

# Impact of device parameters on image quality

## 1 Introduction – Aligning the dots

The traditional world of offset printing was a relatively simple and stable universe until the advent of digital. Advances in digital technology gave rise to the development of various different print technologies. The imaging process in turn changed from the well-known offset process with a universally accepted set of device parameters and quality criteria to a broad spectrum of processes, each with their own characteristics (i.e. specifications) and techniques to optimize print quality. None of these processes and techniques, however, can escape the basic rules of how to generate a (high-quality) image.

If the proliferation of digital technology has not launched an outright specifications war, it has at least contributed to the plethora of dots, spots, pixels and other loosely applied terms, causing a lot of confusion about specifications. These can easily be misinterpreted, and also the relationship between the various specifications is not always clear. The aim of this paper is to clarify those parameters and specifications that play a role in determining digital print quality and to briefly explain how they interrelate.

For the sake of brevity and clarity, without wanting to underestimate the complexity of the matter of image quality, this paper assumes an ideal world and deals only with aspects related to the intrinsic characteristics of an imaging or printing device. This paper also focuses on electrophotographic digital printing; where relevant the offset process is used as a reference or a base of comparison.

## 2 Page elements and quality criteria

At the most basic level, the elements making up a page can be distinguished in two categories:

*Contones*: an abbreviation for 'continuous tone', i.e. a color or grey scale image illustrating continuously varying tonal ranges.

*Line work*: text and graphical objects such as tints, blends, and full density areas (solids, lines, and text).

Table 1 summarizes the key quality criteria we will discuss and their relative importance for each of the page elements.

The evaluation of the overall visual print quality of contones includes, among others, the evaluation of good sharpness, high definition, shadow and highlight detail. The sharper an image, the more detail is visible.

High definition and absence of process grain or image noise are particularly relevant when judging the quality of tints, blends and solids. These should be smooth with no disturbing graininess or visible screening pattern (see 3.2.3). In addition, blends should have smooth transitions between the different densities and/or colors without obvious transitions or boundaries. Uniformity, i.e. the stability and consistency of color tints across a page and from page to page, is of particular importance for contones, tints and blends.

| Quality criteria <sup>(1)</sup>         | Contones                 | Line work                |                                              |
|-----------------------------------------|--------------------------|--------------------------|----------------------------------------------|
|                                         |                          | Tints and blends         | Full density areas (solids, lines, and text) |
| Good sharpness                          | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/>                     |
| High definition                         | <input type="checkbox"/> | <input type="checkbox"/> |                                              |
| Shadow and highlight detail             | <input type="checkbox"/> | <input type="checkbox"/> |                                              |
| Uniformity                              | <input type="checkbox"/> | <input type="checkbox"/> |                                              |
| Smooth tone transitions                 | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/>                     |
| Absence of process grain or image noise | <input type="checkbox"/> | <input type="checkbox"/> |                                              |

Table 1

When evaluating the print quality of lines and text, in essence the ability to accurately produce fine lines is evaluated ('crispness'). Fine lines are important in text to accurately produce serifs of certain fonts or thin strokes such as those used in Japanese and Chinese fonts. Fine lines are also important for the adequate reproduction of guilloches in security features or for the reproduction of hairlines.

These quality criteria represent the challenges for the printing device.

### 3 The reproduction process

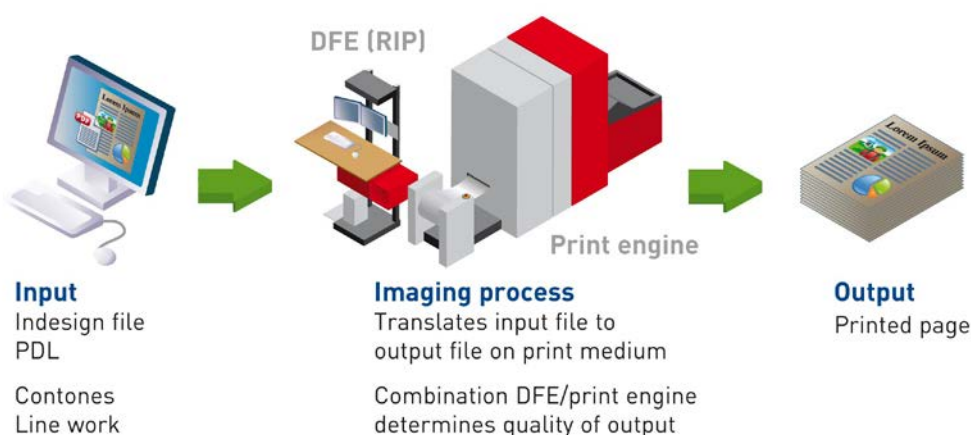


Figure 1

Before discussing the various device parameters or components playing a role in the reproduction of an image, it is useful to briefly describe the workflow to produce a printed page, starting from a digital file, so as to situate each component in the reproduction process. Broadly speaking, the major steps in a typical workflow can be schematized as follows:

**Input:** a typeset page created with for example Adobe Indesign, made up of images (contones), text and graphics (line work). This page is typically device independent and is basically a file of instructions describing line work in the form of vector graphics, text, and fonts, and images in a page description language, specifying all elements of the layout.

**Imaging process:** digital print engines typically print interlacing lines of dots. Contone images or line work can therefore not be printed without converting them to a series of dots. This is done by the RIP (raster image processor), a component of the digital front-

end (DFE) that interprets the instructions of the page description language and translates them into a bitmap, i.e. the actual pattern of dots, producing one bitmap for each process color. Typically every dot in the bitmap contains 8 bits per process color. The amount of information contained in such bitmaps is generally too large to be handled by the printing process. This is why, in order to print this bitmap, it has to be 'halftoned'.

Halftoning or screening is a process that converts a bitmap containing dots of 8 bits per process color in a bitmap containing dots with fewer bits per color. Those 're-sampled' bitmaps are then printed by the print engine.

**Output:** reproduction of the electronic original (input) printed by the print engine.

The quality of the output is influenced by the combination of the DFE and the print engine. Although the design parameters or specifications of these components do not by themselves define the level of perceived (image) quality, they do have a direct influence on the ultimate quality of the output, and as such they can be manipulated to maximize image quality.

### 3.1 Print engine

#### 3.1.1 Imaging technology

The controlled light source used when applying the electrophotographic imaging process can be either a laser or an LED array.

**Laser technology:** the light source used in the print head is a laser. Through a complex system of lenses and rotating mirrors that deflect the laser beam across the photoconductor as it rotates, the laser scans from one end of a line (image width) to another, and then starts on the next line to create the latent image. Typically, the laser beam is either 'on' or 'off' (see 3.1.4).

**LED technology:** the light source used in the print head is a light emitting diode array (LED array, an array with a fixed number of LEDs). The LEDs pulse the light through focusing lenses across the entire image width to create the latent image on the photoconductor as it moves past. The light intensity of the LEDs can be modulated (see 3.1.4).

Both laser and LED technology produce a constant dot size<sup>(2)</sup>.

#### 3.1.2 Resolution

The resolution of a print engine refers to the number of discrete dots it can print within a fixed area, expressed in dpi (dots per inch)<sup>(2)</sup>. The resolution depends on the dot size and therefore on the hardware of the print engine and on its imaging device in particular.

| Resolution | Dot size |
|------------|----------|
| 600 dpi    | 42 µm    |
| 800 dpi    | 32 µm    |
| 1200 dpi   | 21 µm    |

Table 2

For example a 1200 dpi print engine can place 1200 discrete dots per inch, i.e. dots with a size of  $1/1200$  inch = 21 µm. A 600 dpi print engine could place 600 dots per inch, with each dot being  $1/600$  inch = 42 µm. Using LED imaging technology this would correspond to an LED array with 1200 and 600 LEDs respectively.

The number of LEDs on a diode array being fixed, resolution, as it is defined here, is a hardware specification.

#### 3.1.3 Addressability

Another characteristic of the imaging device, in addition to resolution, is addressability. The addressability of a device determines the number of dots that can be printed within a specific grid. These dots can overlap. Addressability is defined in two directions, e.g. 600 x 600 dpi (symmetrical) or 1200 x 3600 dpi (asymmetrical).

For LED imaging technology, by definition, addressability equals resolution in one direction as the number of dots is physically determined by the number of available LEDs. In the other direction the number of dots can be higher depending on the frequency with which each LED can be addressed. In the example of 1200 x 3600 dpi this would mean that the LEDs pulse 3 times per unit time (i.e. the time required to process a line of 21 µm dots), 'oversampling' each dot as it were.

Laser imaging technology allows 'oversampling' in both directions since there is no physical constraint as there is for LED technology, other than the bandwidth of the electronics driving the laser and the maximum rotation speed of the mirror of the laser exposure unit itself.

#### 3.1.4 Bit depth

The bit-depth determines the number of output levels that can be printed.

While a typical laser exposure unit is either 'on' or 'off', the light intensity of LEDs can be modulated to create different output levels (see Figure 2).

A laser has, by definition, a bit depth of 1, which means it can produce  $2^1$  output levels. The laser is either 'on' or 'off', i.e. the device dot is black (laser 'on' and therefore toner is deposited) or white (laser 'off' and therefore no toner is deposited).

In an LED imaging system the light intensity can be modulated. If the imaging system has for example a 3 bit dot density<sup>(3)</sup>, then the number of available output levels equals  $2^3 = 8$  different output levels (see Figure 2).

Note that device dots are composed of toner particles much smaller than the dot size (depending on the technology used, toner particles are typically between 3 and 8 µm).

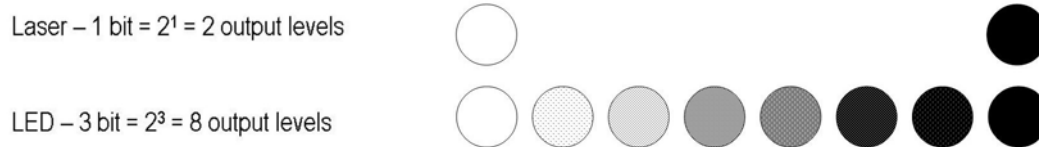


Figure 2

### 3.1.5 Process stability

The parameters imaging technology, resolution, addressability and bit depth are intrinsic parameters of the print engine and of the imaging device in particular. As will be discussed further in this paper, these have a direct impact on the output quality.

In addition to the four parameters mentioned above, there are many others influencing the process stability -and therefore also the final output quality- such as toner charge distribution, toner transfer uniformity, ambient conditions, paper humidity etc. While important, the aspects of process stability and their influence on image quality are outside the scope of this paper.

## 3.2 Digital front-end

The digital front-end is a combination of hardware and software, encompassing the entire suite of software modules necessary to process the files to be printed and to control the print engine. The modules or processes typically impacting output quality are calibration, color management and screening.

### 1. Calibration

The calibration of the imaging device in order to increase the accuracy of its output, i.e. to ensure its output matches certain criteria, is closely linked to all aspects of process stability. Assuming an ideal world, the discussion of calibration, although important, is beyond the scope of this paper.

### 2. Color management

Each device in the digital workflow works with its own color space and therefore has its own color representation (e.g. RGB versus CMYK). Colors from the same input file may look different on different monitors and the colors on the printed output file will look different from the colors displayed on a computer screen. Color management ensures color consistency and predictability among the different devices,

i.e. users will know what a given yellow on a computer screen will look like once it is printed on paper. Since this article assumes an ideal world, color management, although an important aspect of pre-press processing, is not discussed.

### 3.2.3 Screening

As explained above, most digital printing systems cannot print continuous tone images as they can only deposit dots with a limited number of bits per process color, which is why for printing purposes continuous tone images need to be converted to a pattern of dots containing the right number of bits per process color.

The process used to do this is halftoning and relies on the limitations of the human eye: the human eye cannot easily distinguish small dots that are closely spaced. The halftoning process is not new; in fact it was invented in the 19th century to allow the reproduction of black and white photographs. The way in which the dot pattern is created has changed as imaging technology has changed over the years, but the basic principles have remained the same.

The conventional halftoning process converts a continuous tone black and white image into a series of equidistant<sup>(4)</sup> dots of varying sizes (halftone dots<sup>(5)</sup>) placed in a grid pattern (the 'screen', i.e. lines of equidistant dots). Halftone screens are measured in lines per inch (lpi).

The higher the number of lines, i.e. the higher the 'screen ruling' or 'line frequency', the better the representation of detail, but the more difficult the image may be to reproduce (it means that the halftone dots are smaller and closer together, so less discernable).

A newspaper or a large poster to be viewed from great distance would typically use a screen ruling of 85 lpi while higher quality print would typically use 150 lpi or higher (see Figure 3 + further).

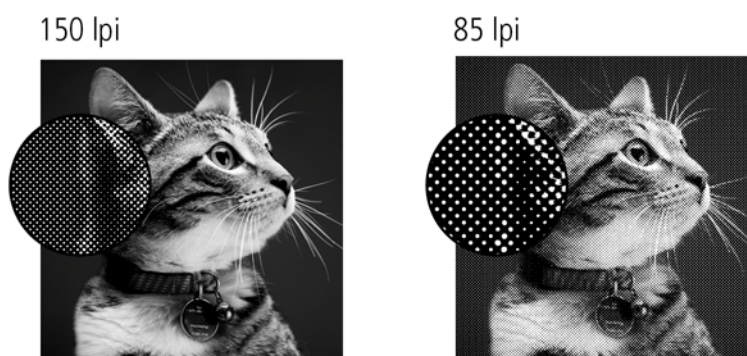


Figure 3

For black only prints, the angle of the halftone screen is usually set at 45 degrees to the horizontal as this improves the apparent quality of the image, the eye being particularly sensitive to horizontal and vertical lines.

For a continuous tone color image, the colors have to be broken down into the four process colors -cyan, magenta, yellow, and black- and the same halftone screening process is applied for each process color.

To avoid image distortion, the screens of the process colors are rotated over a certain angle relative to each other to create the well-known 'rosette' pattern (see Figure 4).

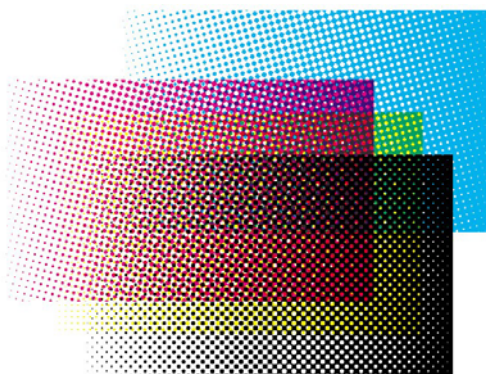


Figure 4

Gradations of intensity and color are reproduced by increasing or decreasing the actual size of the dots in a particular area of the image while the distance between dots, determined by the screen ruling, remains constant:

- The highlights (light areas) are made up of small dots surrounded by relatively large areas of 'white' paper.
- The shadows (darker areas) are represented by larger, overlapping dots.
- The mid-tones are represented by dots of varying sizes according to the tonal values that need to be represented.

At normal reading distance, the human eye will 'merge' the dots into their conventional halftone equivalents. It is being 'tricked' into seeing these dots as a continuous tone (see Figure 5).

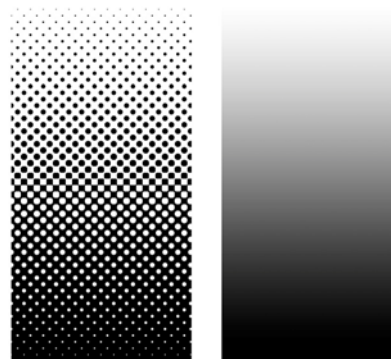


Figure 5

The higher the screen ruling, the better the reproduction of fine detail, but there is a trade-off to be made. A print engine also needs to be able to represent sufficient tones to accurately reproduce for example blends and nuances in skin tones.

The commonly accepted industry standard is 256 output levels ( $2^8$ ), representing a smooth gradation between black and white (or between any of the process colors and white). This is indeed sufficient as the eye can only distinguish approximately 200 output levels (see further).

When printing the halftone screen, the print engine will compose each halftone dot of several device dots. For example, using a conventional offset print engine with a resolution of 2400 dpi, an industry standard for high-quality print, and a screen ruling of 150 lpi, each halftone cell could be divided into a grid of 16x16 device dots (2400 dpi/150 lpi). Offset printing being a binary process (ink/no ink), the combination of this resolution and screen ruling allows creating the desired 256 output levels ( $16 \times 16 = 256$ ). However, using a print engine with a resolution of 600 dpi and a screen ruling of 150 lpi, would yield a grid of 4x4 device dots (600 dpi/150 lpi), which would allow creating only 16 output levels, not near enough for quality print. This is where bit depth comes into play (see 3.1.4).

From Figure 6 it can be seen that if the intensity of each device dot can be modulated, then a 600 dpi print engine could reproduce an output image that would, when viewed from the appropriate distance, resemble the image produced by the high resolution offset print engine.

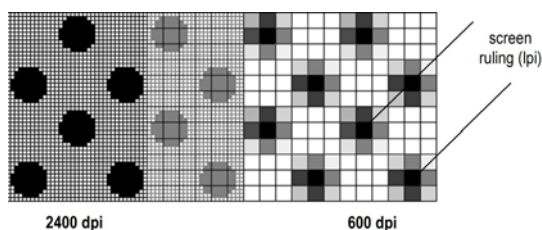


Figure 6

Left: binary offset, 2400 dpi – Middle: the desired halftone dots laid out on the device grids for both the 2400 and the 600 dpi print engine – Right: the intensity of a device dot can be modulated relative to the number of cells covered by the desired halftone dot (see middle).

At constant bit depth, a lower screen ruling would also allow a lower resolution device to increase the number of output levels: using a 60 lpi screen ruling, a 600 dpi device would yield a grid of 10x10 device dots (600 dpi/60 lpi) which would allow creating about 100 output levels. From a normal reading distance, however, the image would look 'coarse' (see further).

As mentioned earlier, the processes described above rely on certain physical limitations of the human eye. The human vision is incapable of discriminating detail below a certain level. This varies from individual to individual and can vary for the same individual from day to day.

Several studies have been undertaken to model the 'average' human eye or human visual system.

The conclusions of a renowned study undertaken in 1971 were the following:

- The human visual system cannot discriminate more than 200 shades (i.e. 8 bit depth is sufficient).
- The human visual system cannot discriminate more than 250 line pairs (i.e. screen rulings of more than 250 lpi make little difference).
- The human visual system cannot discriminate dots smaller than 30  $\mu\text{m}$ .
- The human visual system cannot discriminate simultaneously low contrast and fine detail.

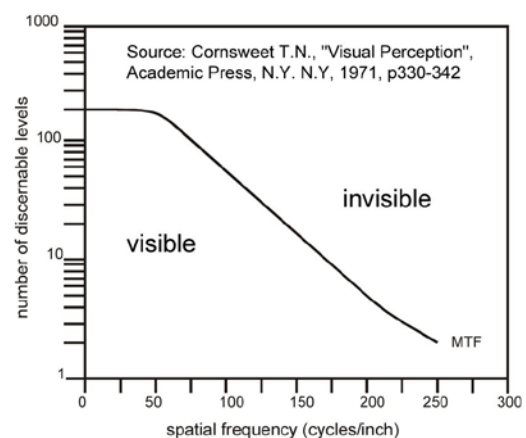
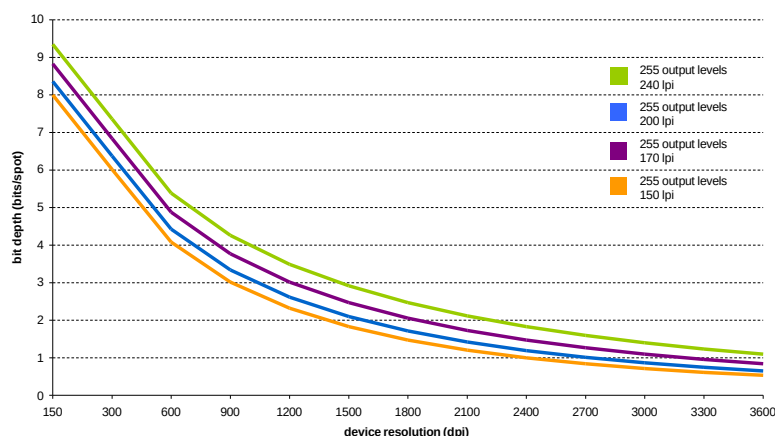


Figure 7

Spatial frequency corresponds to the number of lines per inch (screen ruling). The number of discernable levels corresponds to the intensity levels ('output levels' or 'grey levels') and is, all other things being equal, defined by the bit depth.

Deriving the mathematical relationship between some of the factors influencing imaging quality (resolution, screen ruling and bit depth) is beyond the scope of this paper. In the literature we find the following:



$$bit\_depth = \log_2 \left( \frac{output\_levels}{\frac{device\_resolution}{screen\_ruling}} \right) + 1$$

Figure 8

All other things being equal, the screen ruling is proportionate to the resolution of the system and the number of output levels is proportionate to the bit depth. The hyperbolic line indicates equivalent perceived quality (constant number of output levels and constant screen ruling). The higher the line, the higher the human eye would value the image quality. The graph also shows that for a 600 dpi print engine to produce the same number of output levels as a 1 bit per spot offset print engine of 2400 dpi, a bit depth of 4 would be required (see also Figure 6 on page 6).

#### 4 Impact of certain device parameters on perceived print quality

Having described several device parameters and their role in the imaging process, the question remains: How do these parameters work together to reproduce high-quality contones and line work?

Table 3 summarizes the relative impact of each of those parameters on perceived print quality as defined by the key quality criteria discussed.

In striving for high print quality, there are always trade-offs to be made between fine detail and accurate shade representation. Depending on the mix of elements on a page and the characteristics of the device used to process and print the page, other choices will have to be made.

Screening represents a trade-off between line frequency and the remaining number of tone values. For uniformly colored areas such as tints and blends, it is important not to see the halftone screen. Experiments<sup>(6)</sup> have shown that 150 lpi marks the transition: when a screen ruling is coarser than 150 lpi, a normal observer starts to see the halftone dots at reading distance. This is why for general commercial print work, screen rulings of at least 150 lpi are used. For top-quality print work higher screen ruling can be applied. Studies indicate, however, that the perceivable positive effect diminishes beyond 250 lpi (see Figure 7 on page 6).

The higher the resolution, the higher the possible screen ruling without loss of tone rendition (related to the number of visible output levels), which is important to be able to discern fine details.

| Quality criterion                       | Resolution | Addressability | Bit-depth | Screening |
|-----------------------------------------|------------|----------------|-----------|-----------|
| Good sharpness                          | +++        |                |           | ++        |
| High definition                         | +++        | ++             | ++        | ++        |
| Shadow and highlight detail             | ++         |                |           | ++        |
| Uniformity                              | ++         |                |           | +++       |
| Smooth tone transitions                 | ++         | ++             | ++        | ++        |
| Absence of process grain or image noise | ++         |                |           | +++       |

Table 3

Offset works typically at 2400 dpi or 3600 dpi binary, enabling the use of high screen rulings. Typically, resolutions of digital print engines are lower, but to a certain extent they can compensate this disadvantage due to the fact that they can modulate the dot intensity (see bit depth) to maintain the number of output levels. Several different intelligent screening algorithms exist to optimize the balance between screen ruling and tone rendition. However, ultimately, every method has its limits, determined by the intrinsic characteristics of the imaging device.

When reproducing full density areas, screening does not come into play. The print quality of these features is therefore purely resolution dependent (increasing the addressability can further improve anti-aliasing).

The higher the resolution, the smaller the device dot size and therefore the finer the text that can be printed while remaining legible and the finer the guilloches and hairlines that can be used. Resolution can indeed be defined as a measure of the ability of an output device to reproduce the fine detail of an image.

Table 4 below illustrates several possible combinations of device parameters and the resulting trade-offs. The highlighted areas indicate combinations resulting in too few tone levels (< 256).

## 5 Conclusion

Image quality and the various elements determining image quality are complex issues. Even what has been described above is relatively complex and still it does not deal with all the issues involved (assuming an ideal world).

Comparing headline specifications for different output devices can be confusing and misleading. Therefore, it is important to know exactly what is meant. Resolution, for one, is not to be confused with addressability. The distinction is indeed important given the role of resolution in the representation of for example fine line work.

The higher the resolution of the imaging device, the more degrees of freedom you get to generate quality across all the elements that make up a page (contones and line work). It is, however, important to note that there is no substitute for resolution.

While intelligent combinations of output device and software (screening algorithms) can overcome some of the intrinsic limitations of the output device, the less these algorithms need to compensate for, the better. Compensation also assumes that processes are stable. Process stability has not been discussed here, but is the most complex aspect of all.

Even when the elements making up quality are clearly defined, and their interrelations well understood, quality remains a subjective issue. It is and will remain in the eye of the beholder.

| Resolution (dpi) | Addressability-x (dpi) | Addressability-y (dpi) | Bits/spot | Halftone lpi | Spot size (µm) | # of tone values |
|------------------|------------------------|------------------------|-----------|--------------|----------------|------------------|
| 600              | 600                    | 600                    | 4         | 150          | 42.3           | 241              |
| 1200             | 1200                   | 1200                   | 2         | 150          | 21.2           | 193              |
| 1200             | 1200                   | 3600                   | 2         | 150          | 21.2           | 577              |
| 600              | 600                    | 4800                   | 1         | 150          | 42.3           | 129              |
| 1200             | 1200                   | 1200                   | 4         | 150          | 21.2           | 961              |
| 800              | 2400                   | 2400                   | 1         | 150          | 31.8           | 257              |
| 600              | 600                    | 600                    | 4         | 240          | 42.3           | 61               |
| 1200             | 1200                   | 1200                   | 2         | 240          | 21.2           | 76               |
| 1200             | 1200                   | 3600                   | 2         | 240          | 21.2           | 226              |
| 600              | 600                    | 4800                   | 1         | 240          | 42.3           | 41               |
| 1200             | 1200                   | 1200                   | 4         | 240          | 21.2           | 376              |
| 800              | 2400                   | 2400                   | 1         | 240          | 31.8           | 101              |

Table 4

## Endnotes

- (1) Color fidelity or richness is not discussed here (see also 3.2.1 and 3.2.2).
- (2) In the literature dot and spot are often used interchangeably. This paper uses the term dot to refer to the mark produced by the print engine on the print medium. Although some sources prefer to reserve the term 'dots' to refer to halftone dots only and to use 'spots' to describe the marks deposited by a print engine, the industry standard to quantify resolution is dots per inch, dpi, and not spi, spots per inch. This is why this paper also uses the term 'dots' to refer to the marks produced by the print engine.
- (3) Also expressed as '3 bits per pixel' or '3 bits per spot', with the terms 'pixel' and 'spot' referring to the bitmap and the LED respectively.
- (4) For the sake of simplicity we assume Amplitude Modulated screening (AM screening), although other halftoning algorithms can be applied as well (e.g. Frequency Modulated screening (FM screening)).
- (5) The term 'halftone' is slightly confusing because conventional halftone images do not have any tone. They only appear to have tone when viewed from a distance.
- (6) Campbell, F. W. and Robson, J. G. (1968) Application of Fourier analysis to the visibility of gratings. Journal of Physiology (London) 197: 551-566 cited in Test Targets 6.0 A collaborative effort exploring the use of scientific methods for color imaging and process control RIT School of Print Media, November 2006.