

Impact of CCD Size, Pixel Pitch, and Anti-Aliasing Filter Design on Sharpness of Digital Camera Prints

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Abstract

This paper analyzes the impact of several anti-aliasing filter and pixel pitch combinations on the sharpness of prints made from a digital still camera. MTF curves for the components of the system are shown, as well as the final cascaded system MTF curves. The comparisons illustrate how system performance depends on many factors that limit sharpness. The number of pixels captured is not always the most limiting factor. The MTF curves also illustrate how improvements in sharpening can only partially compensate for the sharpness loss caused by an optical anti-aliasing filter.

This analysis is a case study of alternatives for digital cameras that are based on existing professional 35 mm SLR camera bodies—the context for current Kodak Professional digital cameras. This context presents some complications not found in the design of most consumer digital cameras. Thus, the careful comparison of possible compromises from a system perspective is worthwhile.

System Specification

The quality of prints made from a digital camera is affected by many camera components. Analyzing combinations of pixel pitch, CCD size, and anti-aliasing filter designs would be quite arbitrary without specifying other system components, such as the camera lens and the output device. In fact, a complete analysis would probably include several variations of these other components to examine design sensitivity and manufacturing tolerances. However, to keep this analysis short enough for a single paper, these other components will be fixed.

Camera Body and Lens

The camera system used as an example in this analysis is a digital SLR camera, specifically, one based on an existing 35 mm SLR body. The lens is a typical 50 mm lens working at f/8 that provides excellent, although not outstanding, lens performance. If we chose a lens that was less sharp, that would de-emphasize the importance of other factors in the design.

The selection of this camera body and lens has several implications. One is that the maximum useful sensor size is roughly 24 mm x 36 mm. In practice, cost usually keeps the sensor smaller, but this is the upper limit used in this analysis. A second implication is that the lens and camera body cannot be scaled down to work with a smaller sensor. Because the lens MTF is optimized for a 24 mm x 36 mm field, using extremely small pixels does not necessarily result in significantly better system MTF.

Processing and Print Output

In keeping with the goal of selecting an analysis system that is realistic, but not limiting, the output print is 11 inches by 16.5 inches, made by a continuous tone Kodak thermal printer at 300 dpi.

Following a common practice for best image quality, sharpening is performed on the output image after it has been interpolated to the final print size. This has the advantage that the size of sharpening kernel used is not strongly dependent on the size of image produced from the camera.

Anti-Aliasing Filter Background

The anti-aliasing filters used in this analysis are all birefringent filters with square spot patterns. Many digital cameras have similar filters. The design of these filters is fairly conventional—the spot pattern is optimized based on the resolution of the CCD.

Kodak currently manufactures a range of digital cameras with different sensors and several different pixel pitches. Whereas these cameras are developed using existing 35 mm SLR bodies, the anti-aliasing filter must fit in a fairly narrow location in the optical path. It is challenging to retrofit anti-aliasing filters into these existing systems, especially to design a filter that is easily manufactured. For these reasons, the design of a new camera includes consideration of currently available parts, even if the aliasing performance is sub-optimal relative to the pixel pitch.

Another variation of interest in this analysis is the option of having no anti-aliasing filter. This is of interest for several reasons:

- Having no anti-aliasing filter provides maximum sharpness (although at the cost of leaving aliasing artifacts).
- Previous Kodak Professional cameras have had no anti-aliasing filter (some customers grew accustomed to dealing with the aliasing).
- Current Kodak Professional cameras have removable anti-aliasing filters.

The sharpness of a new Kodak Professional camera design is evaluated both with and without anti-aliasing filters.

Specific Cases

The CCD sensors that were considered for this study are shown in Table 1. There are several factors that affected the selection of these alternatives. The 5.1 million pixel sensor with a 13 µm pixel pitch fills a 24 mm x 36 mm frame. The 10 million pixel sensor with a 9 µm pixel pitch also fills a 24 mm x 36 mm frame. The current market for digital cameras includes models with roughly 2 million, 3 million, and 6 million pixels. Current Kodak Professional camera models include:

- The Kodak Professional DCS 520/620 digital cameras: 2 million pixels, 13 µm pitch
- The Kodak Professional DCS 560/660 digital cameras: 6 million pixels, 9 µm pitch
- The Kodak Professional DCS 330 digital cameras: 3 million pixels, 9 µm pitch[1]

Because smaller pixels sizes have many convenient properties, this study also includes a set of sensors with 7 µm pixels.

Table 1. CCD Sensors Considered

CCD Pixel Pitch (µm)	Pixel Count (millions)	Case
7	2	
7	3	
7	5.1	
7	6	
7	10.7	
9	2	
9	3	DCS 330 camera
9	5.1	
9	6	DCS 560/660 cameras
9	10.7	Full 35 mm
13	2	DCS 520/620 cameras
13	3	
13	5.1	Full 35 mm

[1] The Kodak Professional DCS 330 digital camera has a 3:4 aspect ratio (1.5K x 2K) rather than the 2:3 aspect ratio used in this study. The results aren't changed substantially; the resize factor (for this print, with a 2:3 aspect ratio) goes up by 4%.

The anti-aliasing filter combinations considered include four different spot separations: 7.6 µm, 8.6 µm, 11 µm, and 15 µm. The 11 µm spot separation is used in current Kodak cameras, primarily due to manufacturing considerations and the constraints of fitting a filter within the exiting SLR bodies.

However, not all of these spot separations are of interest for each sensor. The combinations of pixel pitch and filter spot separation used in this study are shown in Table 2.

Table 2. CCD Sensors and Filter Spot Separations Used

CCD Pixel Pitch (µm)	Filter Spot Separation (µm)	Case
7	0	No AA filter
7	7.6	
7	8.6	
7	11.0	
9	0	No AA Filter, 330, 560/660
9	7.6	
9	11.0	330, 560/660
13	0	No AA Filter, 520/620
13	11	520/620
13	15	

The 8.6 µm filter was selected to maintain the same spot separation to pitch ratio currently used in the DCS 330 and DCS 560/660 cameras (11/9), but for a 7 µm pitch. The 7.6 µm filter was selected to maintain the same spot separation to pitch ratio currently used in the DCS 520/620 cameras (11/13), but for a 9 µm pitch.

Basic Component MTF Data

Figure 1 shows a plot of component MTF curves (green channel only) for the camera optical components:

- CCD pixel pitch
- Anti-aliasing filter spot separation
- Camera lens

The full calculation of the sharpness index includes red, green, and blue channels, but the filter and resolution effects being studied are achromatic. Thus, the differences from case to case are illustrated clearly enough by showing a single channel in the plots.

Figure 1 illustrates the relationship of the anti-aliasing filters to the pixel pitches, making quite clear that a significant sharpness loss occurs when anti-aliasing filters are used to reduce or eliminate color aliasing artifacts. It also illustrates that once the pixel pitch is as small as 7 µm, the CCD aperture MTF is no longer much lower than the lens. In other words, for a small pixel pitch, the lens MTF has at least as large an impact on system MTF as the CCD itself.

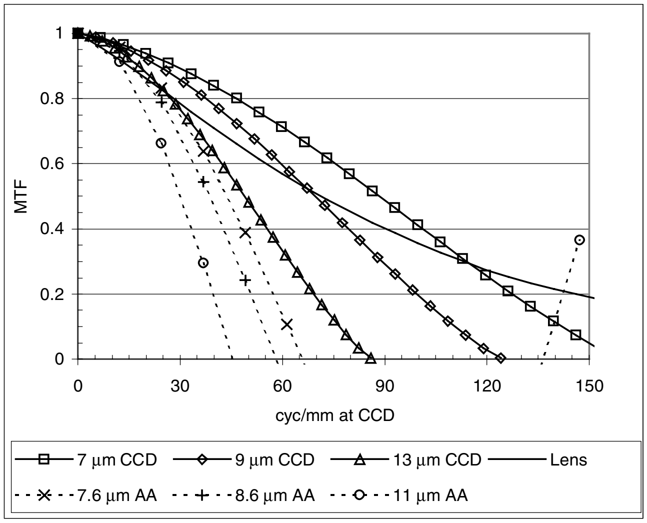

Figure 1. Component MTF data

The basic MTF curves show the component MTF data as it is usually measured, but the scaling of the frequency axis is not very useful for comparing the sharpness of prints made using different system components. For this purpose, the MTF data are scaled to a common frequency axis of cycles/degree at the viewer's eye, making the number of pixels on the sensor a significant factor. This is shown by plotting the CCD aperture MTF in cycles/degree, shown in Figure 2.

Figure 2 shows how resizing the image from the sensor size to the print size (3300 x 4950 pixels) rescales the original component MTF data along the frequency axis. This frequency rescaling happens for all the camera component MTF curves: the lens, the CCD, and the anti-aliasing filter.

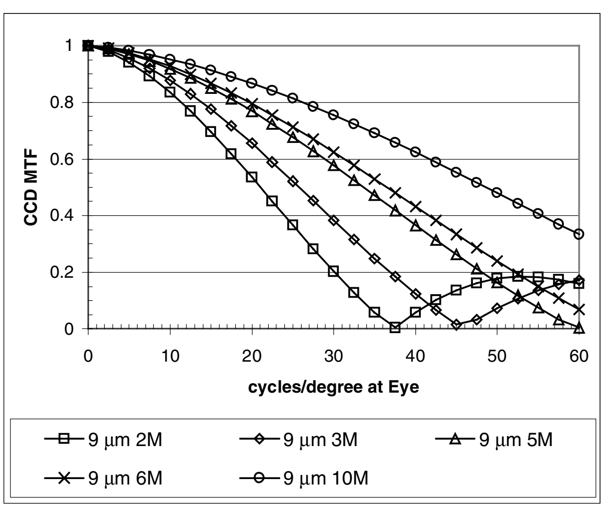

Figure 2. CCD aperture MTF scaled for viewing

Figure 3 shows a plot of lens MTF that illustrates this. The camera lens is plotted in cycles/degree for the various 9 µm and 13 µm sensor sizes. Because the 9 µm 10.7 million pixel sensor and the 13 µm 5.1 million pixel sensor fill the same lens field, the lens MTF curves for these two cases overlap. The curves for the cases with the 7 µm sensor are not shown here, but they would indicate still lower MTFs for a given starting image size.

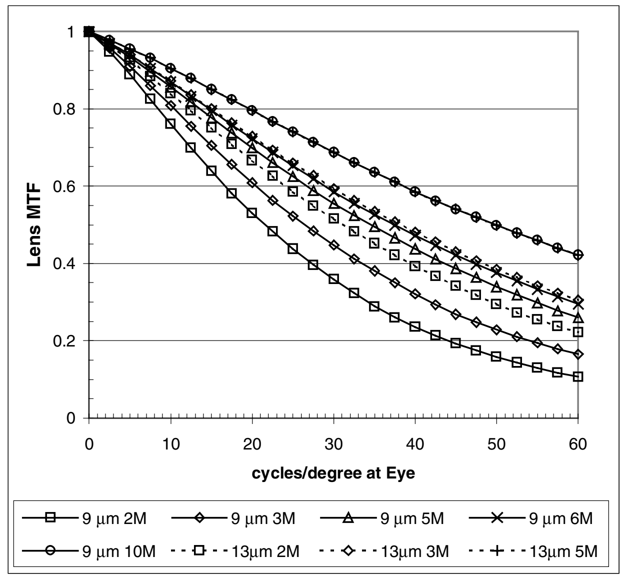

Figure 3. Lens MTF scaled for viewing

Sharpness Index

The component MTF curves are useful for observing underlying details, but the sharpness index provides a more complete system assessment. The sharpness index is computed from the component MTF curves (discussed in previous papers by Keelan[1] and Wheeler[2]). Figure 4 shows a plot of computed sharpness index for the system configurations considered. To make the dependence of sharpness index on system configuration more apparent, sharpening gain was fixed. The sharpening used here was a 7-tap separable unsharp mask, with a gain of 4.0.

This figure illustrates many important points. First, the differences due to sensor size (that is, number of pixels) diminish as the total number of pixels increases, because other components have an effect as well.

Impact of Capture Lens MTF

This analysis also shows the system impact of the lens MTF compared to the CCD response. As expected, the sharpness of the 7 µm pixel with the 8.6 µm anti-aliasing filter is similar to that of the 9 µm pixel sensor with an 11 µm filter. More precisely, because of the effect of lens MTF, the 9 µm pixel system with an 11µm filter is bracketed by the 7 µm systems with 7.6 µm and 8.6 µm filters. If the system requirements suggested precise optimization for this particular lens, the anti-aliasing filter spot separation could be adjusted to compensate for the difference in lens MTF.

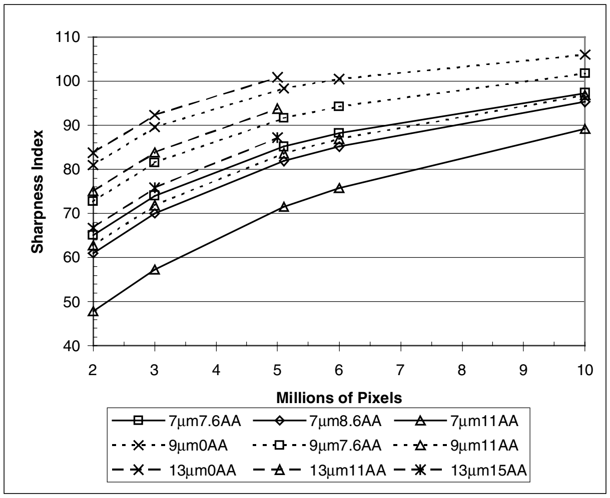

Figure 4. Sharpness index (fixed gain)

Table 4. 8.6 µm to 7.6 µm Spot Separation Sharpness Difference

Size	Sharpness Index			Delta SI		Ratio
	7.6	8.6	11	8.6-7.6	11-8.6	
2	65.1	61.0	47.8	-4.1	-13.2	3.2
3	74.0	70.9	57.3	-4.0	-12.8	3.2
5.1	85.2	81.9	71.6	-3.3	-10.3	3.1
6	88.2	85.2	75.8	-3.0	-9.4	3.1
10	97.3	95.3	89.2	-2.0	-6.1	3.0

Cases without Anti-Aliasing Filters

The systems with no anti-aliasing filters, of course, provide the greatest sharpness, although in practice they will be vulnerable to many aliasing problems. A more complete system analysis would include the impact of aliasing and reconstruction errors.

Impact of Changing Spot Separation

The sharpness loss due to the anti-aliasing filter increases with the filter's spot separation (the increase is greater as the spot separation increases). For example, consider the systems with a 7 µm pixel pitch. The sharpness difference between the 11 µm and 8.6 µm filters is about three times the difference between 8.6 µm filter and 7.6 µm filters. This sharpness difference is tabulated in Table 4. This is consistent with the fact that larger spot separations cut camera frequency response at lower frequencies, where other components have larger MTF values.

Ratio of Spot Separation to Pixel Pitch

Figure 4 shows that the ratio of anti-aliasing filter spot separation to pixel pitch is one of the most important factors in these systems. The curves for systems with similar separation/pitch ratios are fairly close. Specifically, note how close the 13 µm pixel/15 µm filter curve is to the 9 µm pixel/11 µm filter curve and the 7 µm pixel/8.6 µm filter curve.

Comparing current Kodak Professional cameras, we find an unusual relationship, though one that has been confirmed empirically. Specifically, the DCS 520/620 cameras are somewhat sharper than the DCS 330 camera. The price for the increased sharpness is that the DCS 520/620 cameras are more vulnerable to aliasing. Conversely, if we wished to design a camera with a 9 µm pixel pitch and an 11 µm filter, it would need roughly 3.5 million pixels, rather than 3 million, to have comparable sharpness.

A natural response to these results is to increase sharpening for softer images. This works to a point, but at the price of emphasizing noise and reconstruction artifacts. In fact, at the smaller sensor sizes (two and three million pixels), the image cannot effectively be sharpened enough because so much image content is lost in the optics and sampling. Referring back to Fig. 1, no amount of sharpening can replace the image data lost where the zero in the anti-aliasing filter MTF occurs. The increased sharpening can only amplify the modulation preserved at lower frequencies.

Figure 5 shows the effect of increasing the sharpening for softer images. Several sharpening gains were considered for each system and the ones shown are those that came closest to a sharpness index of 100, while still limiting the quality loss caused by oversharpening and other artifacts.

The sharpening gains used for Fig. 5 were not precisely optimized, partly because even an approximate gain adjustment shows that the relationship between cameras is mostly preserved at low resolutions. That is, if we adjust the sharpening for each camera, we can still adjust the sharpening for the 2 million pixel sensor with a 13 µm pitch and 11 µm filter to be at least as good as the 3 million pixel sensor with a 9 µm pitch and an 11 µm filter. Again, the underlying loss of data cannot be fixed.

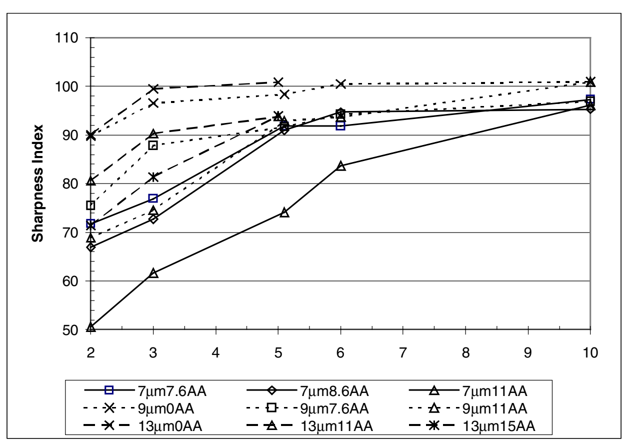

Figure 5. Sharpness index (adjusted gain)

If we were designing the sharpening for all three cameras in a coordinated fashion, we could consider reducing the sharpening applied to the DCS 520/620 camera images. However, this would be somewhat artificial, and users would probably sharpen to get the sharpest image they could.

Conclusion

This system analysis case study demonstrates the importance of considering systems optimization in a multivariate fashion, especially when nonlinear effects and constraints are present.

This case study also highlights the importance of the relationship between the anti-aliasing filter spot separation and the pixel pitch, at least for sharpness.

While this case study deliberately left aliasing and noise out of the optimization, a complete study would include both of these effects as well. Of course, the relationship of spot separation to pixel pitch is the most critical factor for controlling aliasing performance in these systems.

From a sharpness perspective, more pixels are always better (other things being equal). However, other factors are often not equal, and this kind of system analysis allows the quantitative consideration of the tradeoffs between different factors.

In this study, the relationship between the aliasing filter spot separation and pixel pitch has a stronger effect on sharpness than the number of pixels in the sensor. That is, going from a ratio of 11/13 to 11/9 (roughly a 40% change) requires a change in the number pixels from 2 million to about 3.5 million to produce similar sharpness, roughly a 75% change.

References

1. Brian W. Keelan, *Characterization and Prediction of Image Quality*, *Proc. PICS, (2000).*
2. Richard B. Wheeler, *Use of System Image Quality Models to Improve Product Design, Proc. PICS, (2000).*

Biography

Bruce Pillman received his B.S. degree in Chemical Engineering from Northwestern University in 1982 and an M.S. in Electrical Engineering from the University of Rochester (NY) in 1992. He joined Eastman Kodak Company in 1982, working in chemical process research & development. Since 1992, he has worked in the development of digital scanners. His work has included color calibration, image processing software, system image quality evaluation, and image chain modeling and simulation.