Bits, Density and Noise

Probably the greatest misconception about scanner technology is the one about bit depth per color, also called color resolution.

The first thing to remember is that bit depth and dynamic range are NOT the same thing. They are going to sound much the same, but they are not. That difference will be explained in the following article.

Most scanners are at least 30 bits color depth now, and many are 36, 42 or 48 bits. More bits are required to hold numeric values containing better dynamic range, but this one detail does not ensure it. While the two factors are often associated, there is also a second requirement. High-quality, low-noise CCD and electronics (i.e., expensive) are needed for better dynamic range. The fact that a scanner claims to have 48 bits color depth has nothing to do with its real optical density. It only means that 16 bit A/D converters are used.

Many scanner vendors list a dynamic range Dmax – Dmin that is equivalent to the theoretical limits set by the resolution. Some vendors are a bit more cautious and reduce the density range by 0.3 which is equivalent to the unavoidable +- 1 bit digitalization noise.

The following table shows the theoretical maximum density for various bit depths. If these values are found in a scanner specification sheet, it is safe to disregard them completely because they only specify the size of the container, not the content.

Total Bits	Binary steps	Max Density (no noise)	Max Density (1bit noise)
30	1024	3.0	2.7
36	4096	3.6	3.3
42	16384	4.2	3.9
48	65536	4.8	4.5

Real world density ranges are a lot lower than expected. The following table lists density ranges for various materials:

Material	Max Density
Newspaper print	1.8
Reflective photographic paper	2.0
Best print on paper	2.6
Best film transparencies	3.2

The message is clear: 36 bits of resolution can hold all numerical values necessary to represent the density range found with the best film transparencies. A bigger container, 42 or 48bits is a waste, especially because handling more data slows down every system. This is the reason why all Image Access scanners work with 36 bit raw data instead of pushing the bit number to 48 and slowing down the scanning process.

All our large format scanners have 36bit color depth. After gamma, white and black point correction, white balance and other image operations are performed on the 36bit data, the best 24bits are transferred to the application.

But this is not the end of the story, it is only the beginning. Real world noise is the biggest density limiting factor. It comes from many different sources -- some of them are explained in the following article.

First, one should consider the maximum dynamic range of a CCD which is the range between the imminent noise floor and the saturation point. This range implies that all errors that are constant, such as dark currents, sensitivity variations and charge transfer losses; are already compensated for. The dynamic range published in the data sheets is therefore the best possible and is probably a lot less in a real world system. Dynamic ranges of commercially available CCD chips are between 250 and 1000, 4000 being the highest value that we have ever found. Unfortunately they are not truly comparable because the measurement methods vary between different vendors.

Variations in the illumination system, the optical system, the CCD sensitivity and the long term drift of all these parameters make is necessary to perform a white balance for the scanner from time to time. Because of this, the CCD cannot be operated even close to the saturation point. In most cases it is operated a bit above half the saturation point, cutting the effective dynamic range in half.

Up to now, we have only evaluated the electrical system and its side effects. The typical useful dynamic range of 500 will translate into a density range of 2.7; barely enough to capture all details of the best prints on paper. Unfortunately there is also noise associated with the conversion from photons to electrons. If a CCD element is exposed to light, the amount of electrons generated will be different each time, even if the light source and the target are absolutely stable. The variance between different samples is called “electron noise”, “photon noise” or “shot noise” http://en.wikipedia.org/wiki/Photon_noise and equals the square root of the total amount of electrons captured. Assuming a CCD element accumulates 100.000 electrons, the variance will be 314. Therefore, the useful dynamic range is limited to 100.000 / 314 = 318 which equals to a density range of 2.5.

To overcome this, one only has to increase the light level and exposure time but there is another limiting factor called saturation exposure. A given CCD element can only hold a certain number of electrons before it saturates. The saturation exposure in electrons scales with the active area of the CCD element, which is the next caveat. The never-ending, marketing-driven, resolution race forces CCD elements to get smaller and smaller. Their saturation exposure levels get consequently lower; some saturate at levels as low as 20.000 electrons. The noise level due to this computes to 140 electrons which results in a dynamic range of 140:1, a maximum best case density range of only 2,1!

The only way out of this is to increase the size of the active CCD elements but this is very expensive because the lenses have to be of a different class. It is a lot easier to double the resolution at the expense of a higher noise level than to increase the resolution by increasing the CCDs active surface.

Image Access scanners use CCD chips with pixels sizes of approximately 10µm while consumer scanners have sizes of 4,5µm or even 2,5µm. The length of the active scan line is about 75mm, which requires a lens of reprographic quality having an image diameter of more than 75mm.