Inkjet Print Image Quality Considerations:

PEARLS™

March, 2003

Developed By

TORREY PINES
RESEARCH

6359 Paseo Del Lago
Carlsbad, CA 92009
(760) 929-4800
www.tpr.com

Inkjet Print Image Quality Considerations: PEARLS™

Image Quality Overview

The topic of image quality is broad in scope and applies to a vast array of different types of imaging systems. The assessment of image quality applies to image capture, image processing, softcopy display, and hardcopy printing. Within the context of image capture, image quality attributes can be associated with technologies such as conventional photography, digital photography, and both film and print scanning. Image quality can be affected, for better or worse, by chemical, optical, or digital processing and often by a combination of all of these means. The reproduction of a captured image can be accomplished with many different technologies that are often vastly different in their image-forming designs. Considering the number of different combinations of image capture, processing, and reproduction technologies that can be mixed and matched to produce an imaging system, it might seem that our standards for acceptable image quality should only increase as the most optimized and advanced technology couplings are developed and implemented.

Yet history shows that consumers have been quite pleased with imaging systems that produce a level of image quality that is inferior to other pre-existing systems. The tradeoff that is often made is convenience over image quality. Consumers were using 35mm film long before smaller formats, such as the “110” pocket instamatic film format allowed for smaller cameras at the expense of film grain and loss of sharpness. The first digital cameras made available to consumers provided nowhere near the image quality of a photographic print from any film format, yet they sold. The sales of consumer camcorders skyrocketed after the 8mm video format was adopted over the larger tape format making the units much more compact and easier to carry.

Factors other than convenience, such as cost and speed, also seem to scale and offset our individual ranges of acceptable image quality. This is due to an image quality factor that might not be the first that comes to mind but is probably the most crucial – the human element. The human eye is the ultimate image capture device. It is biological and, therefore, likely to be somewhat different in different individuals. The visual cortex exists biologically in the brain and it processes information in a manner that can only be observed and modeled.

While all of this might make it seem nearly impossible to assess and compare image quality from imaging system to imaging system, the playing field can be leveled by restricting such comparisons to individual imaging components. One manufacturer’s color negative film can be compared to a competitor’s film, a 50mm camera lens can be compared to another 50mm lens, the image quality associated with a thermal dye sublimation printer can be compared to that achieved from optically printing a color negative, and one of the most prevalent comparisons being made today by manufacturers, professional users, office users, and consumers at home is the image quality comparison between various color inkjet printers. This prevalence results from the fact that the major manufacturers of most color inkjet printers offer product lines that are diverse enough to minimize the differences in other competitive variables such as cost, speed, and footprint, leaving image quality as the last bastion for comparison. Market studies have confirmed that image quality is one of the most prevalent considerations that consumers use in their choice of which printer to purchase.

Overall image quality is affected by each of the individual imaging components for capture, processing, and output, integrated as a system. When the complete imaging path can be defined, it is desirable to assess image quality at the system level, though the analysis can be cumbersome. Once such an analysis has been performed, the contributions of any one of the components in the imaging path can be evaluated relative to its effect on the final image quality.

Consider, for example, the simple imaging path formed by a digital camera, a PC with software that can be used to alter image attributes such as contrast, lightness, color balance, and saturation, and an inkjet printer. In addition to these physical components, there are two constants in every imaging path – the scene and the observer. In most cases, the observer is a human being who will view the final image under some set of environmental conditions that will also affect the appearance of the final image. All of these components can be characterized, thereby enabling the creation of a model for the imaging path. Once this has been accomplished, then the characteristics of any one of the imaging components can be altered in order to evaluate how those alterations cascade down the imaging path and reach their final destination – the observer.

While it is certainly possible to compare two different digital cameras by comparing how each of them transform input image signals into output signals, the significance of these differences must take into account the effect of the subsequent components in the imaging path. Perhaps the output of one camera is 10% different, in some regard, than the output from another camera. The preferred appearance, or rendering, of the scenes may require image processing on the PC that reduces this difference to 5%. The capabilities of the inkjet printer may further reduce these differences to 1% on the final inkjet print. If the human visual system is capable of detecting a *just noticeable difference* – also known as a *JND* - when this hypothetical image quality attribute is incremented or decremented by 2% or more, then the difference between the two cameras has no perceptible effect on this attribute of image quality at the system level.

The considerations described above also pertain to the comparison of two inkjet printers. When the imaging path is well defined, it include limitations posed by an input device which will determine the range of signals that will be sent to the printers.

Most users, however, are not interested in how two printers compare in a single imaging path. Users expect to be able to use their printers to create pleasing prints regardless of the source of image capture or image processing. Therefore, the image quality capabilities of inkjet printers are usually characterized over the entire range of the printers' input capabilities and the output capabilities should take into account the human visual system.

One means of comparing two inkjet printers is to pass a single captured and processed image to the two printers. This task can also be accomplished by sending the printers the same computer-generated digital *target* consisting of a variety of patterns designed to compare specific image quality attributes. Usually the comparison is based on a combination of both of these sources of input. The resulting prints can be viewed by an individual in order to make a subjective comparison based upon that individual's preferences and priorities, they can be viewed by a group of individuals in order to perform a statistical analysis of the group's assessment, or the prints can be measured for an objective, quantitative analysis.

A combination of objective and subjective image quality assessments is the most meaningful. Measurements yield data that can be used for quantification, but measurement devices lack the processing that occurs in the visual cortex. Subjective image quality assessment, accomplished by viewing images, incorporates the human element but it can be difficult to articulate the assessment except for broad categorical statements. In reference to the vector plots that Color Scientists tend to use to describe characteristics such as hue angle and color saturation, it was once said that "A picture is worth a thousand arrows." While this statement is quite true, the difficult part is getting those pictures into the hands of the entire intended audience. Numerically quantified results can be published ad nauseam, but the numbers may never be fully appreciated. Together, subjective and objective analyses complement one another. This can be accomplished by correlating physical measurements with the statistical assessments of a group of observers.

PEARLS™

As the color inkjet printer playing field becomes more and more level, image quality expectations tend to rise. Today's image quality goal, even for many in-home applications, is to create images (from digital files) that have the look of photographic prints. Let's consider how prints created from digital files differ from photographic prints. First of all, photographic prints are not digital. Some digital output devices are designed to record digital images on film which can then be optically printed, and still other devices are designed to record digital images directly onto photographic paper which is then processed chemically. While these examples of hybrid imaging systems involve digital components, it is the image quality of optically exposed and chemically processed silver halide (AgX) photographs that consumers and professionals alike are pursuing, and that savvy printer manufacturers are beginning to deliver.

Digital images often have the appearance of being just that – digital or discrete. Digital image processing that might be performed to enhance one attribute of image quality can affect other attributes in a way that renders them artificial looking. When such artifacts exist anywhere within an image, it is a telltale sign that the image is not photographic.

Photographic images are produced by exposing tiny crystals of silver halide (e.g., silver iodide, silver bromide, etc.) to light, thus forming a latent image. The silver halide crystals are suspended in gelatin and the resulting emulsion is coated on a substrate. The latent image is an invisible record of an image exposed onto photographic film or paper and is formed by the silver halide crystals that were exposed to varying amounts of light. Photons of light cause miniscule amounts, only a few atoms, of metallic silver to form at discrete sites on the exposed crystals. The exposed film or paper is then placed in a chemical solution known as *developer* which provides a source of electrons to chemically reduce the silver halide crystals containing *latent image sites*, thus forming greater amounts of metallic silver (see Figure 1). The reduction or development results in the latent image sites undergoing a tremendous amplification resulting in much larger filaments of metallic silver. Further chemical processing is used to stabilize or *fix* the developed image. Color photography involves a matrix of several emulsion formulations and more chemical processing steps in order to remove the metallic silver image leaving only colored dyes that, together, represent the color content of the exposed image. With such a process, very small incremental changes in the exposure to light result in very small incremental changes in the amount of metallic silver or optical image density that is formed (the term *optical density* or *OD* refers to a logarithmic metric used to quantify the lightness or darkness of a region of the image). This is why photographic images appear to be continuous in tonescale. This characteristic, often referred to as *contone*, is probably the most significant differentiator between the appearance of digital and photographic images.

Optical density is a very common metric for quantifying the lightness or darkness of neutral gray areas. Color or *status* densitometry can be used to quantify colors. Since the term will be used frequently in this discussion, a brief explanation of its definition may prove useful. Density, specifically *reflection density*, is related mathematically to another metric called *reflectance*. Reflectance is simply the amount or percentage of light that reflects back from the print relative to the amount of light incident to the print. A reflectance of 50% means that half of the light that was used to illuminate the print was absorbed by the print colorants and/or the paper stock (some may have even passed right through the paper, never to return), while the other half reflected back to the detector. The negative log (base 10) of this reflectance value yields the density, so the density corresponding to 50% reflectance is $-\log_{10}(0.5)=0.301$. This means that each increment of approximately 0.3 in density equates to halving the amount light that reflects back from the print. Density, a log metric, is useful because it represents, more accurately, the way in which the eye responds to equal-increment changes in light intensity. The darkest black that can be created by an imaging system is known as Dmax and the whitest white is known as Dmin

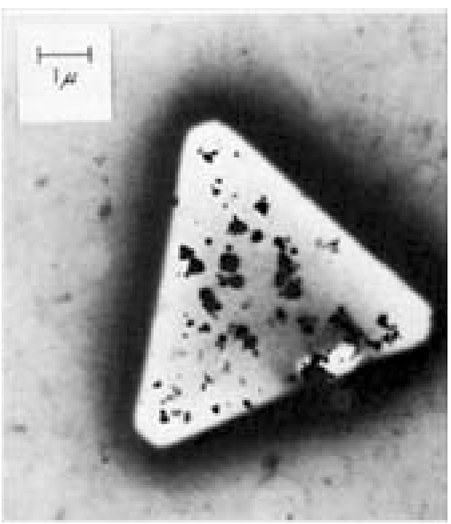

Figure 1a: Exposed silver halide crystal with latent image sites.

Figure 1b: An exposed silver halide crystal reduced by developer, thus forming much larger filaments of metallic silver.

The creation of prints, from digital images, that have the appearance of contone is one of the most sought after image quality goals in the design of digital imaging devices and poses a particular challenge to the manufacturers of digital printers. Yet today's technology has enabled printer manufacturers to offer products that produce prints which look very much like photographic prints. Surprisingly, such technology can be employed without imposing tremendous increases in cost and decreases in speed. This advantage has been most profoundly achieved in the design of inkjet printers.

There are many attributes of image quality that affect the appearance of inkjet prints. Moreover, many of these attributes cannot be fully considered on an individual basis. Image quality tradeoffs often need to be made since an improvement made to one attribute can result in a deficiency to another attribute or attributes. This obstacle is dealt with by carefully balancing image quality tradeoffs and taking advantage of the limitations of the human visual system.

Of the many attributes of image quality, those that are most critical to the evaluation and comparison of prints produced by inkjet printers include:

Permanence
Edge Quality
Artifacts
Resolution/Addressability
Linear tonescale/Color Reproduction
Solid-Area Quality

Permanence refers to the stability of image quality over time and over an assortment of environmental conditions. The governing factors affecting image permanence are associated primarily with the properties of the media (ink and paper). Whether a print tends to fade after being exposed to sunlight over a period of time is a characteristic referred to as *lightfastness*. Fade can occur in saturated colors, neutral midtones, and everything in-between. To make matters worse, one color ink might fade at a different rate than another color ink causing hue shifts to occur over time. Image quality can be adversely affected by moisture. Whether image quality is affected by moisture is a characteristic referred to as *waterfastness*. Whether image quality is affected by a physical disturbance, such as a user's finger coming in contact with the image, is a characteristic known as *smear* and can vary with image density. Image permanence can be evaluated using highly controlled environmental conditions. Lightfastness can be measured by subjecting printed output to intense light consisting of a variety of different spectral output ranging from daylight to tungsten (incandescent). Such testing is often referred to as *accelerated fade testing.* Waterfastness and smear can also be evaluated under these environmental conditions.

Edge Quality is determined by the abruptness of the transition across an edge within the printed image and the visual appearance of the sharpness of that edge. Soft or blurry edges result when the density transition from the image to paper white is too gradual or, when viewed with high magnification, the edges are too ragged. At normal viewing distances, the eye integrates the irregularities of ragged edges making them appear soft by transitioning over several shades of gray. An ideal edge is formed when it consists of a straight line of some density followed by an immediate changeover to paper white. If the image density were measured at very small intervals across such an edge, the resulting measurements could be plotted and would form a step function (Figure 2a). A plot corresponding to a soft edge, which transitions from a high density through several shades of gray before reaching paper white, would appear more rounded (Figure 2b) and the edge itself would appear soft.

Any component in the imaging system, including that used for capture, image processing, softcopy display, or hardcopy printing, can contribute to degradations in edge quality. Whether an inkjet printer creates ragged or sharp transitions from dark to light depends upon factors such as the interactions between ink and media, drop placement accuracy and velocity, dot overlap, and the presence of specific artifacts called *satellites* which are unwanted droplets of ink that sometimes result unintentionally during the placement of intended dots.

Figure 2a: Image line trace simulating a “sharp” edge from printer Dmax to paper white.

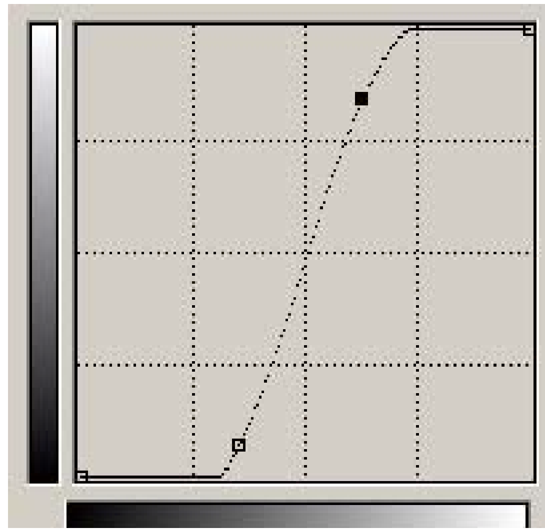

Figure 2b: Image line trace simulating a “soft” edge.

In addition to edges that appear too soft, edge quality can suffer in other forms associated with the spatial addressability limits of the printer. This is particularly true when diagonal edges are produced on a printer that has a relatively coarse spacing which will produce artifacts known as *stair-stepping* or *jaggies*.

While printed edges can be used to evaluate other image quality attributes like sharpness (see “Resolution/Addressability”) edge quality refers to the integrity of the edge itself. A soft edge such as the one whose measurement is depicted in Figure 2b may result from a combination of sources such as the ink *feathering* as it spreads in uncoated paper, drop placement error, and satellites. Edge quality is measured by scanning a printed edge (Dmax to Dmin) with a very small sampling aperture and sampling interval. Slit apertures are often used in order to reduce measurement noise by integrating the signal over a large area parallel to the edge while the slit width is relatively narrow. Typical slit dimensions for reflection prints range from 5x200 µm to 10x1000 µm. A good sampling response can be achieved by setting the sampling interval to half the aperture width. These measurements are usually made with a scanning microdensitometer that records density measurements at these very short sampling intervals. Line traces such as those shown in Figure 2 can be obtained from a microdensitometer. The line trace can then be used to measure the distance, at the print plane, across which the edge transitioned from Dmax to Dmin. This distance should be less than 15 µm for letter quality and less than 5µm to approximate lithographic quality.

<u>**Artifacts**</u> are noticeable anomalies that sometimes find their way into natural appearing scene content. They often occur in digital imaging systems and are thus referred to as *digital artifacts.* As an example of the exception to this rule, a speck of dust on a negative placed in an enlarger will create an enlarged image of the dust speck on the final

photographic print. If this imaged dust speck is noticeable while viewing the print, it can be referred to as an artifact, but not as a digital artifact. Common artifacts in digital images result from sensor defects or insufficient levels of tonescale in the capture device, from improperly resizing the image or applying too much sharpening during the image processing step, or from properties inherent to the output device.

In addition to *satellites*, which have already been described, other artifacts associated with inkjet printers often result from limitations to or problems with the ink delivery system. Nonuniformities in the physical characteristics of any of the components in an individual jet on an inkjet printhead will cause unwanted artifacts. For instance, if the drop volume is not consistent from jet to jet or, worse, if the inconsistencies change with groups of neighboring jets on the printhead, then visible *banding* can occur across the image. Jets that misfire and cause drops of ink to fall in the path of the ink from other jets will cause *streaking* artifacts. Air or debris blockages can cause jets to stop firing altogether causing white lines to appear within the image.

When too few density levels are assigned in the digital halftoning scheme, natural gradients like those found in the sky from horizon to zenith, will show *contour bands* where the image density remains constant over a relatively large area (band) and then jumps several levels higher and remains constant across another band. Moire' is an artifact associated with sampling and measures must be taken to avoid these patterns while digital halftoning and image resizing operations are performed. *Moire'* occurs when the original image contains spatial frequencies that are higher than the new sampling frequency associated with a resized or halftoned image. These frequencies fold back on top of lower spatial frequencies adding artificial content and creating unnatural appearing patterns.

Motion quality, which includes the media transport system and the printhead carriage, must be high enough to avoid motion artifacts. Spatial inaccuracy of the media transport system can cause banding artifacts and/or image distortion. Periodic variations in the velocity of the printhead carriage can cause moire' artifacts.

Grain is a term that is used in the photographic film industry to describe the amount of image *noise* that results when reduced silver halide crystals (black and white photography) or dye clouds are enlarged and imaged on the final print. Generally speaking, faster films, those more sensitive to light, tend to be comprised of relatively large silver halide crystals which, when developed, create relatively large *grains* that can be visible in the final print. Photographic paper also may also suffer from high granularity. This artifact can be measured and quantified in terms of granularity units. The detectors used in scanners and digital cameras (charge coupled devices or CCDs) that convert light into electrical signals can add electrical noise to the resulting signal and produce a noise artifact in the resulting image that looks similar to film grain.

Images from hybrid imaging systems may contain noise from film grain as well as detector noise. Digital image processing can amplify the noise, making it even more visible. The digital halftoning scheme used in inkjet printers may also cause visible noise patterns. Such patterns can result from having too few gray levels or halftone frequencies that are too low. Some error diffusion algorithms result in a specific type of noise pattern called *wormholes.* Computer generated noise is sometimes added to images to cover up other less desirable artifacts, like those resulting from error diffusion. Image noise usually varies with density level and should be quantified at a variety of density levels. Analyses of image noise that originates with a printer can be conducted in either the spatial or frequency domains. In the spatial domain, a signal of known amplitude is sent to the printer. A print is made and scanned using a very small aperture and sampling interval – typically in the tens of microns. The amplitude of the signal, recreated on the print, is compared to the amplitude of the noise. The ratio, know as the *signal-to-noise ratio* or *SNR* is used to quantify the noise. In the frequency domain, Fourier analysis can be used to compute a *Wiener Spectrum* (film) or a *Noise Power Spectrum* which indicates relative amounts of noise at all relevant spatial frequencies in the printed image.

Resolution and **addressability** are two separate and distinct attributes of inkjet printers that work in tandem but are often confused with one another. Addressability refers to the spatial frequency of dot placement as determined by the design of the printhead and the paper transport system. The addressable grid is sometimes referred to as the printer's addressable grid. Resolution describes the printer's ability to resolve detail. It is dependent upon the size and shape of the dot it produces relative to the addressable grid.

Inkjet printer manufacturers often advertise printer "resolution" in terms such as "1200 dpi resolution" when, in fact, they are referring to the printer's spatial addressability or raster grid spacing. Adding to the confusion is the common practice of misusing terms such as dot, dots-per-inch (dpi), halftone cell, pixel, pixels per inch (ppi), and lines-per-inch (lpi). As a practice that others are beginning to use, and for the sake of this discussion, the term *pixel* will be used only in the context of image capture and with reference to a single sample within a digital image file. It refers to the discrete tonal value (or values in the case of color captures) assigned to each sample in the capture. The term *dot* will refer to the ink droplet that has been placed on the paper within the printer's addressable grid cells. The term *dpi* is a unit of addressability that refers to the spatial frequency of dot placement. Specifically, it is the number of dots that can be discretely deposited onto one linear inch of the paper. The term halftone cell will refer to the super set (or super cell) of addressable cells that are used to represent the density level of an image area on the printed page. The term *ppi* will be used to describe the addressability of the capture device. The term *lpi* will be used only to refer to the spatial frequency of halftoning screens that are used in conventional halftoning techniques. The term *hpi* will be used to refer to the digital halftone cell frequency.

In the practice of digital halftoning, multiple grid cells are used to form a single halftone cell. The greater the number of addressable grid cells that are assigned to the halftone cell, the greater the number of density levels that can be produced. If the halftone cells are formed using a 3x3 array of addressable grid cells, then a total of 10 density levels could potentially be produced within the halftone cell depending upon how many (if any) of the grid cells in the 3x3 array contain a dot (see Figure 3). Likewise, if a 16x16 array of addressable grid cells were assigned to each halftone cell, then a total of 257 density levels could potentially be produced within each halftone cell. This example is based on the sometimes unrealistic assumption that a dot can be placed inside a grid cell such that it completely fills the cell without significantly overlapping the dots in adjacent grid cells.

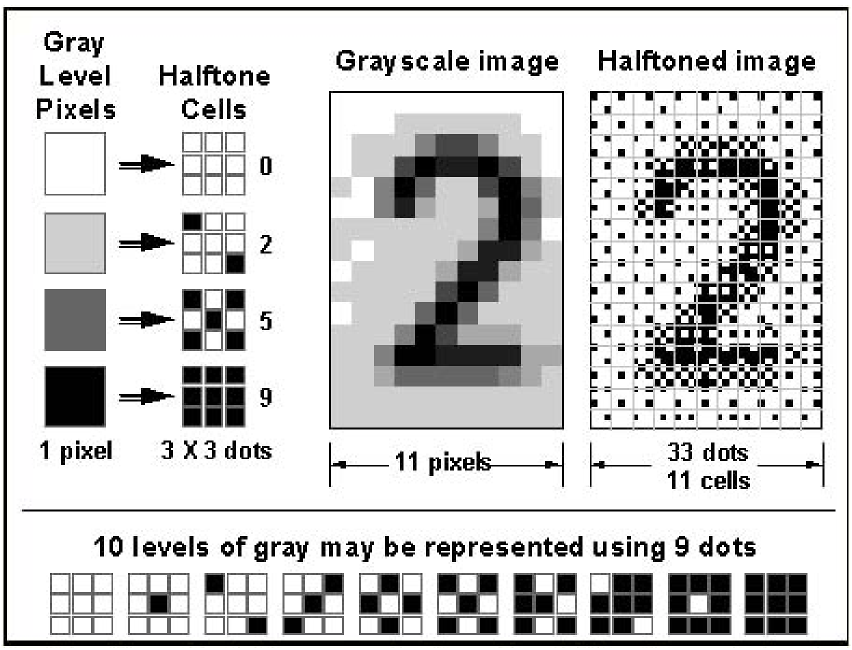

Figure 3: Digital halftoning

In the 3x3 example, the printer is potentially capable of printing higher spatial frequency scene content than that in the 16x16 example since the halftone cell is smaller. This high-frequency detail may be higher than the eye can resolve, thus rendering it of no use in normal viewing circumstances. The printer using the 16x16 halftone cell would not be able to print detail at spatial frequencies as high as the former, but more densities could potentially be produced. Though the printer using the 3x3 halftone cell could potentially resolve more detail than that using the 16x16, whether it will depends upon the actual size and shape of each dot placed in each addressable grid cell. Whether the printer using the 16x16 halftone cell produces more of a contone look than the printer using the 3x3 halftone cell also depends upon the integrity of the dot and the degree to which scene spatial frequency was traded off for the increased number of density levels.

The two scenarios described above illustrate the tradeoffs that occur when increasing potential detail versus increasing potentially greater numbers of density levels which, in turn, can contribute to more of a continuous appearing tonescale (contone). The greater the number of addressable grid cells assigned to each halftone cell, the bigger the halftone cell becomes. Such halftone cells are capable of representing greater density levels, but the large halftone cell size (low halftone cell frequency) can result in higher granularity – the appearance of grain or noise in the image. Some printer manufacturers allow different combinations of these parameters to be selected by the user for different applications. Other manufacturers are adding value to the overall image quality equation by producing printers that are capable of depositing dots of different sizes within any given addressable grid cell. This capability can negate the tradeoffs that occur between resolving more detail or adding more density levels since additional density levels can be achieved within a single addressable grid cell by modulating the dot size.

The size of the final dot depends on factors other than just the volume of the droplet produced by the printhead. *Dot growth* or *dot gain* is a phenomenon inherent to both the ink and the print medium. Ink tends to spread through the tangle of fibers that comprise uncoated paper and this can lead to *feathering,* or the formation of spikey edges around the dots. The final dot, in this case, grows to cover a larger area on the paper and appears fuzzy as a result of the feathering. *Photo grade papers* are papers that are coated with a layer of ink absorbing particles such as silica or alumina (bauxite) suspended in a binder. Such coatings significantly reduce the dot growth by reducing the area over which ink spreads in the paper. Different paper types also exhibit different optical properties. One of these properties is the *optical spread function* of the paper. Incident light can be absorbed or reflected by the ink(s) on the paper. But some light can pass through the ink and penetrate into the paper fibers. Some of that light will immediately exit out the back side of the paper, but some of it will bounce around between the fibers and re-emerge through the surface at some other location. This spread of light by the paper will affect the perceived size of the dot, making it appear to be larger and have softer edges. All of these factors must be considered at the system level in order to accurately control the size of the final dot on the paper.

The modulation of dot size is one method of applying a technique known as *multilevel halftoni*ng. With multilevel halftoning, each of the grid cells that comprises the halftone cell may be black, white, or something in between. Just as only 2 levels (black and white) are used in a binary system, 3 levels are used in a trinary system, and 4 levels are used in a quaternary system wherein 1 or 2 levels of gray can be produced within each addressable grid cell in addition to the production of black and white. Whether any individual addressable grid cell is black, gray, or white depends upon the size or density of the dot within the addressable grid cell.

Figure 4 shows the image quality tradeoff between halftone cell frequency and the number of density levels that can be achieved with each halftone cell in a binary system (each grid cell either contains a black dot or it contains no dot). From this graph and the image quality achieved with each condition, we see that 300 dpi addressability will not achieve "acceptable" image quality. A printer with 600 dpi addressability just barely achieves "acceptable" image quality and 1200 dpi is needed for "desirable" image quality.

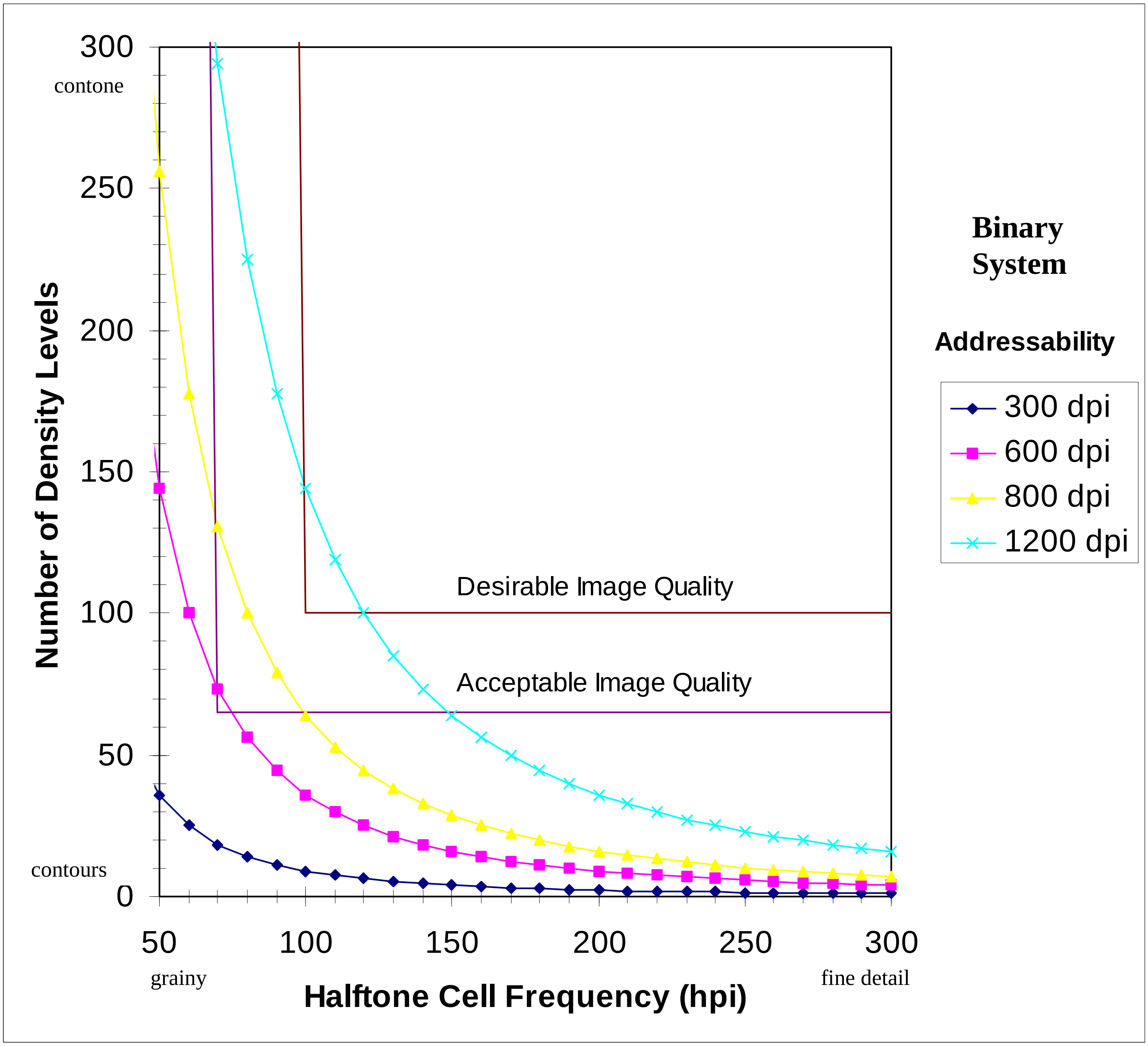

Figure 4: Number of density levels vs. halftone cell frequency in a binary system.

Figure 5 shows the advantage of using multiple dot sizes in multilevel halftoning, even when the addressable grid is rather coarse at 300 dpi. We still see that the binary printer with 300 dpi addressability will not achieve "acceptable" image quality. By adding one additional level to form a trinary system, "acceptable" image quality can be produced without increasing the spatial addressability of the printer. A quaternary printer with 300 dpi addressability will produce "desirable" image quality.

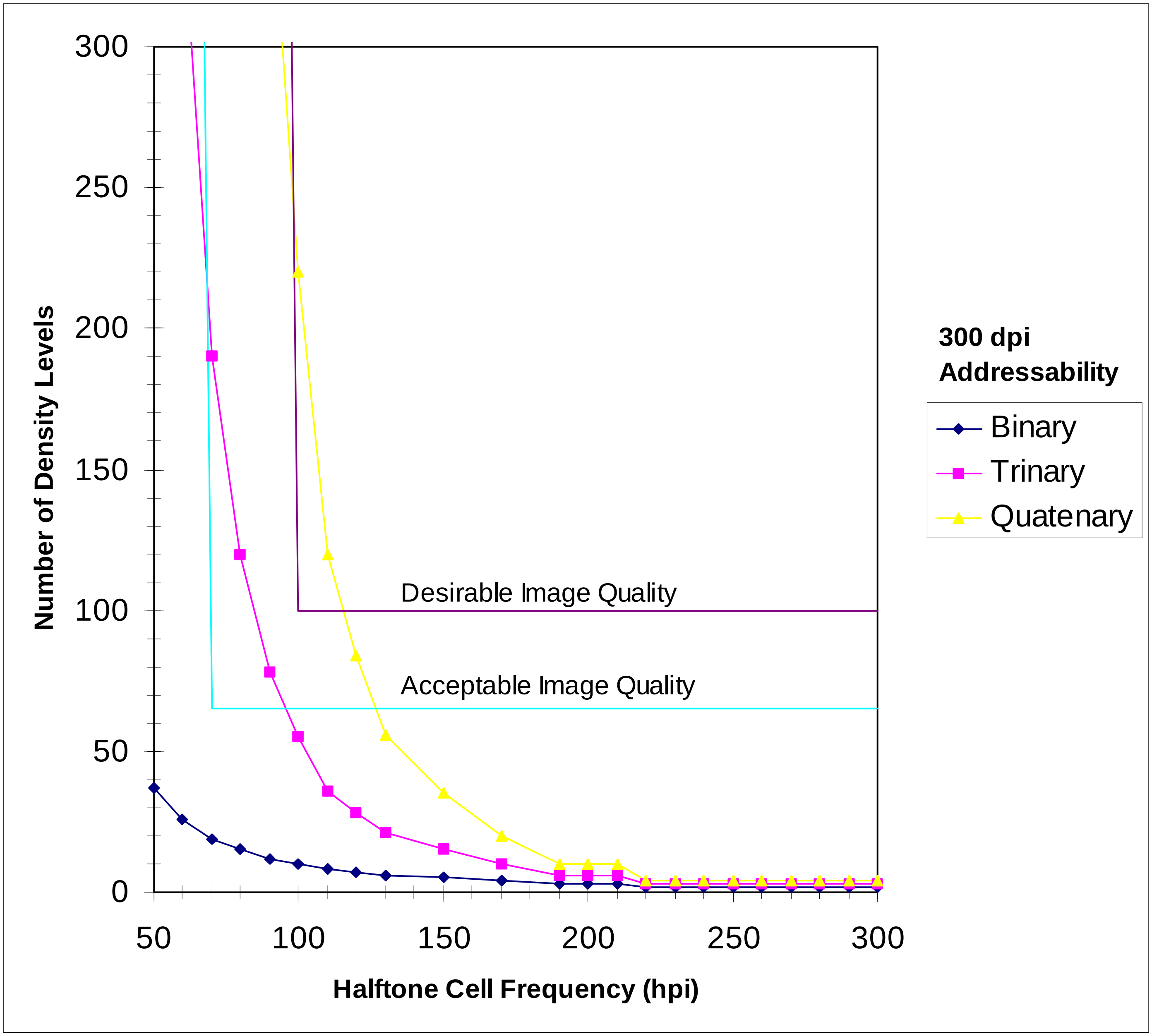

Figure 5: Number of density levels vs. halftone cell frequency in a multilevel system.

Optimum image quality can only be achieved when printer addressability, printer dot size, and the halftone cell size are co-optimized. These factors, along with edge quality, will determine the *resolution* of an inkjet printer – its ability to resolve detail. This capability varies with the spatial frequency content of different portions of an image. High frequency edges are formed when the cycle from black to white occurs over very small spatial distances. Edge quality and resolution usually deteriorate as the spatial frequency increases. This happens when the dark areas spread or blend into the light areas causing the dark areas to become too light and the light areas to become too dark, resulting in a loss of amplitude modulation. Consider the digital capture of a scene consisting of a snow covered field with a large black box in the foreground and a black picket fence in the background. Assuming the actual box exhibited physically sharp edges, the face of the black box will form a high contrast or high modulation edge against the snow. In the image, this interface should appear to be and measure as a single cycle of a well formed, sharp edge similar to that shown in Figure 2a. The picket fence in the background will appear as many cycles of dark-to-light transitions that appear to be much softer than the edge of the relatively large box in the foreground. Measurements of these cycles would show several higher frequency cycles of near-black to near-white transitions. The graph would likely show round corners and a loss of modulation – that is, the whites would be somewhat darker and the blacks would be somewhat lighter than the objects in the original scene. The slope of the line connecting the dark and light portions of the line trace would also be reduced indicating that the edges transitioned through more shades of gray than were actually in the scene.

Sharpness is an image quality attribute that describes how the detail of a scene was reproduced in the printed image. Printers that exhibit a high degree of resolution produce prints that are said to appear *sharp.* When detail is not well resolved, the sharpness of the printed image is low and the print is sometimes described as *soft* or *blurry*.

Inkjet printers and other imaging components can be characterized for sharpness by measuring the devices' modulation transfer function or MTF. This measurement, which can be performed using a variety of techniques and waveforms, shows the normalized modulation of the printer's response at all relevant spatial frequencies. Generally speaking, the greater the area under this curve, the greater the sharpness associated with the device.

Resolution/addressability, as well as the factors affecting edge quality, will contribute to the visual sensation of overall image sharpness. The perception that images appear to be sharp and continuous in tone is achieved with the system optimization of addressability, the way in which the addressable grid is utilized, and the factors mentioned above that contribute to the printer's overall resolution.

Linear tonescale and **Color Reproduction** are also two separate and distinct attributes that, together, influence our perception of overall image quality with respect to the neutral and color tones that comprise the scene. While they are separate attributes, a linear tonescale response is required in order to ensure accurate color reproduction. It should be noted that the word "accurate", in this context, does not necessarily mean an accurate reproduction of the spectral reflectance of the objects in the original scene. User preferences usually include higher neutral contrast and color saturation over that inherent to the scene that was captured. One of the goals of good *color management* is to determine the preferences of the intended user and to set neutral and color *aims* accordingly. It is this set of aims that must be accurately produced by the imaging system.

Aside from its role as a prerequisite for accurate color reproduction, linear tonescale response is also important to ensure that neutrals remain achromatic (no color, gray) throughout the entire dynamic range of the printer. The extent to which highlight and shadow detail can be resolved is also determined by the linearity of the tonescale response at the extreme ends corresponding to near white and near black. The shape of a printer's neutral response varies with the different metrics that can be used to measure the neutral patches that were printed. Such metrics include *density, reflectance, luminance, percent dot,* and others. Since density is a log function, luminance is a cube-root function, and reflectance and percent dot are primarily linear functions, it stands to reason that each of these metrics will yield curves of different shapes. But when values representing a neutral in a specific metric are sent to a calibrated printer, and the resulting output is measured in the same metric, the relationship between the value sent to the printer and the measured value should be linearly related. In an ideal case, the two would be identical. Usually, the relationship is linear throughout most of the range of the printer, but the slope might be somewhat greater or less than 1.0 and there may be an offset as well.

Consider the tonescale responses illustrated in Figure 6. The x-axis of this plot represents the reflectance values sent to a hypothetical printer. The y-axis represents the reflectance measured from the resulting print for each input value. The red line represents a printer with an accurate and linear response. The reflectance printed by the printer is everywhere equal to the input reflectance sent to the printer. For the sake of comparison, the green curve represents a tonescale response that is accurate near the reflectance values of 0 (black) and 1 (white), but the printed reflectance values are too low elsewhere. This will cause the mid-tones of the scene to appear *flat,* or too low in contrast, while the Dmax and Dmin portions of the scene will print accurately. The response illustrated by the blue line illustrates a severe loss of dynamic range. In other words, 20% of the input range on the low reflectance end of the curve will be *clipped* to a single output value by printer, thus producing the same output reflectance over this

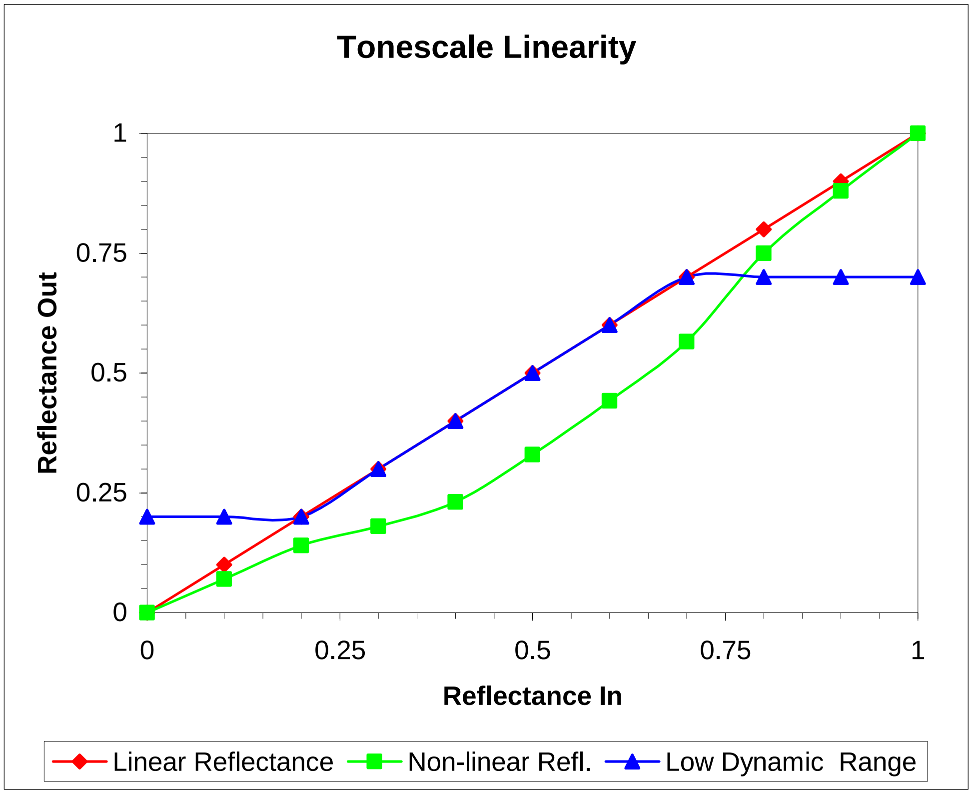

Figure 6: Hypothetical printer tonescale responses.

range of inputs. This is problematic since the shadow detail contained in the scene being printed will be lost, but also because the printer's Dmax will be too light. At the other end of the scale, 30% of the input range will be clipped to a single output reflectance. This, too, will result in the loss of detail, highlight detail this time, and the Dmin will be too dark. These losses in dynamic range are difficult, if not impossible, to correct with tone/color image processing transformations since the problem usually exists because there is no signal with which to work. Instead, the optimization of dynamic range is performed at the system level by considering the ink/media/printhead system and the digital halftoning algorithm.

Non-linear responses like that shown in Figure 6 (green line) can usually be corrected with a relatively simple image transform known as a look-up table or, more specifically, a 1-dimensional look-up table. This transform simply maps a set of input values to a new set of output values. A look-up table, or *LUT*, that transforms a printer response such as that illustrated by the green line, into a response that looks more like that illustrated by the red line, is known as a *linearization table*. Linearization must usually be performed for each of the input channels (red, green, and blue) of the printer. The 3 linearization curves sometimes look very different, depending upon the characteristics of the printer. Determining this printer characteristic is the first step in correcting it. Inkjet printers, like other printers and input devices, must first be characterized and then calibrated. *Characterization* and *calibration* are the means by which the aim tonescale, color and sharpness can best be achieved. It involves understanding of how the device performs – its characteristics – and then using that knowledge to make it perform such that specific aims are achieved.

Once a printer has been characterized and linearized, color transformations can be employed to enable the printer to produce the aim color reproduction or *rendering*. These aims include attributes such as *hue, saturation,* and *lightness.* Color correction is performed with transformations that use all 3 input channels (red, green, and blue) to produce new values which, when output by the printer, produce the desired color aims. These transformations are usually based on multivariate non-linear regression and can be employed in the form of 3x3 or 3x4 matrices, high order polynomials, or 3-dimensional look-up tables (*3D LUTs).* Once this has been accomplished, additional transformations can be used to maintain color reproduction within a single printer over time (print-to-print, or day-to-day for example) or from one printer unit to another unit of the same design.

Any deviation in color output from the predetermined aims can be quantified in a manner that correlates to the human visual system and that expresses how noticeable the errors will be to the average observer.

Solid Area Quality must be sufficient to produce solid black and colored objects that appear uniform and free of artifacts. Printers must be capable of producing high density Dmax and solid areas of uniform density in order to produce good image quality. Optimum Dmax is achieved when ink completely covers the paper, thereby absorbing all of the light incident to the paper. When portions of the paper are left uncovered by ink, these portions will reflect incident light and lower the overall (macro) density of the solid area. When these portions of the paper that are left uncovered by ink are large, the solid area can exhibit a coarse or grainy appearance as well. When the ink coverage is inconsistent, low frequency variations in density can exhibit *mottle.* When the density uniformity of solid areas varies spatially, the solid area can exhibit the appearance of banding.

Dmax is achieved by completely covering the paper with either black ink, or well registered layers of cyan, magenta, and yellow ink – *process black* – or both. In addition to Dmax, the requirement for uniform solid area quality also pertains to colored portions of a print. For instance, prints originating as computer graphics often contain large areas of solid colors. As is the case with Dmax, portions of the paper left uncovered by colored ink can also exhibit the appearance of graininess. Density non-uniformities that vary spatially can cause the colored solid area to exhibit banding, and when more than one color of ink is used in the solid area, this banding can exhibit hue shifts in addition to density fluctuations.

In order to ensure complete paper coverage in creating solid areas, a rule of thumb is to use an ink drop volume that will, after spreading on the paper, produce a dot size that is approximately 10% larger than the diagonal distance of the addressable grid spacing. This will insure complete coverage, even if some of the dots are too small or somewhat misplaced.

Summary

Six attributes of image quality have been identified and examined. The context of this paper has been geared to inkjet printing systems, but these attributes apply to all imaging systems and to most of the components that might comprise any given imaging system.

A crucial concept that this paper attempts to establish is the interrelationship between each and every one of the PEARLS™ image quality attributes. Any one attribute is affected by and dependent upon one or more of the other attributes. When imaging components, such as inkjet printers, are characterized and calibrated, the goal is to optimize image quality. The focus of the optimization might be aimed at one particular attribute, but the effect of the optimization must be evaluated against all of the other attributes.

Another key point discussed herein is the importance of establishing image quality aims by considering the human visual system and the intended viewer. Without this, considerable time and money can be wasted in the quest for improvements that may go unnoticed or without value. Image Scientists have developed statistical methods, such as *Psychometric Scaling* for considering image quality in a manner that incorporates the human element. Peter G. Engeldrum, the author of "*Psychometric Scaling*", articulates this point by saying "We don't see dots per inch. The crux of the problem is that, while we may know, for instance, an imaging system's dot addressability, customers do not see dots per inch. One image quality attribute they do see is 'sharpness.'" This paper, discussing the PEARLS™ image quality attributes, has examined how the perception of sharpness is dependent upon attributes such as resolution and tonescale response, and how resolution is dependent upon attributes such as utilization of the addressable grid, ink and paper spread functions, and other factors. Since all of these attributes are so tightly enmeshed, methodologies such as psychometric scaling are invaluable in establishing the appropriate image quality aims and in the assessment of final image quality.

TORREY PINES
RESEARCH