Counting Photons

The choice we now get in selecting a new camera is bewildering. Canon's new 40D, 1Ds Mark III, and G9, and the new Nikon D300 and D3 are only 5 of the 34 new camera models announced in August this year! With the new D3 Nikon has finally broken its resistance to move to a full frame sensor.

We welcome the competition - it certainly benefits us with highest quality cameras at lowest prices, but it doesn't help us in our decision making. When do we need to upgrade? How important is a full-frame sensor? The pixel race is heating up again. Two recent examples are Canon's latest EOS 40D with 10 Mpixels and its smaller brother, the PowerShot G9 which boasts 12 Mpixels. Does that make the G9 a better camera? No, of course not.

Film vs. Digital

This subject has been the centre of countless discussion forums and test reports. You might still remember the rave review of the 3.1MP Canon EOS-D30, written in the late 2000 by Michael Reichmann (luminous-landscape.com). In this article Michael compared the 3.1MP camera with 35mm Provia 100F. Digital came out superior in almost every aspect.

Today, in retrospect we can safely maintain that with 6MP cameras the resolution wasn't quite up to 35mm film at its best. However, the absence of grain, the smooth tones and the fine colour rendition made the overall image quality (IQ) equal to 35mm film. The emphasis is on '35mm film at its best'. The moment you move away from the superfine-grained to the more every-day variety, the information gets drowned in film grain.

Image 1 shows you a comparison where I photographed an A3-sized resolution chart with different cameras. The crop is a very small part near the centre of the image and corresponds to an A2-size enlargement. Prime lenses (50mm) at f/8 were used for the film camera (ISO 50 Velvia) and the 10 MP digital camera. The 4 MP Canon G2 was set to a mid-zoom range at f/5.6 and both digital cameras were set to ISO 100. The results speak for themselves. Digital at 10MP certainly beats 35mm film, but I would still hang on to my medium format film camera.

The low noise in digital camera files allows us to get away with a lot more sharpening, which makes them look sharper. For the same reason they also respond well to upsizing.

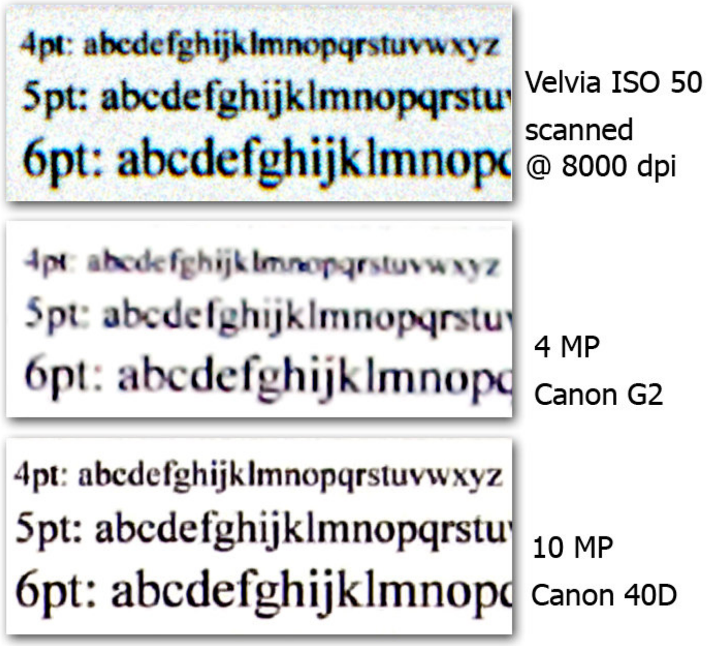

Image 1 - Comparing 35mm Film with Digital Cameras

There are four main factors contributing to digital camera image quality:

1. **Resolution** - This can (in theory) be quantified through 50% MTF frequency and traditional lp/mm resolution data for film. In the end, the eye is a better judge and 8-10MP is usually seen as equivalent to the best 35mm film.

2. **Film grain/Camera noise** - Here digital wins hands down. Digital SLRs have almost no visible noise at ISO 100 and 200 and still very low noise at 400 and 800. Point-and-shoot (P&S) cameras with their small sensors can be quite noisy at ISO 400. Taking both, resolution and noise into account, a 6MP camera will have the leading edge over film.

3. **Dynamic Range** - There is an urban myth going around which says that digital cameras have less dynamic range than film. The opposite is true. Slide film records about 5 stops and print film about 7 stops of information. Digital cameras can handle at least 10 stops - again thanks to their low noise.
Negative film has the advantage of having a beautiful 'S'-curve response: as the light intensity increases, the film density gradually levels off. Digital cameras, on the other hand with their linear response have the habit of blowing out the highlights if the metering is not done with care.
Camera JPEGs with their 256 levels tend to show posterisation especially in the shadows, but also in the extreme highlights. Raw files don't have that problem and they also allow you to recover up to two stops of highlight detail.
Fuji's Super CCD SR technology uses two sensors per pixel; that gives it a slight edge, but is not a major breakthrough.
In theory the dynamic range is also limited by the 12-bit A/D converter used by most cameras until recently. I am not sure if the latest trend of using 14-bit converters is going to give us (visibly) better quality pictures, or if it is more of a marketing gimmick.

4. **Colour Quality** - Digital colour is outstanding and consistent. CCD and CMOS sensors only record lightness values and the colours need to be reconstructed with a Bayer mask (red, green and blue filters above the sensors, with double the number of green-sensitive sensors). In theory this interpolation of the colour values (demosaicing) should bring some resolution loss and moiré fringing.
In February 2002 Foveon made headlines with a new sensor which can record all three colours at each pixel location and should – in theory – have many advantages over the more common Bayer sensor. So far only Sigma has made use of the Foveon X3 sensor in their SLRs.

Sensor Size and Pixel Pitch

The more pixels we squash onto a given sensor size, the higher the resolution, but at the expense of smaller pixels. Smaller pixels collect fewer photons, the signal needs more amplification, and we get more noise.

The optimum pixel size (pixel pitch, measured in microns or μm = 1/1000 mm) is 5-9 microns.

Cameras with >9 micron pixels have problems with aliasing (low frequency artefacts showing up as moiré pattern). This is corrected with anti-aliasing (low pass) filters, which reduce resolution. The early Kodak DCS 14n didn't have an anti-aliasing filter. Users reported severe moiré problems.

P&S cameras with their small pixels suffer from increased noise (especially at high ISO settings), reduced exposure range and are vulnerable to blooming (oversaturated pixels spilling into their neighbours).

The Table below shows you some camera examples.

Camera	Sensor Size (mm)	Diagonal (mm)	Mpixels	Pixel Dimension	Pixel Pitch [μ]
Canon EOS-1Ds	35.8 x 23.8	43.0	11.0	4064 x 2704	8.8
Kodak DSC Pro 14n	36 x 24	43.3	13.7	4536 x 3024	7.9
Canon EOS D30	22.7 x 15.1	27.3	3.1	2160 x 1440	10.2
Canon EOS 10D	22.7 x 15.1	27.3	6.3	3072 x 2048	7.4
Canon EOS 20D/30D	22.5 x 15.0	27.0	8.2	3504 x 2336	6.4
Canon EOS 40D	22.2 x 14.8	26.7	10.1	3888 x 2592	5.7
Canon 5D	36 x 24	43.3	12.7	4368 x 2912	8.2
Canon EOS 1D Mark III	28.7 x 18.7	34.3	10.1	3888 x 2592	8.2
Canon EOS 1Ds Mark II	36 x 24	43.3	16.6	4992 x 3328	7.2
Canon EOS 1Ds Mark III	36 x 24	43.3	21.1	5616 x 3744	6.4
Nikon D100	23.7 x 15.6	28.4	6.0	3008 x 2000	7.8
Nikon D2x	23.7 x 15.7	28.4	12.2	4288 x 2848	5.5
Nikon D300	23.6 x 15.8	28.4	12.3	4288 x 2848	5.5
Nikon D3	36 x 24	43.3	12.1	4256 x 2832	8.5
Canon PowerShot G2	7.18 x 5.32	8.9	3.9	2272 x 1704	3.2
Canon PowerShot G9	7.60 x 5.70	9.5	12.1	4000 x 3000	1.9

Collecting Photons

Looking at the way pixel counts have gone up over the last 8 years - we now get 21MP on a 35mm sensor - one could get the impression that we are going to see better and better cameras with more and more pixels, similar to the improvements in hard disc technology (remember when a 40 MByte (!) drive was the biggest you could get, and costing a fortune).

This is not going to happen and we need to look at how the sensor works to understand the limits. At every pixel site of the sensor, photons get converted into electrons. You can think of a bucket collecting rain drops - the bigger the bucket, the more water (= light) we can collect. The electrons make up a charge which is fed to the A/D converter. Now, the accuracy of the signal (electron charge from the individual pixels) is directly proportional to the size of the signal. The noise in the signal is equal to the square root of the number of photons.

For example, 9 photons would give us a signal-to-noise ratio of 3. For 100 photons the SN ratio improves to 10 etc. Why do we need to know this? Well, it turns out that the noise in modern cameras, from the simplest P&S to the best SLRs is dominated by photon counting statistics (for any signal above a few hundred photons). Read noise is only important if there are less than a few tens of photons and only for very long exposures do we need to consider thermal noise. There is still room for improvement by increasing the quantum efficiency, but not by much. We have seen improved micro lenses over the pixels, gathering more light, but the fact is that we have almost reached the physical limits.

It is difficult to imagine the pixel pitch dropping to lower than 5 microns for professional cameras, which would give us a maximum resolution of 14MP for APS-sized sensors. Full-frame sensors should be able to handle 33MP, however we also need to consider the limits dictated by the lenses. To appreciate the latest improvements in resolution by going from 16 to 21MP, you already need the very best glass.

We can conclude two things so far: a high-quality camera needs a certain minimum pixel size and if you want high quality and high resolution, you have to choose a camera with a larger-sized sensor (= bigger, heavier, more expensive).

Other Consequences from Small Sensors

There are a number of factors to be considered:

- **The Crop Factor**: some people dislike this term and call it "focal length conversion factor", but it is a crop factor because the part of the image circle outside the sensor gets cropped. It is easy to calculate by dividing 43.3 by the sensor diameter. From the Table you can see that the new Canon G9 has a crop factor of 43.3/9.5 = 4.56.

- **Diffraction**: this is the resolution limiting factor at small apertures. The aperture where the system becomes diffraction limited depends on the sensor size (eg. it is around f/5.6 for the Canon G9 with its 7.6x5.7 mm sensor). That's why the smallest stop on a P&S camera is usually f/8.

- **The depth-of-field**: a smaller sensor will give you a larger DOF. In theory, we do get the same DOF with a larger sensor by increasing the ISO setting and stopping down the lens. It all boils down to the number of photons trapped by the individual pixels. But yes, in practice the smaller sensor will give you an apparent larger DOF, making it more difficult to isolate that portrait shot from the background.