Limits of Resolution. 7. Sensor Size

Phil Service
Flagstaff, Arizona, USA
20 January 2016

Summary

Larger sensors can achieve higher resolution than smaller ones only if they have more photosites. To date, the potential of full-frame sensors, in terms of image resolution, has been limited by the fact that FF sensors typically have relatively large photosites. A 36 MP FF sensor has 4.9 µm photosites, and a linear resolution of about 7,400 photosites on its long axis (3:2 aspect ratio). On the other hand, a 20 MP 1-inch sensor has 2.4 µm photosites, and a linear resolution of about 5,500 photosites on the long axis. The 35% increase in resolution provided by the FF sensor is much less than the actual difference in linear dimensions of the sensors — 172%. In order to exploit the full potential of larger sensors with respect to image resolution, it will be necessary to keep photosites small. That will involve some sacrifices in low-light performance, and entail costs in processing very large (> 100 MP) images. Also, in order to fully realize the benefits of photosite spacing of 2 – 3 µm, lenses must perform exceptionally well at f/2.8 – f/4: perhaps close to the theoretical limits set by diffraction. Assuming such FF lenses can be manufactured at reasonable cost, use of such relatively large apertures will compromise the ability to obtain appreciable depth of field while at the same time realizing increased resolution.

Key words: sensor size, image resolution, sensor pixel size, photosite size, line-pairs, equivalent cameras, equivalence

1. Introduction

Many commenters on photography forums note that it is often difficult, or impossible, to see differences in images made with sensors of widely varying sizes. I suggest two principal reasons: first, larger sensors tend to have larger photosites. Consider for example, 24 MP full-frame (FF) and APS-C sensors — approximate dimensions 36 x 24 mm and 24 x 16 mm, respectively. The photosite width, or pitch, of the FF sensor is 6 µm, and that of the APS-C sensor 4 µm. Both sample the image field with exactly the same number of photosites: 6,000 on the long axis of the image. In other words, *both images contain exactly the same amount* of "information", assuming that pixel-level image quality is the same.[1] The images recorded by the two sensors will be perceptually identical if "equivalent" focal lengths and apertures are used to

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[1] Throughout this paper, I make the assumption of "all other things being equal" unless stated otherwise. With regard to photosite size, it is well established that larger means less noisy, all other things …. Therefore, there is a widespread assumption that pixel-level image quality will be superior with larger photosites. However, noise, an important component of pixel-level IQ, will depend on ISO setting, which in turn will depend upon exposure time and aperture. Also, I assume that resolution is not limited by lens quality, and that the only source of image blur is diffraction: in effect, a "perfect" lens.

make images from the same position.[2] It follows that larger sensors can produce higher resolution images only if they also have more photosites. Increases in sensor size without concomitant increases in the number of photosites *may* lead to improved image quality, primarily through better control of noise and higher dynamic range (but see Footnote 1). Such improvements may be relatively minor, particularly for images made at low ISO.

The second reason it is often not possible to see effects of sensor size is that images are generally down-sampled for viewing. A typical 27-inch display is 2,560 x 1,440 pixels, or 3.7 MP — a considerably lower linear resolution than that of many cell-phone cameras. Thus, even if larger sensors have more photosites and are actually capturing more "information", that additional information may be lost because of greater downsizing for display. The highest resolution "consumer" display currently available (January 2016) is the 5K display of the 27-inch iMac, which is 14.7 MP (5,120 x 2,880). Even that requires downsizing for all but the lowest resolution current cameras.

What about printing? The short answer is that print size depends on the linear number of image pixels, which depends on the linear number of sensor photosites — not sensor physical size. For example, the Epson 3880 has a native print resolution of 360 pixels per inch (ppi). Thus, a 6,000 x 4,000 (24 MP) image will print natively at 16.7 x 11.1 in. The physical dimensions of the sensor to do not enter into the calculation. The longer answer admits that there might be differences in pixel-level image quality between 24 MP images made with sensors of different sizes (but see Sec. 2.1 below, and also Footnote 1). Nevertheless, if pixel-level image quality is similar for sensors of different formats but equal megapixel count, the prints will also be similar.[3]

Below, I expand this verbal argument with quantitative examples. The numbers for resolution limits as a function of photosite size and aperture are from previous papers in this series.[4] Please refer to those papers for more details. For convenience, I reproduce here two tables from one of those papers.

2. Quantitative Examples

A quantitative analysis will require that we consider images of line-pair charts. Specifically that we imagine charts in landscape orientation that are completely filled with equally-spaced vertical black and white line pairs. We will compare a nominal full-frame sensor (36 x 24 mm) with a 1-inch sensor (13.2 x 8.8 mm). Assume that we are using an 18.3 mm focal length lens in front of the 1-inch sensor. The "crop factor" for the 1-inch sensor is about 2.73.

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[2] This is the principal of "camera equivalence". Explanations can be found here and here (latter site by subscription only).

[3] The Epson 3880 has a second native resolution of 720 ppi. Thus, it is also possible to print a 12,000 x 8,000 (96 MP) pixel image at 16.7 x 11.1 in. Such a print might well display greater resolution and sharpness than a 24 MP image of the same size. But, the greater resolution comes from increasing the linear sampling of the image field (by having more photosites), not from having a larger sensor *per se.*

[4] Service, Phil. 2014. Limits of Resolution. 3. Diffraction and Photosite Size
Service, Phil. 2015. Limits of Resolution. 6. How Many Megapixels?

Therefore, focal length equivalence means that we will put a 50 mm lens in front of the the FF sensor.

2.1. Equivalent Cameras

To begin, let's consider the case where sensor size has no effect on image resolution — in other words, we have *equivalent cameras.* Therefore both sensors must have the same number of photosites. To be concrete, 6,000 x 4,000 photosites for a total resolution of 24 MP. In order to maintain similar depth of field, numerical apertures must also be scaled by the factor 2.73. If we use f/4 with the 1-inch sensor, we must use f/10.9 with the FF sensor, which is close enough to f/11. Note that if we use the same shutter speed on both cameras, the smaller FF aperture requires the use of a higher ISO setting — specifically a three "stop" increase to compensate for the three stop decrease in aperture. If the size of our line-pair chart is 1.5 x 1 m, the cameras need to be about 2.1 m from the chart in order for the chart image to completely cover the sensors.

The chart in question has 2,350 vertical line-pairs, as do the image fields. In the case of

Table 1. 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. This table and Table 2 from Service, Phil. 2014. Limits of Resolution. 3. Diffraction and Photosite Size.

the 1-inch sensor, that means that the image field contains 2,350 / 13.2 = 178 line-pairs per millimeter (lp/mm). Given an aperture of f/4 and a photosite size of 2.2 μm, it can be seen from Table 1 that the line-pairs will be captured by the sensor with a contrast ratio of about 50% (assuming a perfect lens). In the case of the FF sensor, the image field contains 2,350 / 36 = 65 lp/mm. Given the equivalent aperture of f/11, and 6 μm photosites, these line-pairs will also be captured with a 50% contrast ratio (Table 1). In other words, the captured images will look the same — we've used equivalent cameras to capture equivalent images.[5]

[5] If this result seems surprising, it may help to remember that all variables that affect the resolution of the sensor image are scaled by the same crop factor: 2.73 in this case. These variables are: the width of line-pairs in the image field, the width of photosites used to sample them, and the width of the diffraction blur circle that reduces the contrast of the line pairs.

2.2. Non-equivalent Apertures

What happens if we use the same line-pair chart and same lenses, but allow the FF sensor to be exposed at f/4, the same aperture used for the 1-inch sensor? FF photosite width is still 6 µm and the FF image field still contains 2,350 line-pairs at 65 lp/mm. The sensor will capture the line-pairs with a contrast ratio > 80% (Table 2) — an unsurprising result given that diffraction blur has been reduced to almost one-third of the value at f/11. Of course, the FF image at f/4 will have much less depth of field than the 1-inch image at f/4, although that will not matter in this case because we are imaging a two-dimensional object.

Table 2. 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.

2.3. Finer Detail

What happens if we double the number of line-pairs on the chart (to 4,700) while preserving the chart size? The image field for the 1-inch sensor will now contain 356 lp/mm, and the FF image field will contain 130 lp/mm. (Remember, we're still assuming that the lenses are capable of those resolutions.) In this case image-field line-pair frequencies are greater than the Nyquist rates for both sensors (Table 1), and the sensors may record aliased (false) line pairs or the sensor images will be a more-or-less uniform gray smudge.

2.4. Non-equivalent Sensors

The conclusion of the analysis thus far is that larger sensors *per se* do not increase camera resolution (lp/mm). Although if we are willing to sacrifice depth of field, larger sensors can record images with greater micro-contrast of high-frequency detail. In order to make images with greater resolution, larger sensors need to have more photosites than smaller sensors. In other words, the sensors are no longer equivalent. To illustrate, suppose that our FF sensor also has 2.2 µm photosites. That corresponds to a total sensor resolution of about 16,360 x 10,900 = 178 MP. If we use the 4,700 line-pair chart discussed in the previous section, the 1-inch and FF image fields contain 356 and 130 lp/mm, respectively. As before, the image recorded by the 1-inch sensor will have no (or false) detail because the image-field line-pair frequency exceeds the Nyquist rate for 2.2 µm photosites (227 lp/mm). On the other hand, the 130 lp/mm frequency in the FF image field is comfortably less than the Nyquist rate. The FF sensor will record 130 lp/mm with a contrast ratio close to 80% if the aperture is f/4. To put it more starkly, the 178 MP FF sensor can record an image with 4,700 high-contrast line-pairs, while the 24 MP 1-inch sensor, with the same photosite size, can record essentially nothing.

3. Discussion

3.1. Non-perfect Lenses

As I have stressed, the quantitative comparisons presented here are based on simulations that assume perfect lenses. That is, lenses with resolving power limited only by the physical laws of diffraction. In the real world, lenses are not perfect. Even so, the results presented here may have at least *qualitative* relevance. For example, in the case of equivalent cameras (Section 2.1), I concluded that larger sensors *per se* do not result in greater resolution. That conclusion should hold even without perfect lenses so long as the *ratio* of resolving power of the lenses is the same as the crop factor. In other words, we require that the lens for the 1-inch sensor at f/4 have 2.73 times the resolution of the FF lens at f/11 (with the same contrast).

I do not know if lens resolution scales at anything close to the crop factor. Is it reasonable to think that a lens designed for a 1-inch sensor will have 2.73 times the resolution (lp/mm) of a lens designed for a FF sensor, when aperture equivalence is maintained? If lens resolution scales with a ratio *less* than the crop factor, a large-sensor camera could have greater resolution than an otherwise equivalent camera with a smaller sensor.

3.2. Why Don't Full-frame Sensors Have More Photosites?

When Nikon, for example, introduced a full-frame DSLR (D3 in 2007), the sensor had the same 12 MP resolution as their then top-of-the-line APS-C camera (D300, also in 2007). Currently, many APS-C sensors are 24MP. A FF sensor with similar photosite size would have more than 54 MP. No current FF sensor has that resolution, although the 50.6 MP sensor in the Canon 5DS/R comes close. Clearly, sensor manufacturers have not been in a hurry to maximize resolution of FF sensors. The possible reasons fall into two broad categories: technological feasibility and customer demand. First, technological feasibility: large sensors with small photosites may be too difficult or expensive to manufacture. There is also the possibility of unacceptable image processing bottlenecks with very high resolution images. Lastly, it may not be possible to produce, at reasonable cost and size, FF lenses that have sufficient resolving power to take advantage of increased sensor resolution. In other words, the limiting factor for FF sensor photosite size may be lenses, not sensor technology. Consider that with 2.2 µm photosites, the Nyquist rate resolution would be 227 lp/mm. At f/4, diffraction-limited resolution (*i.e.*, without considering sampling by the sensor) is about 270 lp/mm with 20% contrast.[6] In other words, to take *full* advantage of 2.2 µm photosites when shooting at f/4, a lens would have to perform close to the theoretical limits set by diffraction. Maximum theoretical 20% resolution

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

increases to 386 and 540 lp/mm at f/2.8 and f/2, respectively. But it is a rare FF lens that performs better at f/2.8, or f/2, than at f/4.

With respect to customer demand, there may have been a perceived preference for improved noise/ISO performance, rather than more image pixels. (All other things being equal, ISO performance trades off with resolution.). Second, most images are displayed and viewed in a way that does not really require "super resolution". As mentioned earlier, 15MP is the maximum that permits an entire image to be viewed at 100% on today's highest resolution displays. Although I have argued elsewhere that even moderate-size (16 x 20) prints might benefit from the "capture oversampling" associated with sensor resolutions greater than 100 MP,[7] in practice 24–36 MP appears to be adequate to make high-quality 16 x 20 prints. And, in any event, fine-art photographic printing seems to be becoming something of a niche activity. In summary, even if there are no insuperable technological obstacles, demand for "super-resolution" sensors may simply be too low for sensor and camera manufactures to care.

[7] Service, Phil. 2015. Limits of Resolution. 4. Image Capture for Maximum Detail Printing.