Image Quality Requirements for a Multimedia Environment

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Abstract The image quality of Multimedia presentations is considered in the context of three of the major components of such systems. The role of the image display is studied in terms of how an observer would rate the final image. In addition to the quality of the physical display, the impact of the digital pixel is considered. It will be shown that the inherent differences between common software packages can lead to the introduction of unwanted artifacts. The problems associated with hard copy output will also be discussed. Special attention will be made to the need to develop stochastic halftones that provide high quality images while ensuring artifact free scanning of these output images. The image quality problems associated with digital still electronic cameras will be covered in some detail emphasizing a system analysis and simulation approach. Special attention will be given to the severe color aliasing artifacts generated by the color filter arrays used in most Digital Still Electronic Cameras (DSEC).

1. Introduction

What is Multimedia? In his summary remarks at the SPSTJ Symposia on Fine Imaging, Dr. Ohta of Fuji Film Company indicated that the symposia provided no clear definition for Multimedia and that Multimedia could be whatever one wanted it to be.1 Dr. Ohta's remarks accurately assessed the status of Multimedia. The usage of still images, text, graphics, motion pictures, video sequences and sound combined in a single presentation is still in the experimental and creative stages. It is not clear whether the hardware, software or creative genius is leading the way in creating a new era of interactive Multimedia documents. Only time will provide a clearer picture of what technologies and creative formats will best serve the consumer, commercial and government markets.2

However, one can start to define many of the specifications that any Multimedia system must meet. This paper will consider some the image quality aspects of Multimedia systems, including the concept of digital pixels, image displays, hardcopy output and image input. The scope of this paper is limited to still images and will not (for the most part) consider the problems associated with motion picture and video input.

2. Digital Pixels

Regardless the source of an image to be used in a Multimedia presentation, it will be sampled and digitized for display and manipulation by a computer system. Hence, it is important to establish a concise and reasonable way to define digital pixels from the various sources of images. The digital pixels that are generated from the multitude of paint, draw, and graphics software packages are defined by the relationship between the software, the video display boards used in the computers, the CRT monitors, and the rendering algorithms used to provide image data for hard-copy devices. In all cases, the images are created by defining the boundaries of objects in the image in terms of well defined pixels. The smallest pixels are defined in terms of the resolution of the video board in the computer. A common resolution is 640 by 480 pixels. One can, using a graphics program, create an object that can be viewed on a single screen as long as it does not exceed the 640 by 480 pixels limit. It is possible to scroll through larger images if standard memory is swaped with video memory. As will be pointed out in the following sections, there are definite limits on how small the object

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can be made before it is corrupted or simply lost. Images captured from external sources as film, hardcopy or video signal must be first sampled and then digitized. From a quality assessment point of view, it is important to understand the equivalent number of pixels that each input image provides. First, consider the case of video images.\textsuperscript{3,4} The number of equivalent pixels is established by the number of active scan lines, \(N\), the total number of scan lines, \(P\), the bandwidth of the signal, \(BW\), the frame rate (assuming an equivalent progressive scan), \(FR\), and the fraction of time a single scan line is actively carrying image information, \(a\). The number of equivalent pixels per line, \(M\), is given by

\[ M = 2a \cdot BW / (N \cdot FR) \]  \hspace{1cm} (1)

For HDTV luminance signals, \(BW = 20\) MHz, \(FR = 30/\text{sec}\), \(N = 1050\) and \(a = 0.85\). Thus the number of equivalent pixels per line is \(M = 1080\). Since the number of active image lines is \(P = 950\), the equivalent image size from a HDTV signal is 1080 by 950 pixels. However, the aspect ratio of such an image does not meet the 16:9 aspect ratio of HDTV. To prevent distortion of the image, it is necessary to interpolate the 1080 pixels up to about 1920 pixels to ensure the 16:9 aspect ratio (assuming that the monitor displays a true square grid). It should be understood, that in terms of quality assessment, the original \(M = 1080\) pixels per line must be used.

Photographic images (35 mm format) contain far more information than is normally accessible by most video boards.\textsuperscript{5,6,7} Figure 1 demonstrates how to calculate the effective number of pixels on a photographic image. There are two possible criteria that one could use. The first is based on resolution. The resolving power of a photographic material is nominally defined by the 20% point of its Modulation Transfer Function (MTF). In the case shown in Fig. 1 this criterion gives a MTF = 0.2 at about 80 cycles per millimeter or 160 lines per millimeter. The dimensions of a 35 mm frame are 36 mm by 24 mm. Thus, based on the resolving power criteria, the resolution is 5760 by 3840 pixels and the equivalent square pixel would have a 6.25 micrometer edge. The MTF of a square pixel of edge \(D\) is given by

\[ \text{MTF}(f) = \left| \sin(\pi Df) / (\pi Df) \right| \] \hspace{1cm} (2)

When Equation (2) is used with \(D = 6.25\) micrometers, the resulting MTF is much greater than that of the film, thus indicating that the resolving power criterion is not appropriate. The second criteria is to calculate the effective value of \(D\) by setting the MTF given Equation (2) to 0.5, find the frequency \(f_0\) at which MTF = 0.5 and solve for \(D\). Using this method, \(D\) is given by

\[ D = 0.605 / f_0 \] \hspace{1cm} (3)

From Fig. 1, \(f_0 = 40\) c/mm, thus \(D = 15.1\) micrometers. This value for \(D\) results in an effective image resolution of 2384 by 1589 pixels, which is about 5.8 less the number of pixels defined the resolving power method. Further inspection shows that the 50% MTF method results in a resolving power of 33 c/mm, well below the actual value. This apparent conflict is resolved when you consider that photographic films are continuous in nature (at the macroscopic level being considered here). The proper criteria to impose on a sampled image (that is to have all the properties of a film image) is to assume a pixel size that is defined by Equation (3), but the sampling process uses a dither method that samples the image at a spacing of \(D/2\) in both directions. Using the above example this would result in a final image resolution of 4768 by 3179 pixels. This is much closer to the resolution determined by the resolving power criteria and satisfies the Nyquist sampling criteria.\textsuperscript{8} The use of a dithered scan or over sampling an image scanner is feasible, but it is very difficult to incorporate into a digital cam-

![Fig. 1 A method to determine the equivalent imaging sensor pixel size in a photographic film.](image-url)
era. Thus, one should not expect true photographic quality from a CCD type image sensor based on the pixel size given in Equation (3).

Table 1 shows the equivalent pixel resolutions for a range of imaging systems.

### 3. Video Display Quality

Most Multimedia presentations are viewed by individuals on conventional CRT monitors, but there are times when large screen displays are used for larger audiences. This section will cover some of the image quality aspects of CRT monitors and projection systems. A relationship between the CRT screen structure and the video boards that drive them will be developed. In addition, some of the problems associated with "cut and paste" steps between software packages will be covered.

Figure 2 shows three of the most popular patterns used in CRT monitors\(^8\). In each case a triad of red-green-blue phosphor dots or lines are used to form a single "pixel." In what follows it is always assumed that an observer can not resolve the inner structure of these screen pixels. The exact nature of the shadow masks and electron guns used to ensure that the image modulated electron beams are focused on the dots or lines correctly is beyond the scope of this paper. The emphasis will be on how the observer responds to the nature of the image on the screen. For ease of calculations and understanding the stripped pattern (similar to the Sony Triniton\(^{R}\)) will be used where the color triad, spatial pitch is given by \(a\). Most screens are defined by their triad pitch, \(a\), or line resolution, \(R\), where

\[
R = \frac{1}{a} \quad \text{.................................................. (5)}
\]

Table 2 gives a set of values for \(a\) and \(R\) that span most of the monitors used with Multimedia capable desktop computers. To better understand the relationship between the screen resolution and video board consider Fig. 3 and Table 3. Figure 3 defines the usable area of a screen and the actual area used for a given video board. For a given horizontal, \(H\), and vertical, \(V\), screen usage, the maximum number of pixels (assuming square pixels) are

\[
N_H = H \cdot R, \quad N_V = V \cdot R \quad \text{.................................................. (6)}
\]

The above assumes that each "pixel" defined by one of the triads corresponds to one "pixel" in
Table 2 Typical CRT monitor resolutions.

<table>
<thead>
<tr>
<th>Type of Monitor</th>
<th>Diagonal (inches)</th>
<th>Pitch (millimeters)</th>
<th>Resolution (Dots Per Inch, DPI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumer TV</td>
<td>19</td>
<td>.55</td>
<td>46</td>
</tr>
<tr>
<td>640 × 480 Monitor</td>
<td>11</td>
<td>.35</td>
<td>72</td>
</tr>
<tr>
<td>1620 by 1200 Monitor</td>
<td>20</td>
<td>.25</td>
<td>102</td>
</tr>
</tbody>
</table>

Table 3 Typical CRT digital display monitor characteristics.

<table>
<thead>
<tr>
<th>Nominal Diagonal (inches)</th>
<th>9</th>
<th>12</th>
<th>17</th>
<th>21</th>
<th>20</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Resolution</td>
<td>640</td>
<td>832</td>
<td>1152</td>
<td>1152</td>
<td>1280</td>
<td>1600</td>
</tr>
<tr>
<td>Horizontal Resolution</td>
<td>480</td>
<td>624</td>
<td>870</td>
<td>870</td>
<td>1024</td>
<td>1200</td>
</tr>
<tr>
<td>Pitch (mm)</td>
<td>.28</td>
<td>.28</td>
<td>.28</td>
<td>.35</td>
<td>.3</td>
<td>.25</td>
</tr>
<tr>
<td>Dots Per Inch, dpi</td>
<td>90.71</td>
<td>90.71</td>
<td>90.71</td>
<td>72.57</td>
<td>84.67</td>
<td>101.6</td>
</tr>
<tr>
<td>Vertical Image Size</td>
<td>5.29</td>
<td>6.88</td>
<td>9.59</td>
<td>11.99</td>
<td>12.09</td>
<td>11.81</td>
</tr>
<tr>
<td>(inches)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal Image Size</td>
<td>7.06</td>
<td>9.17</td>
<td>12.7</td>
<td>15.87</td>
<td>15.12</td>
<td>15.75</td>
</tr>
<tr>
<td>Size (inches)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diagonal (inches)</td>
<td>8.82</td>
<td>11.46</td>
<td>15.91</td>
<td>19.89</td>
<td>19.36</td>
<td>16.69</td>
</tr>
</tbody>
</table>

![Fig. 3 Usable display area in a CRT display monitor.](image)

the memory on the video board that drives the monitor. Many modern monitors and video board software allow one to change the video resolution to meet the desired usage. Referring to Table 3 consider the case of a nominal 20 inch monitor with a 1280 by 1024 video board. With a pitch of \( a = 0.3 \) millimeters, the values for horizontal and vertical image dimensions are \( H = 15.12 \) inches and \( V = 12.09 \) inches and a diagonal dimension of \( D = 19.36 \) inches. The same screen could be driven at a resolution of 640 by 480. The monitor software then adjusts the electron beam signal to illuminate two sets of red-green-blue triads for each pixel in both directions. One should note that the top and bottom of the screen show slightly more black, non-scanned area due to the difference between 960 (twice 480) lines used instead of the full 1024 lines. If an intermediate resolution as 832 by 624, is used, then either a small fraction of the screen will be used, or in the horizontal direction a “pixel” will consist of a fractional number of red-green-blue triads. In this case, a pixel is 1.64 triads wide. The vertical size can be adjusted to ensure square pixels. When there is either a mismatch between the video board resolution and the screen resolution or an improper alignment with the red-green-blue triads, one will note a true color moiré on the screen. This moiré pattern can be used to adjust the screen for optimum results. The following procedure can be used. Start with a graphics program and create a large square with a vertical line fill. The vertical line fill should be the highest frequency possible. Copy this pattern into a second (different) graphics or imaging program. This copied image may show some subtle color banding (mostly in the horizontal direction). Adjust the horizontal screen size control until the color banding disappears or results in a very broad band. Next, using the horizontal position control move the image right or left until the
banding is further reduced or disappears. After following this procedure, the monitor will be optimized in terms of artifact free, sharp images for the video board resolution being used.

The sharpness of a CRT monitor will now be considered and once again if it is assumed that an observer does not see the inner structure for the red-green-blue strips, a MTF can be assigned to a set of lines with a spatial pitch of \( a \). The MTF of a CRT is given by

\[
\text{MTF}_{\text{CRT}}(f) = |\sin(\pi af)/(\pi af)| \quad (7)
\]

To correlate the CRT MTF to what an observer would see in terms of sharpness, the concept of Cascaded Modulation Transfer (CMT) Acutance will be used.\(^\text{10,7}\) CMT Acutance was developed for photographic images and should provide a reasonable measure of CRT monitor quality. The CMT value is given by

\[
\text{CMT} = 100 + 66 \log(R_{\text{system}}/R_{\text{eye}}) \quad (8)
\]

Where \( R_{\text{system}} \) and \( R_{\text{eye}} \) represent the integrated system and eye responses, respectively, and are given by

\[
R_{\text{eye}} = \int \text{MTF}_{\text{eye}}(f) df \quad (9)
\]

and

\[
R_{\text{system}} = \int \text{MTF}_{\text{CRT}}(f) \cdot \text{MTF}_{\text{eye}}(f) df \quad (10)
\]

The eye response curve of the MTF, \( \text{MTF}_{\text{eye}} \), is based on a set of experiments and is given by

\[
\text{MTF}_{\text{eye}}(f) = 2.6f[0.0192 + (f/1.6760) \cdot e^{[-(f/1.6760)^{1.1}]}] \quad (11)
\]

Equation (11) has been scaled for a viewing distance of 300 millimeters.

Figure 4 shows plots of MTF and MTF of a stripped monitor. Figure 5 shows the CMT Acutance as a function of viewing distance for three values of \( a \); \( a = 0.2 \) mm, \( a = 0.3 \) mm and \( a = 0.05 \) mm. Based on photographic experiments, a CMT value of 92 corresponds to an excellent image. Using this photographic result for the CRT display allows one to establish the criteria for high quality as a function of viewing distance and triad pitch. From Fig. 5, one can ascertain that a CRT display with a triad pitch of 0.3 mm will produce an excellent image of at a viewing distance of about 600 mm or 2 feet (which is the normal viewing distance to a monitor when working at the computer keyboard). If the monitor had a pitch of 0.2 mm, then one could work as close as 16 inches to the screen. On the other hand, for a pitch of 0.5 mm (found in consumer television sets) one should sit about four feet from the screen for an excellent image.

A projection system using CRT sources can be studied in a similar fashion. The following assumptions are made. First, the beam profile from each of the CRT sources is gaussian and second, the red, green and blue beams are perfectly aligned. The beam profile, \( A(x, y) \), is given by

\[
A(x, y) = e^{-[(x^2+y^2)/2\sigma^2]} \quad (12)
\]

The CRT projector MTF is the Fourier transform of \( A(x, y) \) and is given by
MTF_{\text{crt-proj}}(f) = e^{-2\pi^2 \sigma f^2} \quad \text{(13)}

A further constraint on a beam based projection system (or beam based hardcopy printing systems) is that uniform areas must look smooth and not have any visible line structure. Figure 6 shows two examples of the same uniform area reproduced by gaussian beams. The visibility of the line pattern in a uniform area is a function of the pitch, $a$, of the scanning beam and the breath of the gaussian beam defined by $\sigma$. The top simulation in Fig. 6 is for $\sigma = 0.25 \, a$ and the bottom simulation is for $\sigma = 0.5 \, a$. Clearly, as $s$ increases (relative to $a$) a more uniform area is created. However, Equation (13) indicates that as $\sigma$ increases, the value of MTF_{crt-proj} decreases rapidly. Thus, the price to be paid for ensuring a uniform area is a loss in sharpness for any given beam pitch, $a$. Vision experiments have shown that if $\sigma = 0.4 \, a$ that a uniform area will be seen by an observer.\textsuperscript{12} Figure 7 shows a plot of CMT Acutance as a function of viewing distance for three CRT beam projectors. The results have been scaled to the CRT monitor results shown in Fig. 5 to facilitate comparisons. Each of these curves has been calculated under the assumption $\sigma = 0.4 \, a$. The results indicate that there is a noticeable loss in sharpness when one is forced to ensure that a uniform area shows no lines. In the case of the CRT monitors a 0.3 mm pitch provided an excellent image at 600 mm. However in the case of a CRT beam projector it requires the smaller 0.2 mm pitch for an excellent image. It should be noted that when projection systems are employed the observers are usually sitting farther from the screen than when one works at a computer. Thus, it is entirely possible that a CRT beam projector that as the equivalent scanning beam pitch of 0.3 millimeters will provide adequate quality image when used in larger rooms.

\[\sigma = 0.25 \, a\]

\[\sigma = 0.5 \, a\]

Fig. 6 The display of a uniform area by a CRT projection display.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig6}
\caption{The display of a uniform area by a CRT projection display.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig7}
\caption{The CMT Acutance for a CRT projection display.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig8}
\caption{The alignment error in a liquid crystal display projector.}
\end{figure}
Figure 8 shows the modulators of a Liquid Crystal Projector. There are three separate modulators, one for red, green and blue. The final image is optically combined before passing through the projection lens. Figure 8 also shows a close up of three pixels, one each of the red, green and blue modulators. Here it is assumed, as in all previous cases, that the observer does not resolve the individual pixels. If there is some misalignment of the three modulators then some image degradation will be introduced. As shown in Fig. 8, the amount of displacement is $\delta$ for the rear and front pixel relative to the middle pixel. The $\text{MTF}_{\text{LCD}}$ of each pixel is the same as shown above for the CRT monitor, but with $D$ replaced by $D$.

$$\text{MTF}_{\text{LCD}}(f) = \left| \frac{\sin(\pi Df)}{\pi Df} \right|$$

However, the displacement, $\delta$, introduces an additional loss given by

$$\text{MTF}_{\delta}(f) = \left| \frac{1}{3} \right| \left| 1 + 2 \cos(2\pi \delta f) \right|$$

The net MTF for the liquid crystal type projector is the cascaded value of Equations (15) and (16). Figure 9 shows the resulting CMT Acutance values as a function of viewing distance for $\delta = 0.1D$ and the same three pitches (note that $D = a$ here) used in the previous calculations for CRT monitors and CRT beam projectors. These results indicate that the loss in quality (in terms of sharpness) is less than that found with the CRT beam projectors. The reason for this is that the square pixel has a higher spatial frequency response than the gaussian beams used in the CRT beam projector.

The last topic in this section deals with the difficulty of using several graphics, paint or image programs in preparing a Multimedia presentation. These difficulties are best described by examples. Figure 10 shows what takes place when some simple patterns are sent back-and-forth between different software packages. The original starts in Canvas® and is sent to Photoshop® or Cricket Draw III® and then...

![Fig. 9 The CMT Acutance of a LCD display projector.](image)

![Fig. 10 Artifacts introduced by using “cut and paste” from different software packages.](image)

![Fig. 11 Digital moiré artifacts introduced by rotating graphics objects.](image)
copied back into Canvas. Cricket Draw III interprets the patterns in terms of dithered gray scale patterns, hence it loses the fill patterns generated in Canvas. Photoshop and Canvas have a mismatch in the base dpi used to display and print images. Canvas sends images to Photoshop at 288 dpi which uses 72 dpi as its standard. The net effect of transferring the images back-and-forth (and preserving the original size of the image) is that the final image in Canvas has the fill pattern reduced by a factor of four. Figure 11 shows the problems of rotating graphics imported from Canvas in Photoshop.

The banding artifacts shown in Fig. 11 are classical examples digital moiré. Figure 12 shows the effects of rotating graphics in Photoshop that were imported from Canvas and then exporting them back to Canvas. As can be seen from these examples, care must be taken when one uses several graphics packages to create Multimedia presentations.

4. Hardcopy Output

While Multimedia creations are meant to be viewed on some sort of computer driven display, there will often arise the need to make hard copies of some of the material. The quality needed in the hardcopy will depend on the need. One can separate the type of hardcopy output into two broad categories. The first is continuous tone output and the other is some form of digital halftone output. For current systems it is safe to say that continuous tone hardcopy output is superior to most (if not all) digital halftone systems. However, this quality edge comes with a higher cost as will be outlined later. There is a second issue that may be more important than the quality of the original hardcopy output. Relatively inexpensive desk top scanners when combined with creative software packages have enabled many Multimedia users to import, enhance and create (or copy) interesting images or graphics. These new images are then rendered in some form of digital halftone and printed on one of many output devices. When one of these rendered images is copied by the conventional electronic scanner, the regular patterns in the rendered digital halftones will introduce strong moiré and aliasing patterns that are very difficult (if not impossible) to eliminate by even significant processing efforts. These problems and some possible solutions will be covered in this section.

Before the scanning problems outlined above
are discussed, it is valuable to look at a current “snap shot” of the types of printers that are available today to the general consumer. It should be kept in mind that digital imaging will only start to challenge conventional photography when the consumer can purchase a hardcopy printer that produces excellent images for less than one dollar ($US) a page. Table 4 gives a listing of the various printing technologies, the rendering method, the quality (dpi), the speed (pages per minute, ppm) and the cost range. As can be seen from Table 4, the majority of the printers that are likely to be purchased by a consumer all use some form of digital half tones. The quality of the images will depend on the type of digital halftone and the dots per inch (dpi) resolution of the rendering engine. Digital halftones that use any one of the many regular patterns to form a dot can produce very high quality images at high dpi. However, they all

<table>
<thead>
<tr>
<th>PRINTING TECHNOLOGY</th>
<th>RENDERING METHOD</th>
<th>QUALITY (dpi)</th>
<th>SPEED (PPM)</th>
<th>COST RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>INK JET</td>
<td>DIGITAL HALFTONE</td>
<td>300-720</td>
<td>2PPM-5.5 MINUTES PER PAGE</td>
<td>$300-$2,000</td>
</tr>
<tr>
<td>INK JET</td>
<td>MULTILEVEL</td>
<td>600</td>
<td>2 PPM</td>
<td>$600</td>
</tr>
<tr>
<td>THERMAL WAX</td>
<td>DIGITAL HALFTONE</td>
<td>300-600</td>
<td>2 PPM</td>
<td>$400-$700</td>
</tr>
<tr>
<td>THERMAL WAX</td>
<td>CONTINUOUS (8 BITS PER COLOR)</td>
<td>300-600</td>
<td>ONE MINUTE-SIX MINUTES PER PAGE</td>
<td>$1,500-$4,000</td>
</tr>
<tr>
<td>THERMAL DYE TRANSFER</td>
<td>CONTINUOUS (8 BITS PER COLOR)</td>
<td>300-400</td>
<td>ONE MINUTE TO 13 MINUTES PER PAGE</td>
<td>$7,000-$20,000</td>
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<tr>
<td>B&amp;W LASER</td>
<td>DIGITAL HALFTONE</td>
<td>300-1200</td>
<td>12 PPM</td>
<td>$600-$6,000</td>
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<tr>
<td>COLOR LASER</td>
<td>DIGITAL HALFTONE</td>
<td>300-600</td>
<td>ONE MINUTE TO SIX MINUTES PER PAGE</td>
<td>$7,000-$25,000</td>
</tr>
</tbody>
</table>

Table 4 Summary of hardcopy printing technology.

Fig. 13 Effect of scanning an image that has been rendered as a halftone.
have a similar problem in that when their output are scanned the rendered halftone patterns give rise to the strong moiré and aliasing patterns outlined above. Figure 13 demonstrates the problem with a uniform gray patch and an image. The images on the left are the originals, the ones in the center have been produced using an ordered dither and the images on the right are what takes place when the halftone images in the center are re-scanned. The artifacts introduced by the re-scan (exaggerated here due to the low resolution of the dither pattern) are very difficult to remove by means of digital image processing. Figure 14 shows the origins of the problem in more detail. The spectrum on the upper left is that for the original image, the one on the upper right is the spectrum of a uniform area rendered by the ordered dither pattern (at 50% fill), the one on the lower left is the spectrum of the image after it has been rendered by the ordered dither and the one on the lower right is the spectrum of the re-scanned image. This sequence of spectra shows how the spectrum of the ordered dither dominates and results in the introduction of aliased, low frequency signals (lower right).

The ordered dither patterns acts as a carrier signal (in two dimensions) and the modulating signal is the original image. Unlike a radio or television signals, the carrier signal is not stripped away before the reproduction. When the halftone image is re-scanned, the major spectral components belong to the dither pattern rather than the original image, hence there is very strong aliasing and moiré.

The solution to the above problems is to create a “white noise” halftone image that has an underlying random (stochastic) structure. When such an image is re-scanned, there will be no moiré and minimal aliasing artifacts. The simplest example is to create a random noise mask. This can be done in one of two ways. The easiest method is to invoke a random number generator that provides a threshold value for each pixel as it is about to be printed. Assume that the original image has 256 levels (ranging from 0 to 255). Adjust the random number generator to give out (for example) 64 integers equally spaced between 0 and 255. The pixel value from the original image is compared with the threshold value from the random number.
generator. If the image value is greater than the threshold, the output image is set to "255" and if not the output image is set to "0". A second method to achieve the same result is to first create a two-dimensional mask of 64 random integers that are equally spaced between 0 and 255. The image pixel value is then compared to the corresponding mask value, and if the image pixel is greater than the mask threshold value, then the output image pixel is set to "255" and otherwise it is set to "0". The advantage of the second method is that one can use the same stochastic mask for all images, but it does require the use of considerable memory for images rendered at high dots per inch. For example, an eight inch by ten inch image at 600 dpi would require 3.6 mega bytes of memory. Figure 15 shows an original, continuous tone image in the upper left and one created with a random mask with 64 levels as described above at the upper right. The problem with such random masks is that they introduce a lot of visible noise patterns that can only be suppressed by using very high printing densities (about 2400 dpi).

A very popular method to improve the visual quality of the random halftone is to invoke the concept of error diffusion.\textsuperscript{17,18,20,21} Figure 16 shows a simplified explanation of the process. The process starts in the upper left hand corner of the image. The first pixel value, $P(1,1)$ is compared with a threshold value, $T$, and set to "0" in the output image, $O(1,1)$, if equal to or lower than $T$. Otherwise it is set to "255". The error, $E(1,1)$, between the input and output image is given by,

$$E(i,j) = O(i,j) - P(i,j) \quad (16)$$

is then distributed to the three nearest neighbors in equal amounts as shown by the error matrix in

Fig. 15 Different halftone renderings.
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P(I,J)

P(I,J)

P(I,1) P(I,2) P(I,3)
P(1,1) 100 P(1,2) P(1,3)
P(2,1) 100 P(2,2) P(2,3)
P(3,1) 100 P(3,2) P(3,3)

T = 128
O(I,1) = 0
E(I,1) = 0

ERROR MATRIX =

\[
\begin{bmatrix}
0 & 1/3 \\
1/3 & 1/3
\end{bmatrix}
\]

ERROR DISTRIBUTION:
P(1,2) = P(1,2) - 1/3 E(I,1)
P(2,1) = P(2,1) - 1/3 E(I,1)
P(2,2) = P(2,2) - 1/3 E(I,1)

Fig. 16 The error diffusion process.

Thus, after each pixel is processed, the error is distributed to the unprocessed, nearest neighbor pixels before the next thresholding process is considered. In this way the error is continuously propagated forward. One of the problems with this method is that if a single threshold value, say \( T = 128 \), is used, visible boundaries will be seen in areas of smoothly varying gray values. To overcome this problem, one can have the threshold value, \( T \), vary in a random fashion. For example, the value of the threshold might be given by

\[ T = 96 + \text{Random}[1, 64] \]  

where Random[1, 64] represents a random number generator that puts out integers between one and 64. This process and other like it tends to reduce the visible boundaries. The image in the lower left of Fig. 15 shows results of using the error diffusion process. Note that the dot pattern tends to move in a diagonal direction. This is a direct consequence of how the error is propagated forward. This may have an additional advantage in that the human visual system does not "see" as well along directions 45 degrees from the horizontal or vertical. It may not be clear from Fig. 15 that the frequency distribution of the error diffusion image tends to have more high frequency content than that of the white noise image; refer to Fig. 18. However, the use of the error matrix can be shown to be equivalent to the application of a high pass filter. One major drawback of the error diffusion method is that requires considerable computational power to invoke, particularly as the algorithms become more complex. Multi-level error diffusion algorithms have been developed to render high quality images.

Drawing from the results of the error diffusion work, researchers have considered the use of what have become to be called "blue noise" masks. Consider a white noise mask, as defined above, with 64 randomly distributed levels. Through a series of image processing steps (too complicated to be discussed here) the distribution of these 64 levels is manipulated in such a way that for each gray
level (in a uniform area) the corresponding spectrum has a shape similar to that shown in Fig. 17. The concept of the blue noise mask is to push as much of the mask information as possible to the higher spatial frequency domain, thus making it less visible to the observer. A variation of this approach is outlined in Fig. 17. The first step is to create the white noise mask. Set all the values less than or equal to half the maximum level (50% fill) to “255” and the rest to “0”. Next, take its Fourier transform and multiply it by the high pass filter shown. The inverse Fourier transform results in an image that has the appropriate spectra but is not discrete. The next step is to form the image histogram and find the median value. Then, set all the values below the median to “255” and all those below to “0”. At this point one has a 50% fill (50% gray level) mask with a spectrum with a slightly modified shape from that of the original high pass filter. For the sake of discussion assume that 64 levels are being used over the range of 0 to 255. The lower 32 values are placed in a random nature where a mask value of “255” is found and the upper 32 values are randomly placed where a value of “0” is found. This completes the formation of the pseudo-blue noise mask. The image in the lower right corner of Fig. 15 shows the use of this type of pseudo-blue noise mask.

Figure 18 shows the spectra of a uniform area with 50% fill for a normal digital halftone dot, a Bayer dither, a Screw dither, a white noise mask, an error diffusion process and the pseudo-blue noise mask. The spectrum of the three ordered dithers give rise to strong spectral peaks and hence potential moiré and aliasing, while the three random processes do not. The error diffusion and pseudo-blue noise methods produce spectra with no strong spectral peaks, but do push the spectral energy to higher spatial frequencies. Figure 19 shows the rendering of a 50% gray patch by each of these methods.

Using the above filter techniques it is also possible the shape the spectrum in such a way that the resulting halftone images have their spectral energy directed along well defined directions. Figure 20 shows the resulting halftone image using different two-dimensional spatial frequency filters combined with the pseudo-blue noise mask technique. Figure 21 shows the filters used and the resulting spectrum from a 50% gray level. Considerable experimental work remains in deciding which pattern produces the best images. The reader is left to decide which of these reproductions is best for this image.

It is important to have some form of metric to decide which halftone screening produces the best image. A straightforward approach is to use the human visual response function, MTF_{eye}, defined by Equation (11) to calculate a metric.
Fig. 19  A uniform 50% gray patch rendered by six different halftoning methods.

Fig. 20  An image rendered by pseudo blue noise masks that have different angular distributions in the mask spectra.
that corresponds to what the observer sees. Using well-defined dither patterns, a white noise mask, an error diffusion process or a pseudo-blue noise mask, one first creates a halftone version of a uniform area. The resulting image is then transformed to the Fourier domain and multiplied by a two-dimensional form of the eye response function. The resulting spectrum is then transformed back to the spatial domain and its standard deviation calculated. This results in a measure of how the human observer "sees" the uniform area. Figures 22 and 23 show the eye RMS response results for rendering resolutions of 400 dpi and 800 dpi, respectively. In these calculations it is assumed that the observer is viewing images of the rendered uniform areas from a distance of 300 millimeters. Figure 19 shows the 50% fill pattern for each of the halftone methods employed. Consider Figure 22. At 400 dpi, the results indicate that an observer would detect the structure in a uniform area produced by the screw dither pattern and a white noise mask with the same ease at all levels. A uniform area produced by a pseudo blue noise mask would be less visible than the above in the mid tones. The normal dot digital halftone would be much less visible than the screw dither pattern or white noise mask, but more noticeable than the images created by either the Bayer dither pattern or the error diffusion method. If the rendering engine has a printing resolution of 800 dpi, Fig. 23, then all the rendering methods produce images with less visible structure. However, it is very clear that all the structured dither patterns are less visible than the methods using white or blue noise masks. While the error diffusion method is considerably less visible than the other random processes, it is still more visible than the ordered dithered patterns. The reason for these changes as a function of printing resolution can be understood with the aid of Fig. 18 that shows the spectrum of the 50% fill level for each of the methods used. As the resolution increases the spectral spikes that are characteristic of the ordered dither patterns move outside the band pass frequency range of the eye response curve. On the other hand, the random halftone methods have spectral energy well within the band bass of the eye response function, hence the greater response. Considering the above, clearly the patterns like the Bayer dither will produce superior halftone images at

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Fig. 21 The filters used generate the pseudo blue noise masks used to render the images in Fig. 20 along the rendering of 50% gray patches and the resulting spectra.
Image Quality Requirements for a Multimedia Environment

Fig. 22 The RMS response based on the Eye MTF for a series of rendering algorithms at 400 DPI.

Fig. 23 The RMS response based on the Eye MTF for a series of rendering algorithms at 800 DPI.

moderate and high printing resolutions. To better understand this process refer to Fig. 24 which shows the spectra of a 50% gray level as seen by an observer (viewing from 300 millimeters) when rendered by the screw dither pattern at 200 dpi, 400 dpi, 600 dpi and 800 dpi. The original spectra on the upper left has no filtration by the eye response function. In this demonstration the spectrum is held constant and the eye response function is scaled to represent the changing resolutions. As higher resolutions are used to render the uniform gray patch the eye response function shrinks around the center, thus eliminating the higher frequency spectral spikes and lowering the eye response RMS as demonstrated in Fig. 22 and 23. Note that since the eye response has a value much less than unity at zero spatial frequency, the central peak of the screw pattern spectrum is greatly reduced. Preliminary experiments indicate that the Bayer dither and error diffusion renderings of a uniform gray patch blends more quickly to a
uniform looking patch than do the white noise or pseudo blue noise renderings of a uniform patch. Observers were asked to walk away from the rendered, uniform gray patch until they could no longer see the underlying structure. More comprehensive experiments are now underway.

The above analysis does not take into consideration the effect of the re-scanning of the halftone images. Based on these results it would indicate that the some form of error diffusion process is best if one wishes to affect a compromise between print quality and immunity to moiré and aliasing upon the re-scanning of the print.

A final word is in order on what printing resolution is required to produce the same quality as a continuous tone printer when using one of the ordered dither patterns. For the sake of this calculation assume that one needs 64 gray levels or 6 bits per pixel. This means that each pixel is made up of an eight-by-eight matrix of "255"s and "0"s. Referring to Fig. 4, the resolving power of the eye can be taken to be about 6 cycles per millimeter at a viewing distance of 300 millimeters. The means that a resolvable pixel is about 0.083 millimeters on an edge. Thus, each of the 64 sub-pixels must be 0.0104 millimeters on an edge. This translates to a printing resolution of 2438 dpi. Hence, it will require a 2438 dpi printer to produce the equivalent quality of a 300 dpi, 6 bit per color continuous tone printer. If we assume the Bayer dither pattern, a 50% fill level will result in a checkerboard whose spectrum starts with peak frequencies (at the four diagonal corners) of about 17 cycles per millimeter. A scanner with a resolution of 1200 dpi (assuming that the imaging pixels have no gaps between them) has a Nyquist frequency of about 24 cycles per millimeter. While the main peaks are well within the Nyquist frequency, the outlying spectral spikes will be beyond the Nyquist frequency and will introduce some aliasing. If a 600 dpi scanner is used, the Nyquist frequency will be about 12 cycles per millimeter, thus introducing very strong aliasing. From the above, using a random noise halftone at 2438 dpi might well provide an excellent print and be immune form aliasing and moiré upon re-scanning.

5. Digital Camera Input

Digital Still Electronic Cameras (DSEC) will provide an increasingly large number of images for Multimedia presentations. Most of these cameras employ a single imaging sensor, usually a Charged Coupled Device (CCD) with a Color Filter Array (CFA). The sparse sampling of each color introduces strong aliasing with broad color bands. Some of these sampling artifacts can be eliminated by sophisticated interpolation techniques, but the low frequency color banding introduced by the CFAs
can not be eliminated unless the image is optically filtered before it is captured by the CCD sensor. In this section, the problems associated with the CFAs will be demonstrated, explained and some possible solutions outlined.

Table 5 lists some of the current DSECs and their major characteristics. In addition to these cameras there are digital camera backs that attach to large format film cameras and others that use linear scanning devices to record images. Only single sensor DSECs with a CFAs will be discussed in this study for they represent the cameras that will be most popular with the consumer, advanced amateur and professional.

Before analyzing the DSEC it is appropriate to look at some images from these cameras. Figure 25 shows two images of a test chart taken with the Apple QuickTake DSEC. The top image was taken from a distance of eight feet while the bottom image was taken from a distance of ten feet. The banding (here in black and white) demonstrates the aliasing problem. In color, the banding would have the cyan-yellow coloration associated with the Bayer filter array. The sensitivity of the banding to the imaging distance reflects the critical relationship between the sampling nature of the CCD sensor and the image that is projected on to it. A slight change in the magnification takes the images well beyond the Nyquist frequency and results in the very broad banding. The Apple QuickTake DSEC employs an optical pre-filter that is designed to reduce the aliasing. However, due to the low resolution of the CCD sensor, the optical pre-filter has been introduced to reduce but not eliminate the aliasing. Figure 26 shows an image of the second vertical line patch from the right (on the top row) of the test target shown in Fig. 25 when taken with a Kodak DSC420 DSEC. In this image, all three color separations are shown. While this camera has higher resolution, it does not employ an optical pre-filter. Again the color banding (not seen here) is characteristic of the Bayer CFA. Note that there is very little banding in the green separation since it has a sampling rate twice that of the red or blue separations. Figure 27 shows two images taken with the above cameras. The image at the top was taken with the QuickTake 150 and the one on the bottom was taken with the Kodak DSC420. Figure 28 shows an enlar-

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Table 5 Examples of Digital Still Electronic Cameras.

<table>
<thead>
<tr>
<th>CAMERA</th>
<th>RESOLUTION</th>
<th>COLOR FILTER ARRAY</th>
<th>SENSOR ARCHITECTURE</th>
<th>PRICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>APPLE QUICKTAKE 150</td>
<td>640 x 480</td>
<td>BAYER PATTERN</td>
<td>FRAME TRANSFER</td>
<td>$700</td>
</tr>
<tr>
<td>KODAK DCS40</td>
<td>756 x 504</td>
<td>BAYER PATTERN</td>
<td>FRAME TRANSFER</td>
<td>$1000</td>
</tr>
<tr>
<td>KODAK DCS420</td>
<td>1524 x 1012</td>
<td>BAYER PATTERN</td>
<td>FRAME TRANSFER</td>
<td>$10,000</td>
</tr>
<tr>
<td>KODAK DCS460</td>
<td>3060 x 2036</td>
<td>BAYER PATTERN</td>
<td>FRAME TRANSFER</td>
<td>$28,000</td>
</tr>
<tr>
<td>FUJIX DS-515</td>
<td>1280 x 1000</td>
<td>NEW SONY PATTERN</td>
<td>INTERLINE TRANSFER</td>
<td>$13,000</td>
</tr>
<tr>
<td>NIKON E2S</td>
<td>1280 x 1000</td>
<td>NEW SONY PATTERN</td>
<td>INTERLINE TRANSFER</td>
<td>$16,000</td>
</tr>
</tbody>
</table>

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Fig. 25 Test pattern recorded by the Apple QuickTake DSEC.
Fig. 26 Test pattern recorded by the Kodak DSC420 DSEC.

Fig. 27 Images taken by the Apple QuickTake and Kodak DSC420 DSECs.

Fig. 28 Enlargements of the images in Fig. 27.

The higher resolution Kodak DSC420 provides the better image.

Figure 29 shows a detailed flow diagram of the important components of a DSEC system.

Each of these components can be defined exactly (or approximately) by a response function or MTF. Assuming that a linear system analysis provides an adequate approximation of the DSEC system, it is possible to use CMT...
Acutance as a sharpness quality metric. This will be outlined below. As mentioned above, the aliasing introduced by the sampling and the CFA introduces significant artifacts. CMT Acutance like metrics have not been developed to measure the loss of quality due to these types of artifacts. However, there is a way to predict the potential or probability for a aliasing induced artifacts for a given DSEC system. This method will also be outlined below.

The details of the analysis are given elsewhere. The lenses in the analysis are assumed to be diffraction limited and thus defined by their F-number and the wavelength of light (550 manometers). The optical pre-filter is assumed to be a bi-refringent material that creates two images, slightly displaced. For a Frame Transfer Device with a CFA, when the displacement is equal to one-half the size of the sensor pixel, optimum filtering for this method is obtained. The CCD sensor is assumed to have square pixels that have MTFs identical to Equation (2). The image processing in the camera or in the computer will take the three sparsely sampled images (due to the CFA) and introduce some form of interpolation to fill in the missing...
points. Each interpolation algorithm will introduce some form of image loss. The fully reconstructed image can also be enhanced by image processing. The fully processed image can then be printed using, for example, a laser beam (with a gaussian beam profile) writing onto photographic paper. Figure 30 shows one example of the component MTFs for a DSEC system. As can be seen from Figure 30 the interpolation filter introduces the greatest loss in image quality. Figure 31 shows the DSEC system MTF along with the eye response curve. While the large amount of image enhancement introduces very good low frequency response, the interpolation filter has reduced the high frequency response that is important for high image quality. Figure 32 shows the same system, but assuming no color filter array; this would be equivalent to a three sensor camera. Figure 33 shows the system response. Note the significant increase in both the low and high frequency responses, thus ensuring a much higher CMT Acutance value.

The CFAs provide the color encoding for a single chip CCD DSEC. Figure 34 shows several CFA configurations. The Hitachi pattern was the first used in a video cameras. Today, the most popular CFAs are the Bayer pattern and the Sony Pattern. Figure 35 outlines the interpolation process for the Bayer pattern. Note that the interpolation kernel introduces a loss of sharpness as defined by the MTF at the bottom of the figure. As pointed out above, the sparse sampling introduces aliasing. Figure 36 shows the effect of under sampling a one dimensional sine wave signal. The spectra are shown on the right. The fully sampled image spectrum reflects the 10 cycle per millimeter signal. When the original signal is sampled at 1/16 the rate of the original, there is still enough information to identify the signal as 10 cycles per milli-
meter as shown by the spectrum. However, when sampled at $1/256$ the rate of the original, the sampled signal appears to be a low frequency sine wave and this is reflected in the spectrum. The spectrum shows a very strong signal at two cycles per millimeter plus some lesser peaks at slightly higher higher frequencies. The net effect is to shift energy from the high frequency region to lower frequencies. When an image contains a lot of high frequency information (test charts, fabric patterns, buildings, etc.) the sparse sampling of the CCD sensors introduce these aliased, low frequency artifacts (in color). The above example can be extended to two-
Fig. 37 Aliasing of a random noise pattern due to insufficient sampling.

Fig. 38 The method used to calculate the potential for aliasing in a DSEC.
dimensions. Consider the simulation shown in Fig. 37. The image on the upper left is a 64 by 64 random array and its spectrum is shown on the upper right. The array on the lower left was obtained by sampling the upper array every fourth pixel in both directions and then replicating each sampled image 16 times in a 4 by 4 array. The spectrum of the sampled and replicated array on the lower right clearly shows the build up of noise around the zero frequency peak. Again, this demonstrates how high frequency signals (noise) will be aliased to low frequencies, making the aliased signal (noise) more visible.

The above simulation lays the foundation for a metric that will correspond the potential for aliasing for a given DSEC system. Consider a one-dimensional analog to the simulation in Fig. 37. The input signal is a one-dimensional white noise spectrum. Using the model outlined above it is possible to isolate the signal that is not corrupted by the sampling and to compare it with the signal that is aliased into the same frequency band. All the signals are modified by the eye response function, for aliased signals that can not be "seen" should not be considered as an artifact. The ratio, $R_{alias}$, of the integrated aliased signal to that of the integrated non-aliased signal provides a measure of the potential for aliasing. Figure 38 demonstrates the concept of the calculation. When an image (signal) is sampled, the resulting spectrum is not the original spectrum, but an altered spectrum that is located at the origin of the spatial frequency domain. There are also an infinite number of replicas of the altered spectrum and they are uniformly distributed in both directions as a function of the sampling distance used. The spacing, $f_a$ along the frequency axes is $1/a$ where $a$ is the sampling distance. When the spectrum exceeds $f_a$ (in both directions) the first replicated spectra will overlap the central spectrum. If the spectrum is broad enough, as shown in Fig. 38, the second set of replicated spectra will also fall into the central spectrum. The overlapping parts of the replicated spectra constitute the aliased image (signal). The shaded areas (due to all the replicas) that fall into the central spectrum represent the amount of aliased signal. The total shaded area divided by the area of the central spectrum gives the value of $R_{alias}$. Figure 39 shows the results from modeling a 500 by 750 Interline Transfer Device with a Bayer CFA and no optical pre-filter. This system was chosen to emphasize the aliasing problem. Note that there are considerable aliasing contributions from the second replica (Aliased Signal 2). The value for $R_{alias}$ is 1.17 that indicates that more signal is aliased into the spatial frequency region of the original spectrum than is in the original spectrum. Such a system would be very prone to strong aliasing. Table 6 shows how $R_{alias}$ varies as a function of system parameters. In Table 6, the values under PRE-FILTER correspond to the fraction of a pixel that the

<table>
<thead>
<tr>
<th>PRE-FILTER</th>
<th>SENSOR</th>
<th>LENS</th>
<th>CFA</th>
<th>$R_{alias}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>Interline</td>
<td>F/16</td>
<td>Bayer</td>
<td>1.17</td>
</tr>
<tr>
<td>0.0</td>
<td>Interline</td>
<td>F/16</td>
<td>Bayer</td>
<td>0.92</td>
</tr>
<tr>
<td>.5</td>
<td>Interline</td>
<td>F/16</td>
<td>Bayer</td>
<td>0.77</td>
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<td>1.0</td>
<td>Interline</td>
<td>F/16</td>
<td>Bayer</td>
<td>0.58</td>
</tr>
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<td>0.0</td>
<td>Interline</td>
<td>F/22</td>
<td>Bayer</td>
<td>0.69</td>
</tr>
<tr>
<td>0.0</td>
<td>Frame</td>
<td>F/32</td>
<td>None</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Fig. 39 The aliased spectra in a 500 by 750 pixel DSEC using a Bayer CFA.
whole image is displaced by the bi-refringent material in the optical pre-filter. Under SEN-
SOR, Interline refers to an Interline Transfer Device that has a pixel dimension half of the
spacing between pixels and Frame refers to a Frame Transfer Device. The values under
LENS refer to diffraction limited lens of the
given F/Number. The introduction of an optic-
cal pre-filter reduces the potential for aliasing as
does the a poorer lens (higher F/Number) when
the optical pre-filter is removed. However, the
greatest gain is made when a Frame Transfer
Device is used.

Figure 40 shows a simulation that demon-
strates the aliasing in a complex test pattern.
The simulation is of a 525 by 525 CCD sensor
with a Bayer CFA. The simulation starts by
creating an image that is 1024 by 1024 (the
original test pattern). The first step in the simu-
lation is to average down to a 525 by 525 image
by taking the average over 4 by 4 arrays of
pixels. This averaging and sampling process
introduces the first level of aliasing and
effectively simulates a Frame Transfer Device.
The next step is to simulate the Bayer CFA and
create three sparse images as outlined in Fig. 35.
These sparse images are then filled in via the
interpolation process shown in Fig. 35. The
image on the right in Fig. 40 contains no optical
pre-filter and a camera lens with a unity MTF
has been assumed. Note the strong banding and
artifacts in the higher frequency patterns. Also
note the jagged nature of the three pictorial
scenes. The image on the left has been opti-
cally pre-filtered by the introduction of a
diffraction limited F/22 lens. For this simula-
tion, the value of $R_{\text{alias}}$ moves from 1.63 for the
no pre-filter case to 0.61 when using the pre-
filter. As indicated by these values for $R_{\text{alias}}$ and
the images in Fig. 40, the optical pre-filter helps
eliminate the worst aliasing artifacts, but does
not eliminate them. Note that the banding in
the highest frequency patches (far right) has
been greatly reduced and that some of the arti-
facts in the checkerboard patterns have been
reduced or eliminated. In the case of the high-
est frequency patches the pre-filter has eliminat-
ed the signal, thus ensuring no aliasing artifacts.
Further, note that the pictorial scenes are less
jagged, but much softer. This simulation dem-
onstrates the sharpness-artifact trade off that
come with the use of optical pre-filters.

6. Closing remarks

Developing high quality Multimedia presenta-
tions will require careful consideration of the
nature and quality of all input and output
images. Special attention will have to be made

![Fig. 40 A simulation of a 525 by 525 pixel DSEC using a Bayer CFA with and without optical pre-filtering.](image-url)
to the relationship between the images generated or captured and the device used to display them. Furthermore, because output from one Multimedia presentation will be used as input for other Multimedia presentations, the nature of the output must be carefully considered. In particular, hardcopy output must avoid the introduction of artifacts due to moiré and aliasing when they are scanned by moderate to low resolution desk top scanners. To avoid these problems it will be necessary to carefully model and simulated proposed Multimedia systems. On the basis of these results, one should be able to define the appropriate image quality specifications for each component.

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