Limits of Resolution.
4. Image Capture for Maximum Detail Printing

Phil Service
Flagstaff, Arizona, USA
31 January 2015

Summary

The maximum amount of detail that can be contained in an ink-jet print is set by the native resolution of the printer and the size of the print. In the case of the Epson Stylus Pro 3880, maximum detail requires that the image be printed at 720 pixels per inch (ppi). Printing at 720 ppi ensures that the *visible* detail in the print will be oversampled, and therefore printed with greater sharpness than if the image were captured with fewer pixels and printed to the same size at 360 ppi. In order to fully exploit the capabilities of the Epson 3880 in a modestly large (~ 50 cm) print, it is necessary to have an image on the order of 110 – 120MP. At present, the only way to make maximum-detail prints larger than 25-30 cm, is by stitching multiple frames to make larger images.

Key words: maximum print detail, print resolution, print sharpness, oversampling, Epson Stylus Pro 3880, Ming Thein, Ultraprint, image stitching, panorama, fine-art ink-jet printing, photographic printing

1. Introduction

Given the capabilities of a printer, and a desired print size, how can we ensure that the print will contain the maximum possible amount of detail with the highest possible acuity? The answer to that question has two parts. First we need to know the maximum amount of "information" that the printer can reproduce in a print of a given size. Second, we need to know how to capture that amount of "information" in a digital image. Those two concerns are the subject of this paper.

2. The Printer

For illustration, I will assume that the printer is an Epson Stylus Pro 3880. My largest prints are generally on 17 x 22 in. paper with 2 in margins. Thus the maximum printed dimension is usually 18 in. (45.7 cm). The 3880 has two "native" printing resolutions: 360 and 720 pixels per inch (ppi). Images that are not prepared for printing at one of those resolutions will be resampled by the printer, or printer driver, to either 360 or 720 ppi, depending on the setting chosen in the printer dialog.[1] 360 ppi corresponds to 180 line-pairs per inch or 7.0866 line-pairs per millimeter (lp/mm). The 3880 can, in fact, print a black and white line-pair pattern

[1] Checking the box labeled "Finest Detail" will result in 720 ppi printing.

at 7 lp/mm. When the line-pairs are "stacked" in the direction of paper transport, the pattern is crisp and visible to the naked eye at close range, with good light, when printed on glossy paper.[2] When the pattern is printed so that the line-pairs are "stacked" in the direction of print head movement, the individual line-pairs are still printed, but may require a loupe to be seen. 720 ppi corresponds to 14.1732 lp/mm. The 3880 can actually print line-pairs at that resolution provided that the line-pairs are, again, stacked in the direction of paper transport. However, a loupe is required to see them. Line pairs at 14 lp/mm are not resolved, even with a loupe, when printed across the paper. *For all practical purposes, then, the maximum visible print resolution of the Epson 3880 is 7 lp/mm, and that really in only one direction.*[3]

3. Image Capture Requirements

3.1. Hypothetical Case — No Lens or Sensor Limitation

Let's use line-pairs as a measure of the "information" that can be contained in a print. Our goal is to make a print with maximum information. For an 18-inch (45.72 cm) wide or tall print, the maximum information is 457.2 x 7.0866 ≈ 3,240 line-pairs. Therefore, to have a maximum resolution 18-inch print, we need an image file that contains 3,240 line-pairs of information in its long dimension.[4] A minimum of two sensor photosites is required to sample a line-pair in the image formed by the lens. However, a general rule-of-thumb is that a sampling rate of 4 – 5 sensor photosites per line pair is necessary to reproduce a line-pair pattern with good fidelity.[5] In other words, "oversampling" by the sensor is required to obtain a good sample of the lens image.[6] I'll use four photosites (2x "oversampling") for this example. That means that the camera sensor must have 4 x 3,240 = 12,960 photosites on its long axis. If the aspect ratio is 3:2, then the short axis will contain 8,640 photosites. The total resolution of the sensor will be 112MP — or about 3 times the resolution of the currently available 36MP "full-frame" cameras from Nikon and Sony. If the sensor is full-frame, the long dimension is about 36 mm, and the photosite pitch will be about 2.78 µm. The required resolution of the lens would be 3,240 / 36 = 90 lp/mm. I am not aware that any full-frame lens can resolve at that level with reasonably high contrast (≥ MTF50), nor is there a currently available 112MP camera.[7]

---

2 Note that this means that each black line of a line-pair is printed in the direction of print head movement.

3 Line-pairs printed in the direction of print head movement are visible to the naked eye at 6 lp/mm under optimal viewing conditions.

4 For the moment, I assume that the goal is to make the print from a single capture. I'll take up the subject of panoramas later.

5 Service, Phil. 2014. Limits of Resolution. 1. Sampling Frequency and Limits of Resolution. 3. Diffraction and Photosite Size

6 I use the term "lens image" to mean the image formed by the lens. The lens image is distinct from the sample of that image that is recorded by the sensor, which is the "sensor image".

7 The theoretical resolution, with 50% contrast, of a perfect lens at f/4 is ~ 150 – 200 lp/mm. Service, Phil. 2014. http://philservice.typepad.com/Limits_of_Resolution/Limits_of_Resolution_2_Diffraction.pdf

To print an image that is 12,960 pixels on its long dimension at 18 inches requires a printing resolution of 12,960 / 18 = 720 ppi. There are two consequences of printing the image at 720 ppi. First, some of the detail that is captured by the sensor and printed will be *invisible,* or nearly so, without the aid of magnification — specifically, detail that corresponds to capture at a spatial frequency of fewer than four photosites per line-pair — detail that has an equivalent resolution of *more than* 7 lp/mm on the print. Second, *visible* detail and edges will be captured and printed with higher acuity (sharpness) than would be the case if the image had half the linear resolution and the print were made at 360 ppi. That is because the visible detail, equivalent to seven or fewer line-pairs per millimeter, is effectively being oversampled — four or more photosites per line-pair. The net result of printing at 720 ppi is that more and more detail becomes visible as the print is inspected at closer and closer distances, right up the point at which the viewer can no longer focus on the image. In other words, the experience of viewing the print is like viewing any other physical, real-world object: we see more as we get closer.

In theory, images captured with resolution that permits printing at 720 ppi will have greater fine-scale contrast and edge sharpness than images captured with resolution sufficient for printing at 360 ppi at the same size. This, perhaps, is the true value of being able to print at 720 ppi. Visible resolution (lp/mm) is not appreciably greater than when images are printed at 360 ppi. However, 720 ppi printing permits a higher sampling rate of the lens image by the sensor — without entailing subsequent downsampling for printing.

3.2. Actual Lens Resolution 50 lp/mm

A high-quality full-frame lens might realistically have an MTF50 resolution of 50 lp/mm. Assuming again 2x oversampling, a full-frame sensor would need 200 photosites/mm or 7,200 photosites on its long axis. Given a 3:2 aspect ratio, the sensor would be 7,200 x 4,800 = 34.6MP — essentially the same as the Nikon D810 or Sony A7R. Since we are assuming 4 photosites/lp, the maximum amount of good-quality information that will be captured in a single image is 7,200 / 4 = 1,800 line-pairs. That is much less than the 3,240 line-pairs of information that the Epson 3880 is capable of displaying at 18 in. There is no bar to making a print that is 18 in. wide. In fact, it could easily be an excellent print — it just wouldn't contain the maximum amount of information that the printer is capable of displaying. If printed at 360 ppi, the image would actually be 20 in. wide, so very modest downsampling would be necessary to print at 18 in. Printing at 720 ppi without resampling would result in a 10-inch print. In order to make a maximum-detail 18-inch print with this lens + sensor combination, it would be necessary to stitch several images together in order to make an image with 3,240 line-pairs of information.

3.3. Unknown Lens Resolution

For the most part, we do not know the actual resolutions, in line-pairs per millimeter, of the lenses that we use.[8] However, if a lens is well matched to the sensor, we can reasonably expect that the sensor image resolution, with good contrast, will be equivalent to one line-pair per four photosites. In other words, if the sensor has 6,000 photosites on its long axis, a

[8] Ideally, we would like to know the "true" resolving power of lenses — that is, independent of the sensor used to record images.

reasonable estimate of the sensor image information is 6,000 / 4 = 1,500 line-pairs. Again, this is far fewer than the 3,240 line-pairs required for a maximum-detail 18-inch print.[9] To print the image at 18 in. and 360 ppi would require very modest upsampling from 6000 to 6480 pixels.

3.4. Image Stitching (Panoramas)

The above examples argue that, with current lenses and cameras, it will be necessary to combine multiple frames in order to create an image file that can fully exploit the capabilities of the Espson 3880 in an 18-inch print. Specifically, we need to create an image with a total information content equivalent to 3,240 line-pairs. If we again assume that the resolution of the imaging system is one line-pair per four photosites, the final stitched image will need to be 12,960 pixels wide. Suppose that the scene that we want to capture, can be photographed in a single frame in landscape orientation with a 24 mm lens, and that we are using a camera with a 24MP (6,000 x 4,000) APS-C sensor. With a 24 mm lens, the horizontal and vertical fields of view are 52.4º and 36.0º. To make the stitched image, we need a lens that has a horizontal field of view of (6,000 / 12,960) * 52.4 = 24.3º. The required focal length would be about 55 mm.[10] A 55 mm lens on an APS-C sensor has horizontal and vertical fields of view of 24.6º and 16.6º. To make the captures for the stitched image, we might well turn the camera to portrait orientation in order to lose as little as possible of the "original" 36º vertical FOV. Now, we need to capture 52.4º horizontally in increments of 16.6º. If we allow 30% overlap between images, then each image in the series is effectively capturing 16.6 x 0.7 = 11.6º. Therefore we will need 52.4 / 11.6 = 4.5 images in the series in order to make the desired final image, which can be printed at 720 ppi.

The many issues in making panoramas do not need to be elaborated here. Suffice it to say that there are challenges in capturing the image sequence in the first place; and then subsequently in combining the separate captures to make a final stitched image. Panoramas are simply not possible with some types of subjects.

3.5. Ming Thein and Ultraprints

Ming Thein makes and sells what he calls Ultraprints. He does not share detailed information about the process behind ultraprinting, but it appears very similar in practice to the maximum-detail image capture and printing that I have described above. Here is some of what he has to say about Ultraprints:[11]

> The Ultraprint resolves at the equivalent level of 720 PPI; that's beyond the naked human eye's ability to distinguish. What this means is that we can look at the prints as near as our eyes will focus, and there will *still* be the impression of more detail – you really need a 3-5x magnifying loupe to fully appreciate how much detail is in one of these prints. Think of it as the condensed essence of the image.

---

[9] Note that when resolution is expressed as photosites per line-pair, the physical dimensions of the sensor and of the photosites no longer need to be specified.

[10] I assume that camera position remains unchanged in order to maintain perspective.

[11] http://blog.mingthein.com/2014/02/27/introducing-the-ultraprint/

> Production of an Ultraprint starts with the right file: a perfect, sharp-at-100%-actual-pixels 36-39MP (D800E, CFV-39) capture will yield a clean 10×15″ image. Any larger, and you can see that the process is capable of resolving more detail. Our tests have found that ~720 PPI is the maximum the print process can resolve; you can clearly see the difference between a 16MP and 36MP capture at 10×15″, but not at 8×12″.

Note that a D800 image has 7,360 pixels on its long axis. To print it at 15 in. and 720 ppi would require relatively modest upsampling to 10,800 pixels.

4. Discussion

I frequently read comments to the effect that 16MP or 24MP images are "large enough." I think that is true for most images because they will never be printed at large size: in fact probably never printed at all. The 27-inch display that I am currently working on has a resolution of 2560 x 1440 = 3.7MP. The spatial resolution is 109 ppi. Even the 5K display of the current iMac has a total resolution of "only" 14.7MP (at 218 ppi). Smart phones such as the iPhone 6 have much greater linear pixel densities (326 ppi), but total resolutions of only about one million pixels. Thus images are typically viewed on low-resolution devices. For the uses to which most images are put, we do not need 100+ megapixel cameras. But for making large prints, this paper argues that such cameras would be very welcome. It is not clear that the current demand for such cameras is large enough to encourage their development and marketing.

There may also be technical hurdles to overcome. More photosites in the same area means smaller photosites, which means that noise will be more apparent. Also, small photosites on large sensors may place unrealistic demands on lens resolving power. The very large files that will result will require greater in-camera data processing bandwidth. In short, the road to super-resolution camera sensors may be long and difficult.

Finally, nothing in this paper should be taken to mean that excellent, highly detailed large prints cannot be made with images from current cameras. I regularly print 18-inch images from 14.75MP Sigma DP Merrill files. Before upsampling to 360 ppi for printing, the resolution is 261 ppi. Anyone who prints images from a Nikon D800 knows that 36MP is enough for excellent, large prints. The point of this paper, however, is that even 36MP does not exploit the full capability of a printer such as the Epson 3880 when making large prints.