Measuring and Managing Digital Image Sharpening

Don Williams, Image Science Associates, and Peter D. Burns, Carestream Health, Inc, Rochester NY, USA

Abstract

With the development of digital image collections, comes the opportunity to capture and manipulate captured object information not previously available with photographic methods. With this advantage, however, come a host of choices beyond selection of image capture hardware, and acquisition software. In establishing imaging practice for a particular institution or project, it is important to understand the influence of the various choices on imaging performance. While this need is well understood for color management, it is less often considered in the capture of image detail. Captured image detail, and the related visual impression of image sharpness are commonly manipulated during image capture by image processing aimed at 'sharpening' the digital images. We propose an approach for sharpening management within the framework of existing ISO standards by use of the spatial frequency response (SFR) as referred to a known or implied SFR aim.

Introduction

For image capture and storage systems, image quality requirements are often described in terms of the intended use of the digital image content. For the consumer the quality of an image will usually depend on the perceived degree of excellence of the viewed or printed scene, which is often compared to the memory of a particular time, place and event. There are two basic aspects of image quality; the subjective impression of a viewer, and the technical or design details of the product or service that are needed to satisfy the customer's needs or desires.

In this paper, we focus on the influence of imaging practice and digital image processing (software) on the capture of image detail. We start with the premise that the management of imaging performance requires a good understanding of what imaging characteristics are important, and a reliable way to make objective measurements of them.

Our approach is similar to that used in the development of color management programs. If color accuracy is important, as it usually is for archives and museums, establishing a colorimetric objective (desired color encoding) is a first step. Successful quality assurance then requires consistent periodic measurement of performance against the acceptable color-tolerances. Without these two steps, the best color-profiling system may deliver variable or inaccurate imaging performance. As for color measurement, the development of procedures for managing the capture of spatial detail has benefited from the development of performance standards for other applications. For example, the understanding of the factors that influence captured image sharpness has been helped by shifting away from simple sampling rate in favor of current ISO standards for spatial frequency response (SFR).

One operation that is a common part of the digital imaging path is digital image sharpening. Generally, any operation that is aimed at modifying the visual impression of image detail, or sharpness, can be call image sharpening. Perhaps the most common time to apply sharpening is during image editing. Many image acquisition software (driver) programs also apply similar spatial image processing operations. Sharpening selection options, however, are often ambiguously labeled, e.g., 'soft-look', 'standard'. Adobe Photoshop® software offers five different sharpening filter operations with a range of user interfaces. It is not surprising, then, that common selection, and evaluation practice for image sharpening is qualitative and subjective. This can lead to variability of performance and confusion when comparing different systems.

We propose an approach for sharpening management by use of the spatial frequency response (SFR) as referred to a known or implied input SFR aim. This idea was previously addressed by MacDonald.[1] A method for routine performance evaluation will be described, along with the required test targets and analysis. Interpretation of results from collection images, and measurements will be emphasized.

What is the SFR?

Slanted-edge analysis has been applied to the evaluation of digital camera resolution for several years.[2-3] This method is based on the image (or system output) due to an input edge feature of high optical quality. Often the measured edge response can be taken as an estimate of the MTF of the system. In other cases, the output modulation is divided by the input edge modulation frequency-by-frequency to yield the measured system MTF. In this paper we will refer to a measured or idea edge-based MTF as an SFR.

Spatial frequency response (SFR) is a curve that characterizes how an imaging system maintains the relative contrast of increasing spatial frequency detail. The input variable along the horizontal axis of the SFR curve is spatial frequency, increasing to the right. Higher spatial frequencies translate to more finely spaced details. The output response along the vertical axis is the relative fraction of transfer (preservation) of contrast from object to digital image by camera or scanner. Ideally, one would like to maintain sufficient contrast of low, moderate, and high spatial frequencies. This is reflected by the SFR curve remaining relatively high with increasing spatial frequency (*i.e.*, along the horizontal-axis). A typical SFR plot demonstrating this behavior is shown in the highest SFR plot, corresponding to the rightmost image, of Fig. 1.

Due to factors such as lens design, assembly and defocus, and camera motion, blurring of the image occurs. This progressively reduces the spatial frequency content in the digital image, and is seen as a reduction in contrast and merging the light spaces with dark lines. Spatial details ultimately become unresolvable because so little contrast exists between adjacent image areas. The spatial frequency at which fine detail is no longer detectable, either visually or by machine, is the limiting resolution. For many cases, this limiting resolution occurs at the spatial frequency corresponding to a 10% response level of the SFR.* This value is consistent with historical treatments of resolving power and effective resolution over the past century. It is also correlates well with proposed ISO software solutions for reporting summary measures of camera resolution under ISO 12233 edition 2.[4]

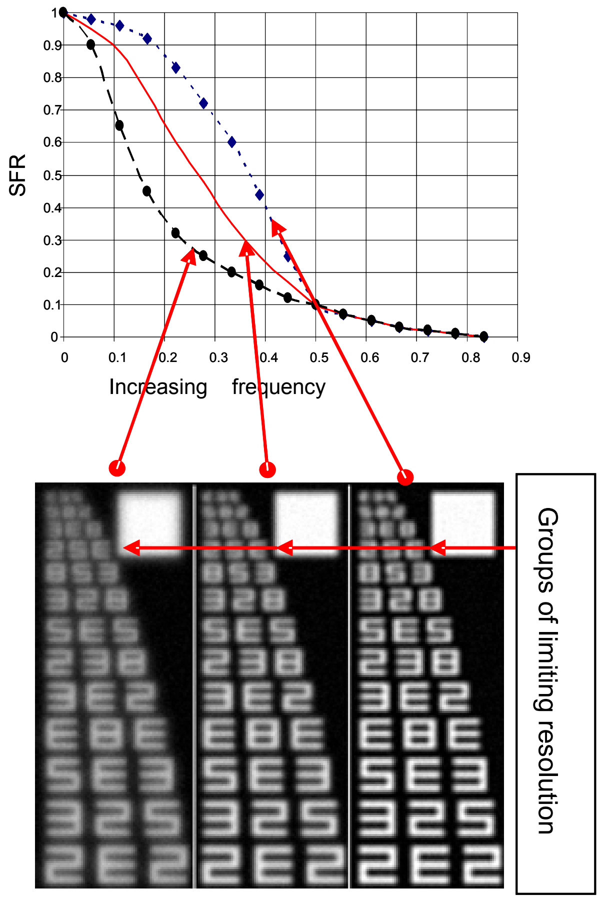

Figure 1: SFR plots (top) and associated images demonstrating image sharpness and limiting resolution

Though limiting resolution is a reasonable summary metric for objectively reporting spatial resolution, it does have limitations, particularly in predicting image sharpness.

For instance, using a 10% SFR criterion, all of the images in Fig. 1 have the same limiting visual resolution. This is indicated by the loss of text visibility at the fourth text grouping from the top in each case. Notice, however, the remarkable differences in image sharpness between the three images. The rightmost clearly has the best image quality. The higher SFR values at all of the spatial frequencies in the companion graph predict this. This is followed by the middle and left most images with decreasing image sharpness, but equivalent limiting resolution.

Figure 1 illustrates the importance of focusing on the low to middle spatial frequency range for the measuring and predicting of perceived image sharpness and overall quality. This fact has not been lost on the image processing community and is the region where digital sharpening operations are generally beneficial, when applied in moderation.

Sharpness vs. Sharpening

It is often said of digital imaging that *sampling is not resolution*.[5] Image sampling indicates the interval between pixels on a particular plane in the scene (camera), or on the object (scanner). Limiting resolution refers to the ability of an imaging component or system to distinguish finely spaced details. Although image sampling (e.g. 300 ppi vs. 600 ppi scanning) can enable a level of detail in a digital image, it is not the same as, and does not guarantee, the capture of a particular level of limiting resolution. High image sampling is a necessary but insufficient condition for resolving detail.

Likewise, high (perceived) limiting resolution does not guarantee an overall impression of high sharpness in a displayed image. This was shown recently in Fig. 3 of Ref. 5, part of which is reproduced in Fig. 2. This graph shows the measured spatial frequency response, of the two image capture paths from digital still cameras. The results are based on the standard analysis of an edge feature in a sample image from each camera. The differences in the solid and dashed black lines at high frequencies help explain the perception of limiting resolution for the two systems. The frequency at which the SFR falls to 10% is indicated as the measure of limiting resolution. The system responses in the lower frequency range, 0.1-0.2 cy/pixel correspond to the differing impression of image sharpness from the two systems.

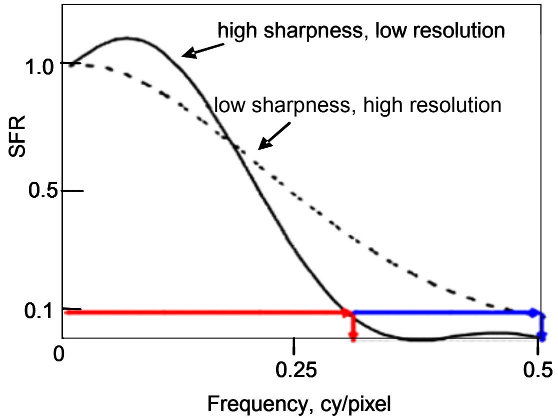

Figure 2: Measured spatial frequency responses for two digital camera paths. Unsharp capture followed by digital sharpening (solid line), and well-focused optical capture without sharpening (dashed). From Ref. [5].

As indicated by the caption for Fig. 2, the camera image corresponding to the solid line had been subjected to an image sharpening operation. Many digital cameras and scanners apply such image processing operations as a routine part of image capture. These operations can take many forms, but all aim to enhance certain important image content. Sharpening image processing operations operate on a digital image after capture, and so do not completely compensate for, e.g., poorly focused optics, but can be useful in improving the appearance of an image after capture. Sharpness is a visual attribute of a displayed image, and there are image quality models which attempt to predict the level of sharpness that a viewer would perceive. Understanding both image sharpening operations and sharpness models can be done using the spatial-frequency description provided by the system SFR.

Several models have been developed for image sharpness, based on the system SFR. If a viewer observes a displayed or printed image, then the sharpness metric, often called acutance in the photographic literature, is based on an integrated weighting of the system SFR. Since the SFR is a measure of the transfer of image information (contrast), one can argue that the viewer does not 'see' the SFR, but the SFR indicates the likely reproduction of a distinct object in the viewed image. The relative importance to an observer of image information as a function of spatial frequency is often expressed as a visual Contrast Sensitivity Function (CSF). A commonly-used CSF weighing is shown in Fig. 3. [6] While this is used in the prediction of image differences (often from ideal or standard version), it is similar to several weighting functions for image sharpness modeling.

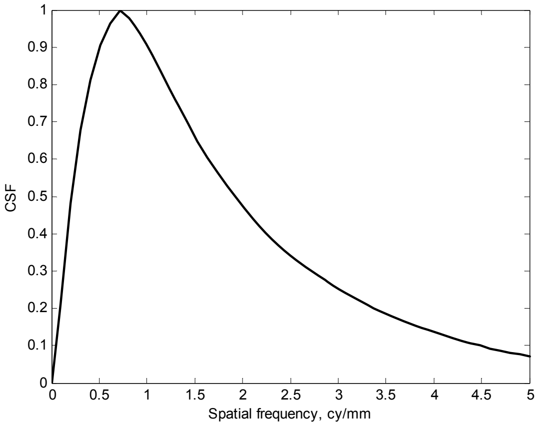

Figure 3: A visual contrast sensitivity function commonly used for image quality modeling. A viewing distance of 0.3 m, and luminance of 100 cd/mm2 are assumed. This is the cross-section along x- and y-axis.

Sharpness Metric

A typical sharpness metric, CMT acutance [7] is computed as follows. First the system (object-to-display) SFR is measured, then weighted by a one-dimensional CSF

$$a = \int_0^{f\max} SFR_{system}(f)CSF(f)df \,. \qquad (1)$$

This value is then scaled by the corresponding value for an ideal system, where $SFR_{system} = 1$. The visual response value, *R*, is the ration

$$R = \frac{a}{\int_0^{f\max} CSF(f)df} \,. \qquad (2)$$

This value is then modified to give the computed sharpness value for the system,

$$CMT = 100 + 66\log_{10}(R) \,, \qquad (3)$$

where *R* is constrained to the range [0,1].

Measuring sharpening using SFR.

Sharpening operations are manifest through the SFR. Among the many reasons for adopting the SFR as a standardized protocol is its resiliency in detecting sharpening behavior in images. In fact, image scientists and engineers have used it to build 'image quality' into digital cameras and scanners. This makes it a valuable tool for managing sharpening too. Figure 4 compares SFRs from the same camera system where sharpening has been applied at increasing levels.

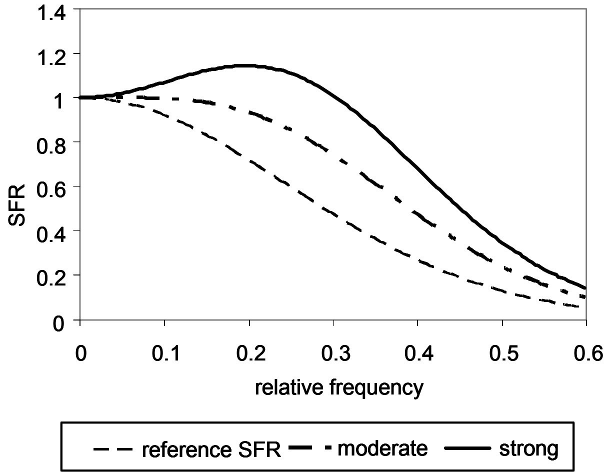

Figure 4: Examples of increasing digital sharpening amounts relative to a reference SFR without sharpening

The SFR where no image sharpening is applied can be considered ideal for a digital capture device. It has a naturally occurring monotonically decreasing shape characterized by an initial high response that decreases to 10% at the half sampling frequency (0.5). The two companion SFR curves of Fig. 4 are from images with increasing amounts of sharpening applied that range from mild to strong. Notice how a characteristic SFR "bump" occurs as the sharpening becomes more aggressive. This SFR bump is a signature behavior of digital sharpening operations. If its maximum amplitude becomes too great, typically greater than 130-150%, over-sharpening artifacts such as haloing (Fig. 5) can occur in the image. Exploiting such SFR behavior for measuring sharpness is our proposal. The cited amplitude rules could be one simple technique for measuring sharpness, and in turn monitoring and managing it.

Figure 5: Example of haloing effect around characters due to aggressive over-sharpening

Why does sharpening need to be managed?

Some practitioners will claim that they can already measure, and thus manage, sharpness by way of the multitude of settings provided to them in any number of photo editing software packages. For instance, a popular pair of sharpening parameters are the *radius* and *amount* settings of *unsharp mask* filters. Generally speaking the larger the radius the more the sharpening bump moves to lower frequencies. The greater the amount setting, the greater is the bump amplitude.

One problem with adopting such an approach is that the net sharpening result on the image will vary depending on the quality of the upstream image components. For instance, using the same sharpening settings for an F8 aperture setting is likely to yield a dramatically different SFR than that for an F16 setting, even for the same lens. Similarly, the same F-number but with different lenses will also yield a different SFR result. In turn the sharpness of the images will differ because it is not a systemic delivered-file solution.

More importantly though there is no standardized agreement on what *radius* and *amount* actually mean. Such terms and their associated numbers are arbitrary. Just as undefined RGB values are insufficient for describing colors, so too are the numbers associated with today's sharpening operators. Fig. 6 illustrates the variability this introduces. It shows two different SFR curves from a synthetic edge image using the same *radius* and *amount* sharpening setting but from different photo manipulation software. The uninitiated would be led to believe that the resulting image enhancement is the same because of the same parameter selection. They would be wrong.

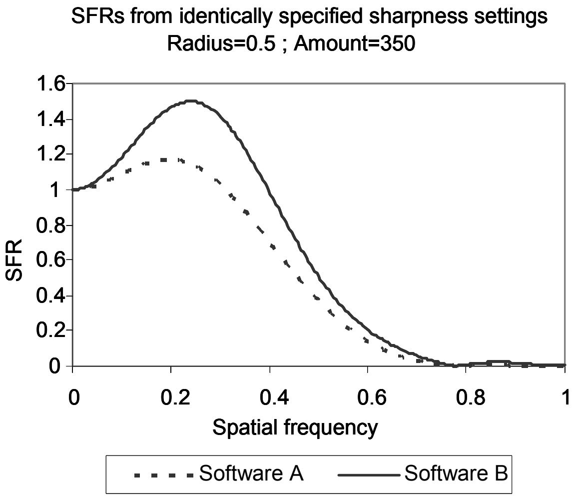

Figure 6: Difference in net SFR behavior for identical images sharpening setting but with different software

To add to the confusion, it is worthwhile noting that Software B curve of Fig. 6 is also identical to that achieved with a wine list of other sharpening options such as *sharpen more*, *smart sharpen*, and *custom filter*. This vernacular terminology illustrates why standardized protocols employing verifiable reference techniques and tools are needed to better managing sharpening operations in digitizing workflows. Doing so will prevent excessive artifact generation, provide greater inter- and intra- institutional imaging consistency, and ultimately help manage image quality for specific usage.

Managing and executing sharpening

Sharpening can be managed just as any other digital imaging attribute can. It requires;

1. Physically characterized targets
2. Established and standardized processing protocols
3. Selected aims.

In color management, a physically characterized and standard color target is scanned to establish reference values (color coordinates) for each color patch (test signal value). This reference data is then used to create a color profile by means of standardized processing protocols (ICC specification) that will achieve the users selected color aims and intent. The same is true for grayscale scanning. A spectrally neutral target is scanned to establish the starting reflectance-to-count value encoding. This data is then used to build look-up-tables (LUT) that are used in subsequent processing to achieve a desired gamma function aim. This in turn ensures the desired capture tone reproduction (signal encoding).

The same techniques can be applied to managing sharpening. Current ISO standards call for simple slanted edge targets that are characterized in terms of their frequency response. These can be considered as calibrated 'sharpening' standards the same way the color and grayscale targets are used for color and tone reproduction. As indicated earlier, the processing protocols for analyzing the data collected from these targets provide a standard approach to establishing a baseline SFR. This SFR is then compared to a predefined aim SFR and an appropriate filtering kernel designed (or selected) that when applied to subsequent images will yield the desired calibrated aim SFR. A graphical example of this is shown in Fig. 7.

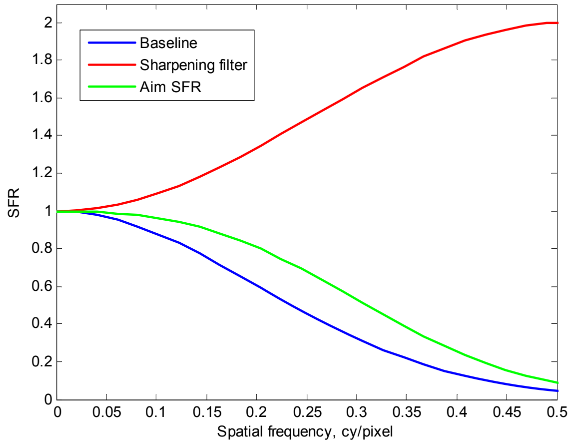

Figure 7: Example of how a baseline SFR can be sharpened by use of a sharpening filter to achieve a predetermined aim SFR.

We should point out that we have addressed the most common types of image sharpening algorithms used today. When more adaptive image processing is employed, the level of image sharpening (or noise-reduction) can vary with the presence of particular image features, such as edges, text characters, etc. In these cases, specifying the reproduction of important image features, such as edges, it still important, but may not provide a complete picture of sharpening performance. Evaluation of the capture of additional test features, such as at several contrast levels, may be required.

Aliasing and noise

Our focus here has been on sharpening operations intended to modify the visual impression of sharpness and sometimes compensate for native image capture SFR performance. Practical image sharpening, however, has its limits. As we stated above, it can be very useful when the amount or degree of image manipulation is moderate. With high sharpening, image noise and image sampling artifacts can be amplified along the signal content. For this reason a comprehensive imaging performance evaluation program should also include measurement of image noise. [8] Both measured SFR and noise levels are then taken into account prior to managing the image sharpness in the way described here. One simple approach is to first define an upper level of sharpening (*e.g.*, as a function of spatial frequency) based on consideration of both SFR and noise levels. During testing the computed degree of image sharpening, can be compared to this upper value. When a level of sharpening is called for that is greater than this limit, an error condition is indicated. Reference 8 provides a technical discussion of sampling artifacts from the standpoint of digital camera design.

Conclusions

Because of the controlled capture environments and unique content, the cultural heritage imaging community is well positioned to institute imaging measurement and management in their digitizing workflows. We have described tools and processes using accepted ISO measurement protocols, and how these can be applied. Digital mage sharpening is not well understood, and often applied arbitrarily. Using practices that are consistent with control of other imaging characteristics, such as color and exposure management, *do-no-harm* sharpening management can be achieved. This requires calibrated targets, standardized processing protocols and establishing SFR aims.

References

[1] L. MacDonald, Framework for an Image Sharpness Management System, *Proc. IS&T/SID 7th Color Imaging Conference*, IS&T, 75-79, 1999.

[2] D. Williams, Benchmarking of the ISO 12233 Slanted-edge Spatial Frequency Response Plug-in, *Proc. PICS Conf.*, IS&T, pg. 133 (1998).

[3] P. D. Burns, Slanted-Edge MTF for Digital Camera and Scanner Analysis, *Proc. PICS Conf., IS&T*, pg. 135 (2000).

[4] D. Williams, D. Wüller, H. Yoshida, K. Matherson, P. Hubel, A Pilot Study of Digital Camera Resolution Metrology Protocols Proposed Under ISO 12233 Edition 2, *Proc. SPIE-IS&T Electronic Imaging Symp.*, SPIE vol. 6808, 680804, (2008).

[5] P. D. Burns and D. Williams, Ten Tips for Maintaining Digital Image Quality, *Proc. Archiving 2007 Conf.*, IS&T, 16-22, 2007.

[6] S. Daly, The Visible differences Predictor: An algorithm for Assessment of Image fidelity, Ch. 13 in Digital Images and Human Vision, A. B. Watson, Ed., MIT Press, Cambridge, 1993.

[7] R. G. Gendron, "An improved objective measure for rating picture sharpness: CMT acutance," *J. Soc. Motion Pict. Telev. Eng*. 82, 1009-1012 (1973).

[8] M. Stelmach and D. Williams, When Good Scanning Goes Bad: A Case for Enabling Statistical Process Control in Image Digitizing Workflows, *Proc. Archiving Conf., IS&T*, pg. 237-243, 2006.

[9] M. A. Kriss, Tradeoff Between Aliasing Artifacts and Sharpness in Assessing Image Quality, *Proc. PICS Conf.*, IS&T, 247-256, 1998.

Author Biographies

Don Williams is a consultant on digital image fidelity for the cultural heritage sector, and previously worked at Eastman Kodak Company for 25 yrs. He is currently contributing on imaging performance metrology and monitoring for the Library of Congress, Office of Strategic Initiatives. He co-leads the ISO/TC42 standardization efforts on digital print and film scanner resolution (ISO 16067-1, ISO 16067-2), scanner dynamic range (ISO 21550) and is the editor for the second edition of ISO 12233, digital camera resolution. Don is the subgroup committee lead on sharpness metrology for the I3A Cell Phone Image Quality initiative.

Peter Burns is with Carestream Health. His work includes medical and dental image processing, and the development of imaging performance evaluation, analysis and software tools. He also worked in this area at Eastman Kodak and Xerox, and is a frequent speaker at technical conferences. He has taught several imaging courses: at Kodak, SPIE and IS&T Conferences, and at the Center for Imaging Science, RIT.

---

[*] This 10% value is generally applicable, but can vary with certain content and background image noise levels.