatest and am not familiar with it. I suspect that there are a number of ways in which two labs might obtain widely different results with the same lens and camera. That would be true, for example, if post-capture processing of target images were not standardized. With those and other caveats in mind, I will use published test results of two lenses on two different cameras, obtained from two different "labs".[7]

It is generally accepted that uncorrected optical aberrations have diminishing effects on image quality as lenses are stopped down. On the other hand, diffraction blur *increases* with smaller aperture. Therefore, most lenses achieve highest resolution at intermediate apertures, usually f/4 or f/5.6 — apertures at which the combined effects of aberrations and diffraction are minimized. If performance at smaller apertures is limited mostly by diffraction, it is at smaller

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[6] At least over the range of conditions — aperture, photosite size, etc.— considered in these simulations.

[7] DxOMark appears to have the most extensive on-line data base of lens test results. However, resolution data are presented in terms of "perceptual megapixels", P-Mpix, rather than in more conventional metrics such as lp/mm or line-widths per picture height (LW/PH).

apertures that we should expect closest agreement between actual lens test results and simulations of perfect lenses.

**Nikkor AF-S 85mm f/1.4G on a Nikon D3x** These data are published by Photozone.[8] The results are reported as line-widths per picture height (LW/PH) at MTF50. I have converted the data to lp/mm by dividing by two in order to obtain line-pairs per picture height, and then by 24 (the height of the D3x sensor in millimeters) to obtain lp/mm. The reported center resolution data are shown in Table 5, together with the simulation results for a perfect lens and a photosite size of 5.9 µm (the nominal size of the D3x photosites).

**Table 5. Test and Simulation Results for Nikkor 85mm f/1.4G on Nikon D3x**

| Aperture | Photozone Results, lp/mm @ MTF50* | Simulation Results, lp/mm @ 50% Contrast | Difference, % ((Simulation - Actual) / Simulation) |
|---|---|---|---|
| 1.4 | 73 | 85 | 14.6 |
| 2 | 75 | 84 | 11.1 |
| 2.8 | 79 | 84 | 6.1 |
| 4 | 84 | 83 | -0.8 |
| 5.6 | 83 | 82 | -1.3 |
| 8 | 83 | 78 | -6.1 |
| 11 | 76 | 66 | -14.6 |

* Data obtained from http://www.photozone.de/nikon_ff/606-nikkorafs8514ff

**Table 6. Test and Simulation Results for Zeiss Otus 55mm/f1.4 on Nikon D800E**

| Aperture | LensRentals Results, lp/mm @ MTF50* | Simulation Results, lp/mm @ 50% Contrast | Difference, % ((Simulation - Actual) / Simulation) |
|---|---|---|---|
| 1.4 | 40 | 103 | 61.0 |
| 2 | 42 | 103 | 59.1 |
| 2.8 | 52 | 102 | 48.7 |
| 4 | 55 | 101 | 45.5 |
| 5.6 | 56 | 97 | 42.7 |
| 8 | 53 | 87 | 39.4 |

* Data obtained from http://www.lensrentals.com/blog/2013/11/otus-is-scharf

8 http://www.photozone.de/nikon_ff/606-nikkorafs8514ff

**Zeiss Otus 55mm f/1.4 on a Nikon D800E** These data are published by LensRentals.com.[9] The results are reported as line-pairs per picture height (LP/PH) at MTF50. They have been converted to lp/mm by dividing by 24 mm, the height of the D800E sensor. The photosite pitch of the D800E sensor is approximately 4.84 µm. Test results, for image centers, together with simulation results are shown in Table 6.

**Results** The first thing to note is that the reported resolutions for the Nikkor are much greater than for the Otus. In itself, that is a strong indication that the two "labs" are implementing Imatest, or reporting results, in different ways. It is also a strong indication that at least one, and possibly both sets of test results are unlikely to agree with simulated data. For the Nikkor, highest center resolution was obtained at f/4, where agreement between actual and simulated results is very close (Table 5). At larger apertures, the lens underperforms relative to a perfect lens, as expected. However, contrary to expectation, the test resolutions for f/8 and f/11 were considerably better than predicted by simulation. For the Otus, resolutions at all apertures tested were less than expected by simulation (Table 6). That is not surprising for apertures larger than f/5.6 (the "best" aperture), but is for f/8 where presumably diffraction has greatest influence on realized resolution. At least the degree of "under performance" by the Otus declines with decreasing aperture, as expected.

The discrepancy between actual and simulated results for the Otus would be less if diffraction blur were calculated as the diameter of the Airy disk, instead of 70% of the disk. However, that would exacerbate the apparent "over performance" of the Nikkor. Similarly, there is general agreement that the Bayer filter array common to most sensors reduces linear resolution by a factor of 1.2 – 1.5x. Increasing the effective size of the D800E photosites by a factor of 1.5 would go a long way toward reducing the discrepancy between actual and simulated resolutions in Table 6. However, of we did the same for the Nikkor on the D3x, the over performance would be even more exaggerated. In summary, both of these "real world" tests are inconsistent with each other, and neither seems likely to offer a good benchmark against which to evaluate the simulation model.

### 4.3. Diffraction-limited or Sensor-limited Resolution, or Neither?

The term "diffraction-limited" is commonly encountered in discussions of resolution. I used it above when describing the decline in lens performance that occurs as the aperture is narrowed beyond the setting that maximizes resolution. We know that as aperture becomes smalller, diffraction blur increases, so this seems to be an uncontroversial use of the term. However, when the discussion turns to the question of whether diffraction or photosite size is limiting resolution, diffraction-limitation becomes less clear-cut. When photosites are large, changes in aperture have relatively little effect on resolution for the f-stops and photosite sizes simulated here. Look, for example, at the right-hand column of Table 2. It is natural in that circumstance to think that resolution is sensor-limited. On the other hand, if photosites are small, changes in aperture have profound effects on resolution (Table 2, left-hand column), and it is reasonable to think that resolution is diffraction-limited. In reality, neither view is strictly correct because sensor-image resolution depends upon both aperture and photosite size. For

[9] http://www.lensrentals.com/blog/2013/11/otus-is-scharf

many photosite size and contrast combinations (Table 2 – 4), *any* increase in diffraction reduces resolution. In these situations, "diffraction-limited" ceases to be a meaningful term.

One popular on-line source, Cambridge in Colour, provides a calculator to help determine at what apertures resolution will become diffraction-limited by their definition. Three levels of diffraction limitation are recognized: when the diffraction blur diameter is 2, 2.5, or 3x the photosite size. The purpose of such a calculator is to provide rough guidance about when diffraction is likely to have noticeable effects on image quality. However, it necessarily over simplifies.[10] Note that for relatively small photosites (2 – 5 µm), increases in diffraction blur can decrease resolution, if only slightly, even when the diffraction blur diameter remains *less* than the width of a photosite (Table 3, and next text section).

### 4.4. Resolution Can Increase When Diffraction Blur Diameter is Less than Photosite Size

A perhaps unexpected result of this analysis is that resolution can continue to improve with larger apertures, even when diffraction blur diameter is *less* than photosite size. The effect is strongest when contrast ratio is high. For example, in Table 3, for 6µm photosite size, when diffraction blur is decreased from 7.52 to 5.26 µm (f/8 to f/5.6), resolution increases from 54 to 66 lp/mm. A further decrease in diffraction blur to 3.76 µm (f/4) increases resolution to 74 lp/mm. Two points need to be made: (1) marginal gains in resolution decline rapidly with further widening of the aperture; (2) performance of real lenses, as opposed to perfect ones, usually declines at apertures larger than f/5.6 or f/4.

### 4.5. Camera Equivalence

*Camera equivalence* is the idea that cameras with different sensor sizes can be made to take images that are indistinguishable. For cameras to be "equivalent", photosite size,[11] lens focal length, and f-number must scale with the difference in sensor dimensions. Camera equivalence is most commonly invoked in the context of equalizing field of view and depth of field when using cameras with different formats. However, equivalence extends to other aspects of the image, including resolution and fine-scale contrast. As an example, a "full frame" sensor is nominally 1.5x larger than an APS-C sensor: 36 x 24 mm vs. 24 x 16 mm. Equivalence requires that the focal length and f-number of the lens on the full-frame camera be 1.5x larger than on the APS-C camera: say 90 mm @ f/8 vs. 60 mm @ f/5.6.

Resolution equivalence is defined as equal number line-pairs per picture height. If both cameras have 24MP sensors, the photosites also scale by a factor of 1.5: 6 µm on the full-frame sensor and 4 µm on the APS-C. The resolution limit for 6 µm photosites and f/8 at 50% contrast is 76 lp/mm (Table 2). On the full-frame sensor, that corresponds to 76 x 24 = 1,824 LP/PH. The equivalent APS-C camera must be used at f/5.6, at which aperture the 4 µm photosites have

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[10] To be fair, the authors of the tutorial clearly state that the purpose of the calculator is "to give an idea of how gradual and broad diffraction's onset can be, and how its 'limit' depends on what you're using as the image quality criterion."

[11] Equivalently, both sensors will have the same number of photosites if they have the same aspect ratio.

a resolution of 114 lp/mm (Table 2); which results in 114 x 16 = 1,824 LP/PH. Thus, the "information" in both sensor images is the same.[12]

The full-frame sensor *can* achieve greater resolution than the APS-C sensor, with equal depth of field, if we relax the requirement of photosite equivalence. Suppose the full-frame sensor also has 4 µm photosites. Then, at f/8 the resolution limit is 92 lp/mm (Table 2), which translates to 92 x 24 = 2,208 LW/PH. In this case, the "cost" of maintaining depth of field by using the smaller aperture on the larger sensor is that total "information" is increased by only 21%, instead of 50% (the increase in height of the full-frame vs. the APS-C sensor). But the main point is: in order for larger sensors to record more information than smaller ones, they must also have more photosites (or they must sacrifice depth of field). Whether that additional information is visible in a displayed image is, again, beyond the scope of this paper.

### 4.6. Final Thoughts

These simulations are intended to give a general understanding of the way that diffraction and photosite size influence digital camera resolution and fine-scale contrast. They make it very clear that, at least in theory, smaller photosites — higher sampling frequency — increase resolution and contrast. Also, *any* narrowing of aperture can produce lower resolution and contrast, except in the case of the largest photosites simulated. Additionally, it is clear that increasing sensor size without increasing the number of photosites does *not* increase total resolution (LP/PH).

The resolution limits given here may not be a good yard-stick against which to compare test results of actual lenses and sensors, as shown by the two examples discussed above. With very few exceptions, current sensors use a Bayer array so that full color information can be interpolated for each image pixel. Interpolation reduces resolution. Many sensors also have anti-aliasing filters that can further reduce resolution. Lastly, sharpening (local contrast enhancement); and exposure, white level and black level adjustments are standard steps in digital image processing. They can be expected to *increase* fine-scale contrast in the "final" sensor image.

The introduction of sensors with high photosite counts in enthusiast and professional cameras — particularly full-frame cameras with 36MP sensors — has generated much discussion about whether current lenses are "good enough" in the sense that their resolving power can take advantage of the increased resolution of the sensors.[13] The current simulations don't really address that issue, in part because a perfect lens is assumed, but also because the effects of anti-aliasing and Bayer filters are not simulated. However, these simulations do suggest the ultimate

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[12] It is fortuitous that the total resolutions (LP/PH) are exactly the same in this example. Normally, rounding of the table entries to integers and the fact that the spacing of the standard f-values is not exactly 1.5x will result in slightly different values.

[13] A 36MP full-frame sensor has a photosite spacing of about 4.8 µm, which is not particularly small compared to the 4 µm photosites of a 24MP APS-C sensor, the 3.75 µm of a 16MP m4/3 sensor, or the 1 – 2 µm of a typical smart phone camera. Yet few people seem to worry about whether lenses for those cameras have sufficient resolving power.

limits to which digital images may be improved by better lenses, by removing anti-aliasing filters, and by developing sensors that record full color information at each photosite.[14]

[14] Post-capture image adjustment could improve fine-scale contrast even further.