F. Cao, F. Guichard, H. Hornung, R. Teissières, An objective protocol for comparing the noise performance of silver halide film and digital sensor, Digital Photography VIII, Electronic Imaging 2012.

http://dx.doi.org/10.1117/12.910113

An objective protocol for comparing the noise performance of silver halide film and digital sensor

Frédéric Cao, Frédéric Guichard, Hervé Hornung, Régis Tessière
DxO Labs, 3 Rue Nationale, 92100 Boulogne, France

ABSTRACT

Digital sensors have obviously invaded the photography mass market. However, some photographers with very high expectancy still use silver halide film. Are they only nostalgic reluctant to technology or is there more than meets the eye? The answer is not so easy if we remark that, at the end of the golden age, films were actually scanned before development. Nowadays film users have adopted digital technology and scan their film to take advantage from digital processing afterwards. Therefore, it is legitimate to evaluate silver halide film "with a digital eye", with the assumption that processing can be applied as for a digital camera. The article will describe in details the operations we need to consider the film as a RAW digital sensor. In particular, we have to account for the film characteristic curve, the autocorrelation of the noise (related to film grain) and the sampling of the digital sensor (related to Bayer filter array). We also describe the protocol that was set, from shooting to scanning. We then present and interpret the results of sensor response, signal to noise ratio and dynamic range.

Keywords: Digital photography, analog versus digital, image quality evaluation, signal to noise ratio, dynamic range, characteristic curve.

1. INTRODUCTION

The comparison of the performance of films and digital sensors is an exciting topic, although passionate enough so that truth and facts are not always cleared from speculations. Film industry has designed methods to evaluate the performance of film from an objective point of view[1,2,3,4,5] (making measurements in labs) and correlate these metrics with subjective image quality[6]. Unfortunately, many of these protocols are not relevant for digital images. Instead of trying to apply film evaluation protocols to digital sensors, we chose the reverse approach: since films have gone digital through scanning, we can apply (up to a few modifications) the same protocols as for sensors. This allows a fair comparison with more than 150 DSLR camera sensors tested on a website called www.dxomark.com.

We first describe the image quality attributes that are, in our opinion, the most relevant for comparison between film and digital sensors. We shortly describe how they are characterized for films and sensors and explain why the results are not directly comparable. To make the comparison possible, we choose to apply the digital procedure to a digitized (i.e. scanned) film. We describe in details the operations we need to consider the film as a RAW digital sensor. We then present and interpret the results in terms of sensor response, signal to noise ratio and dynamic range. We finally conclude and give some perspectives of other comparisons.

2. EVALUATING IMAGE QUALITY

2.1 Image quality attributes

When comparing image quality of films and digital cameras, several topics are usually emphasized: resolution, graininess, tone and color rendering or dynamic range. In this paper, we will only focus on the comparison of graininess and dynamic range. Graininess is the random variation of the photograph of a perfectly homogeneous zone. It can give a special look to picture, but it objectively destroys some part of the signal. Therefore, if the camera is thought of as an instrument to accurately capture a scene, graininess adds some noise to the image, that is, unpredictable variations that can be mistakenly interpreted as a variation of the scene, or can hide some subtle variations of the scene.

Dynamic range is the ability of the camera to capture both shadows and highlights on a same picture. Any good photographer knows that backlit scenes should be avoided because the contrast is usually not pleasing to the eye. However, some scenes still contain very luminous and very dark parts in the same time. When the picture is shot, if the shadows are too dark or the highlights are burnt, there is no way to recover the lost information. Digital sensors are traditionally known to have a low dynamic range. Even though very recent cameras show outstanding progress, demanding photographers still complain about the necessary trade-off they sometimes have to make between shadow and highlights. Dynamic range also relates to exposure latitude and this also has a direct impact on image quality.

2.2 Film and sensor characteristics

Before going in details on graininess and dynamic range, a preliminary step is necessary to understand the type of response of film and sensors to light.

The response of film to light is characterized by the film density at all levels of exposure. The density describes the opacity of the film, and is the logarithm in base 10 of the film absorption (once developed). A high density corresponds to a large opacity, and therefore a very dark film. For a negative film, density is an increasing function of the film exposure (the film becomes darker when exposed to light). For a positive film, density is a decreasing function of the film exposure (the film becomes brighter).

In both cases, the characteristic curve has a sigmoid shape. The response varies very slowly for very low light; it becomes larger for mid light; for high light, the film again responds more slowly to a given increase of exposure. A very important fact is that even though the response of the film varies very slowly in highlights, it still does vary, meaning that the film still records some information

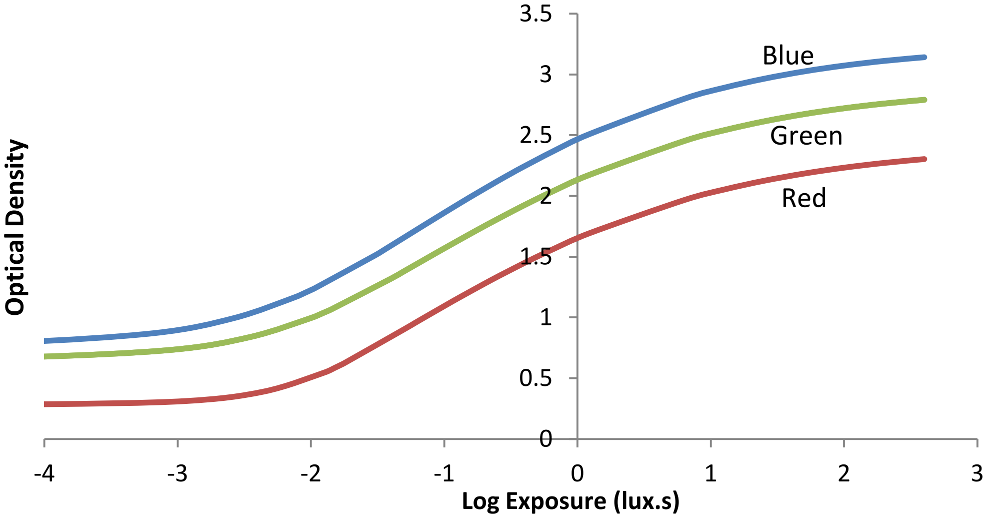

Figure 1. Characteristic curves of a film (in this case Kodak Portra 160NC). Note the very slow start in low exposure, the regular slope in the mid-tones, and very slow convergence to a maximal density in the highlights. Remark the scales on both axes are logarithmic.

The response of a film is characterized by the curves of the three photosensitive layers (red, green and blue). The sensitivities of the different channels are tuned for a given type illuminant (indoor or outdoor). While the sensitivities of each layer are fixed, the ratio of the sensitivities are tuned for a given type of illuminant (indoor or daylight). For color negative films, the ratios can be adjusted so that a single film can give pleasing results in situations with mixed or multiple illuminants, for example, tungsten and daylight.

If we now compare the response of a film with a RAW digital sensor for commercial cameras, we can observe some important differences. First, the response of a digital sensor is essentially linear. (Some sensors for very specific applications do not have a linear response, but they are not used for digital photography.) A given increase in exposure always yields the same increase of response. The second very noticeable difference is the behavior in highlights. At a given exposure, the sensor response suddenly stops increasing, no matter how high the exposure. The saturation is related to the full well capacity of the sensor. Beyond the saturation point, all the information of the scene is lost, except the fact that the exposure exceeds the sensor capacity. Also note that before saturation, a digital sensor can be easily used as an exposure measurement device since the response is linear with respect to exposure. In the shadows, the sensor usually has a positive response to a null input signal (pedestal).

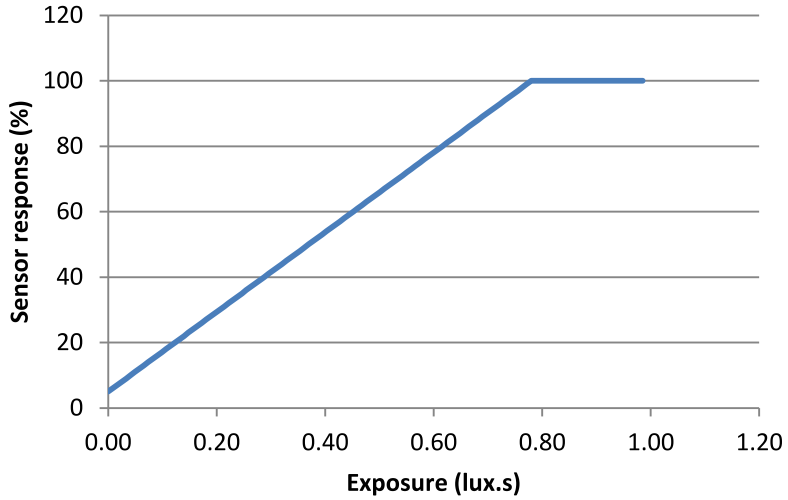

Figure 2. Characteristic curve of a digital sensor. The sensor usually has a non null response even when not exposed (pedestal); then the response increases linearly with the exposure before a sudden saturation corresponding to the pixel full well capacity.

2.3 Different measurements for films and sensors

Any measurement is corrupted by noise and this will be the main topic of interest in this article. Photon shot noise is on the luminous signal itself, and therefore independent from the sensing device, film or digital sensor. Moreover, the structure of a film is very locally irregular, since the sensitive surface is made of big aggregates of silver halide crystals, whose size and shape are not perfectly constant. Larger grains are sensitive to lower exposure whereas smaller grains need more light to react. On a digital sensor, photo response of pixels may differ of about 1%. Sensor technologists would say that the photo response non uniformity (PRNU) is much larger on films than on sensors.

The granularity of a film can be measured in different ways. A commonly used protocol leads to the RMS (root mean square) granularity[8] which is the standard deviation of the density of the film integrated through a hole of 48µm diameter. Some studies in the film industry, at Eastman Kodak in particular, showed that some other metric could be derived, with a very good correlation with subjective image quality, as the Print Grain Index[6] (PGI).

However, this measurement is really adapted to film grains that are pretty large (typically 15µm). On a sensor, noise is spatially white (independent from one pixel to another) and the channels are interleaved on a color filter array (usually a Bayer filter, another Eastman Kodak invention). The RAW image is processed in a RAW converter, modifying the structure and other characteristics of the image. Since there are huge differences between RAW converters, the final converted image may not be representative of the quality of the sensor itself. Comparing the unconverted RAW images is the only way to really compare sensors. On the other hand, it does not make sense to directly apply a subjective metric as the PGI or ISO visual noise on a raw image, since this image is meant to be heavily processed.

The dynamic range (DR) is the ratio between the highest and lowest exposure that can be acquired on the sensing device. This definition is not accurate enough, since we also need to define the highest and lowest possible exposures. For a digital sensor, we define the dynamic range as the ratio of the saturation exposure and the exposure that is needed to obtain a given (low) SNR value, typically 0dB. This value is very low and may not seem reasonable in a photographic point of view, but it is widely used in the sensor industry. However, it also anticipates that digital noise reduction is usually applied on the images in the RAW conversion. Moreover, choosing a different value would essentially offset the values of dynamic range but would not change the comparison of sensors. With this definition, the dynamic range of the best sensors to date is about 13 f-stops. Film specialists will find this value way too high, but the explanation is that the definition of dynamic range is very different for films.

The definition of the dynamic range of films does not rely on noise at all, at a first sight. A useful definition is the range of exposure above 0.2 density step of the characteristic curve toe, and below 90% of the maximal density on the curve shoulder. With this definition, DR varies from 9 f-stops for usual films to about 12 f-stops for professional films, or even

14 f-stops for black and white. Although SNR is not directly involved in this definition, we can argue that beyond these two points, the variation of the film density with respect to exposure would be very small anyway and would not provide any reliable information on the scene. This argument will be made more explicit in the next section.

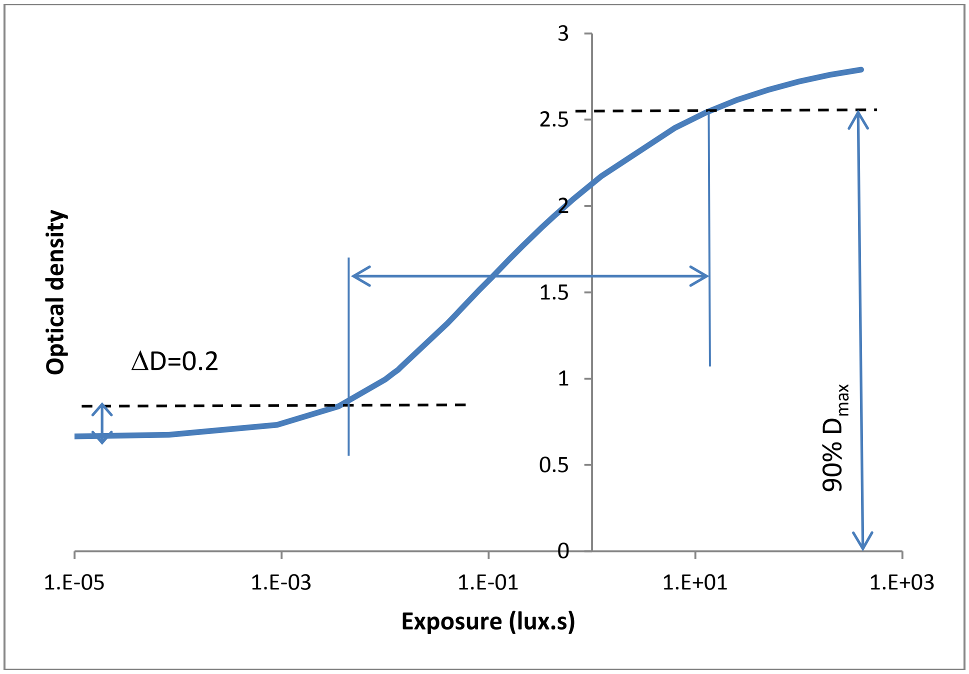

Figure 3. The dynamic range of a film is traditionally defined from its characteristic curve only as the range of exposure between values defined by the toe and shoulder of the curve.

These values don't seem to support the common knowledge that film dynamic is much higher than sensor dynamic. Again, this is only due to the completely different definition of DR, and some work is needed to compare both technologies. To do so we need to go back to noise and calculations of signal to noise ratios, and create a way to normalize the two very different systems and their different noise characteristics.

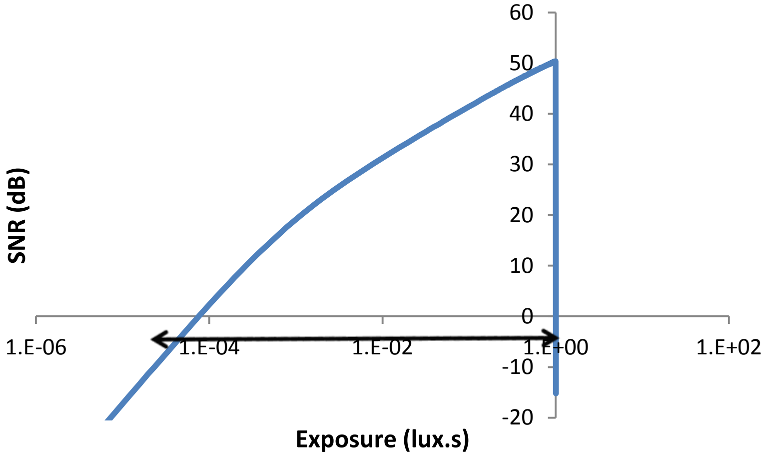

Figure 4. The dynamic range of a digital sensor can be defined as the range of exposure for which the signal to noise ratio (SNR) is larger than a given threshold (here 0dB). In the shadows, the SNR is limited by photonic and sensor noise, and by the full well capacity of the sensor in the highlights.

3. MEASUREMENT DEFINITIONS

Everything seems so much different between films and sensors that it seems impossible to compare them at all. We have either to adapt film protocols to sensors or the other way around.
The main problems to solve for a fair comparison are the following:

- Find a correct definition of signal to noise ratio, since the outputs of film and digital sensors are different in nature.
- Take the scan resolution into account. In the same way, how to take the sensor resolution into account.
- Take the film grain size into account.
- Consider the fact that a digital sensor uses a Bayer filter array, whereas a scanned film has 3 channels per scanned pixel.

3.1 Signal to noise ratio

Let us briefly describe how noise is measured on a digital sensor. The first crucial point is that measurements are all performed on the RAW image, delivered by the sensor. No processing is applied to this image before measurement. It is worth noting that some sensors can actually process the image before delivering the raw, so we make sure that it is not the case or properly accounted for.
Noise on a raw image only depends on the sensor exposure and the ISO setting. We actually measure noise as a function of the sensor response. Noise is measured as the standard deviation of the response in a perfectly homogeneous area. Our lab protocol is detailed in dxomark.com. Noise is usually spatially white, and modeled by a Gaussian distribution (a better model of shot noise is a Poisson process, but it is also well approximated by a Gaussian); it is characterized by its standard deviation (noise has zero mean) or equivalently the signal to noise ratio (SNR). We use a transmissive noise chart with 4 density steps (therefore 13.3 f-stops). We bracket several shots to ensure that we cover the sensor dynamic by a good margin.
The SNR can be plotted as a function of the sensor response or as a function of the sensor exposure. For a patch with average gray level x, we measure the standard deviation of the gray level inside this patch, denoted by $\sigma(x)$. The SNR in dB is

$$\mathrm{SNR}_{\text{gray level}} = 20\log\frac{x}{\sigma(x)}.$$

Now, since a film does not output gray levels, we prefer to express the SNR as a function of the input sensor (or film) exposure. Denote by l the sensor exposure and by x the device output (it can be a gray level or a density.) The output is related to the input by the system response

$$x = R(l).$$

A small error λ on l yields a measurement variation η on x. If the error is small enough, then $R(l+\lambda) = R(l) + \lambda R'(l)$, where R' is the derivative of R. Therefore, $\eta = \lambda R'(l)$. We denote by $\sigma(x)$ the standard deviation of η, with the obvious assumption that it only depends on the average value of the output. The values x and $\sigma(x)$ are the values that are actually measured on an area where the input signal is constant. If we know the response curve of the system, we can deduce the incertitude on the input that can provide the same range of errors on the output. We define the SNR of the system in the exposure domain by

$$\mathrm{SNR}_{\text{exposure}}(l) = 20\log\frac{l}{\sigma(R(l))}R'(l)\,.$$

If we know the input exposure l, and the sensor response, we can compute the SNR in the exposure domain. In practice, this is not exactly how it is computed, since we deduce the exposure l from a measurement and the response of the sensor that has been previously computed. Therefore, we measure the SNR in the exposure domain with a different parameterization as

$$\mathrm{SNR}_{\text{exposure}}\left(R^{-1}(x)\right) = 20\log\frac{R^{-1}(x)}{\sigma(x)}R'\left(R^{-1}(x)\right).$$

This allows the comparison of systems with common input but outputs of different nature. Remark that for a sensor whose output is a linear function of the input $x = al$, then $\mathrm{SNR}_{\mathrm{exposure}}(l) = \mathrm{SNR}_{\mathrm{gray\ level}}(x)$. In particular, for a digital sensor in the linear domain, this relation is true (assuming that the pedestal has been removed). This relation does not hold for a non linear sensor. In particular, for a digital sensor in the saturation region, $R'(l) = 0$ for all l above saturation. Therefore, the exposure SNR equals minus infinity (in dB). Even though the noise that can be read in gray levels on the sensor is equal to 0 (all gray levels are saturated), the incertitude on the input exposure is infinite, since the only information we have is that the input is larger than the saturation value. Remark that this calculation is equivalent to invert the response of the system to go back in the exposure domain, and compute the signal to noise ratio on the linearized output.

Figure 4 shows a typical noise curve for a digital sensor. For very low exposure value, the SNR is very low. On a log scale (SNR in dB vs. log exposure), the SNR tends to minus infinity for very low exposure. When the exposure increases, the SNR also increases at a rate of 3dB for 1 f-stop, except in very dark shadows where limitations of sensors (readout noise, thermal noise) are dominant.

The same procedure can be applied for a film, knowing its characteristic curve (Fig. 1). The exposure SNR is penalized in the shadows and the highlights because the film response has a very small derivative. The shape of the SNR curve is similar to the noise characteristic of a digital sensor for low and medium exposure; the SNR is first very low, due to photonic noise, to the fact that the film response is very flat. When exposure increases, the SNR increases as well. Finally, for very high exposure, the response of the film becomes very small again, and the SNR decreases. However, there is no sudden drop as for digital sensors due to the sensor saturation.

3.2 Resolution normalization

Films are scanned at a given resolution. In practice, we used a 20Mpix scanner (for a 24x36mm film). At this resolution the film grain is visible, so we can be sure that we do not underestimate the film noise by averaging out the signal. However, we would like the measurement to be independent from the scanner resolution. In the same way, we compare digital cameras with different resolutions. For a given sensor format, more pixels means smaller pixels, less light on each pixel and eventually a lower signal to noise ratio. This is well known from photographers as the megapixel race; a blessing for some, a curse for others. There is a simple way to make noise measurements independent from the pixel count: we can normalize the noise for a given sensor resolution. For instance, a 16Mpix sensor can be transformed into an 8Mpix sensor by averaging pixels by pairs, resulting in a twice smaller noise variance. More generally, for a sensor with N Mpix, we multiply the noise variance by a factor 8/N. With this normalization, SNR essentially depends on the sensor size, when photon shot noise dominates. Doubling the pixel count of a sensor introduces a correction offset of 3dB. In the following, results are normalized with respect to a 8Mpix resolution, corresponding to a 12”x8” print with a regular printer.

3.3 Film grain and autocorrelation, and noise laundering

Another difference between films and sensors is the spatial structure of the grain. On the digital sensor, noise is uncorrelated between adjacent pixels. This is not the same for films; silver halide grain can clearly be seen on a scan. A similar visual appearance can be obtained by applying a low pass filter on a spatially white noise. Assume that the image u is obtained from a perfectly spatially white noise n blurred by a convolution kernel K, that is $u = K * n$. Let us denote by σ^2 the variance of n. Classical calculations show that the auto-correlation of u is

$$E\big(u(0)u(x)\big) = \int K(x)K(x+t)\,dt.$$

In particular, the variance of u equals $\sigma^2 \int K^2$. Therefore, if we can compute this integral, we can deduce the variance of the white noise σ^2. Going in the Fourier domain shows that the Fourier transform of the autocorrelation of u is the squared modulus of the Fourier transform of K (also known as power spectrum), denoted by $|\widehat{K}^2|$. Now, the Fourier transform is an isometry for the quadratic norm, therefore the integral of $|\widehat{K}^2|$ and the integral of K^2 are equal. Therefore, by computing the power spectrum of the correlated noise, we can retrieve the variance of the white noise before convolution. All the measurements we show use this “noise laundering” procedure. We shall see on film measurements that the correction factor is larger for lower exposures. Indeed, small silver halide grains have a smaller probability to be hit by less numerous photons and the grain appears larger indeed.

3.4 Bayer normalization

For our measurements, films were scanned with a 20Mpix RGB scanner. Therefore, the normalization to an 8Mpix image is equivalent to a gain of 4dB. This results in the noise for each channel of an 8Mpix image with three color channels (RGB). Due to the color filter array (Bayer case), a digital sensor with 8Mpix has actually 4Mpix on the green channel, and 2Mpix on the red and blue channels. Therefore, from an 8Mpix RGB scan, we can make an 8Mpix Bayer image by averaging the pixels. Two green pixels in the film are averaged to make a single green pixel on the Bayer. Four red and blue pixels are averaged to make a red and blue pixel on a Bayer. Another 3dB for the green and 6dB for the red and blue are added to the film SNR for the final comparison.

3.5 Measurement protocols

The previous sections describe the definition, the theory of the measurements and the calculations we performed to compare films and sensors. To make the picture complete, we have to give a few words on the protocol to practically measure all these characteristics.

The film was used in our lab to shoot the same test charts that are used for digital sensor. On the film, we never used very long exposure in order to avoid non reciprocity issue. The images were scanned in RAW mode, and no processing was applied on the images. As a device with a digital sensor, the scanner is obviously prone to measurement noise as well, with a very low SNR in the shadows and a much better SNR in the highlights (about 50dB). In order to measure the characteristic curve of the films, we first measured the transmission of the optics that was used (an EF 50mm f/1.2L USM Canon lens) to obtain the actual film exposure. Then, we scanned the developed film at different scanner exposures, in order to ensure that the scanner noise was negligible compared to the film noise. The response of the scanner was carefully calibrated to ensure that we could recover the film density from the scans.

Finally, in order to make sure that we could reach the film saturation, we shot a light source with no optics. In addition, despite we used a high-end lens, very high exposure shots showed that some optical flaws as flare and veiling glare made it impossible to image a scene with a very high dynamic without shadows being polluted by highlights.

4. MEASUREMENT RESULTS

We measured the response and the noise characteristic of three negative films,

- Kodak Portra 160NC (negative color film)
- Fuji Reala 100 (negative color film)
- Kodak Tri-X 400 (negative B&W film)

and a positive film (Fuji Velvia 50).

We compared these films to three digital cameras; two DSLR, the very good Canon EOS 600D (a.k.a. Rebel T3i) and the very high-end professional Nikon D3x and a DSC with a RAW output (Canon S95).

4.1 Noise characteristics

The plot below shows the noise characteristics of the Nikon D3x and the Kodak Portra 160NC for an equivalent resolution of 8Mpix. In the shadows (low log Exposure), all the curves look more or less similar, starting from very low SNR values and increasing as the exposure increases. For the digital sensor, the SNR increase becomes constant (3dB per f-stop) until it suddenly collapses when the sensor reaches its saturation. Meanwhile, the film SNR increases more slowly and reaches a kind of plateau in which the SNR remains almost constant, before slowly decreasing due to the lower and lower response of the film to the increase of exposure.

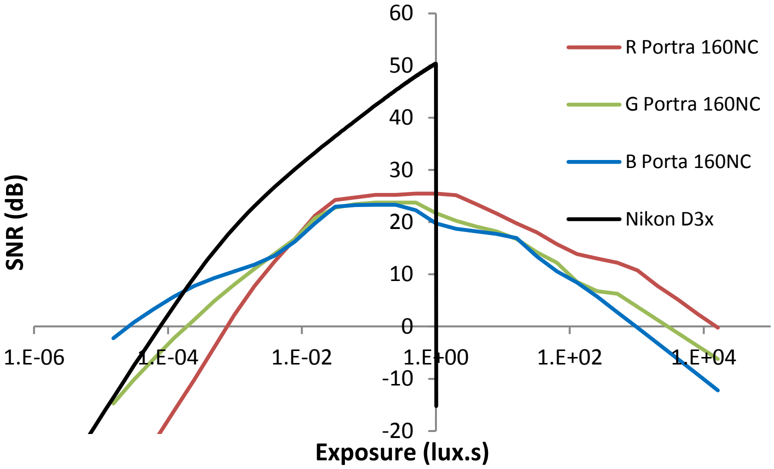

Figure 5. Comparison of sensor and film noise characteristics. The film noise curves account for the film response, the grain correlation, the resolution of the scanner and the fact that the compared sensor has a Bayer color filter array.

4.2 Signal to noise ratio: welcome to a new digital world

In this domain, digital sensors have done more than catching up with films. The values can be summarized by the SNR18% value which is the SNR for an exposure equal to 18% of the exposure of saturation of a digital sensor. This value is usually chosen because natural scenes reflectance is usually around 18%. If we assume that a 100% reflectance attains the saturation of the sensor, it makes sense to evaluate the SNR at 18% of the saturation exposure. This saturation depends on the ISO sensitivity of the camera (following ISO standard 12232). For each film, we compute the saturation exposure of the digital sensor whose ISO is the nominal ISO value of the film. For instance, ISO 100 corresponds to sensor exposure equal to 0.78lux.s. Therefore, we report the SNR value for exposure 18%*.78=0.14 lux.s. Between the Kodak Portra 160NC and the Nikon D3x, the difference is more than 20dB, almost 7f-stops! The Kodak TriX400 is better, although it is ISO 400, because it is a black and white film and each grain can therefore capture the light in the whole visible spectrum. However, the difference is still 15dB (equivalent to 5 f-stops). Even the compact camera with a pixel pitch of 2µm has a much better SNR (about 10dB) than the professional film.

The effect is that smooth areas in an image look much grainier on a film than on a digital sensor, even if no noise reduction is applied.

Table 1. Summary of SNR18% and dynamic range values for the different tested cameras and films. The values are given for an equivalent resolution 8Mpix. See text for more comments.

Camera or film	**SNR 18% (dB)**	**Dynamic Range (f-stop)**
Fuji Reala 100	22	18.2
Kodak Portra 160NC	23.7	**23.9**
Fuji Velvia 50	29.7	11.4
Kodak TriX 400	28.5	21.7
Nikon D3x	**43.9**	13.7
Canon EOS 600D (Rebel T3i)	38.8	11.5
Canon Powershot S95	33.1	11.3

Figure 6. Comparison of Canon EOS 600D (T3i) at ISO 100 (left) and Kodak Portra 160NC (right). The left image was generated directly from the RAW image with minimal image processing: white balance, demosaicing, color matrix and gamma curve. It is not the JPG out of the camera, in particular there is no noise reduction.

4.3 Dynamic range: an advantage for films?

Table 1 also shows the dynamic range of different films and sensors, for an acceptability threshold of 0dB. As can be seen on the noise characteristic, when we apply the definition (DR = range of exposure with SNR more than 0dB), the dynamic range of film is much higher than the dynamic range of digital sensor. The difference is not in the shadows where digital sensors can be sensitive to only a few incoming photons.

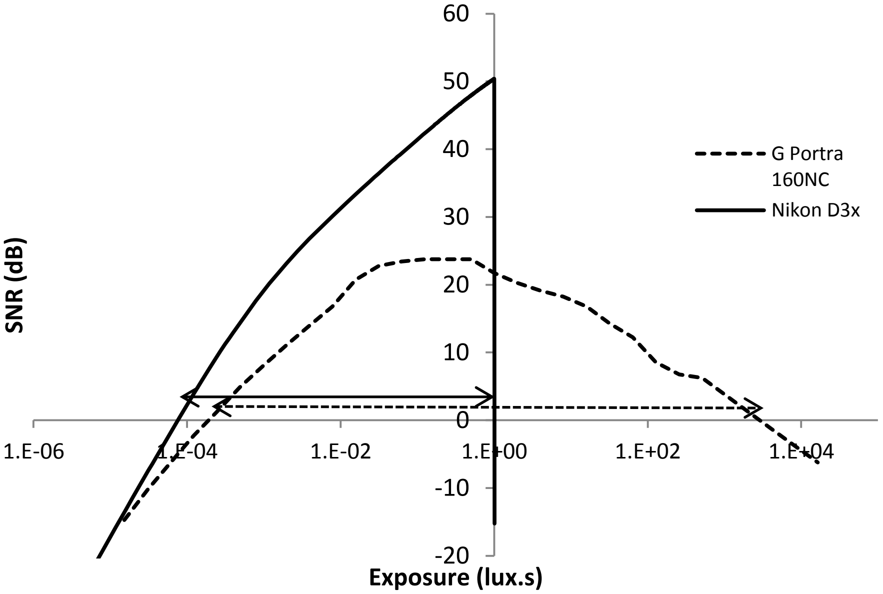

Figure 7. Comparison of dynamic range of film and sensor (Kodak Portra 160NC and Nikon D3x) at equivalent resolution 8Mpix. The dynamic of sensor is softly limited in the shadows by SNR but the hard limit is in the highlights. Both limits are soft for the film.

The big loss of sensors is this very abrupt cut-off at the saturation exposure. Suddenly, the sensor completely stops to record information. In outdoor scenes with white clouds on a pale sky, this is almost unforgiving. The only possible way to render details in such areas is to underexpose the picture and apply some local tone mapping afterwards, or bracket different exposures to generate a HDR image.

There is also quite a difference between films for casual and professional photographers (almost 6 f-stops). Low end films are still much higher than digital sensor. It is also worth noting that positive films have a much smaller dynamic range. This is well known by photographers, but it shows that the dynamic range is actually smaller than on digital sensors.

4.4 How to interpret the results

The results above show very contrasted results depending on what image quality attribute is important for the photographer, graininess or dynamic range. The dynamic range values may seem too high for a film specialist. So let's help our reader to figure out the different relations of these results with what can be seen on real pictures.

The SNR is probably much easier to interpret. For mid-tones, the response of the film is actually close to a gamma curve (linear in a log-log diagram), and therefore similar with a digital image after processing. The grain is visible for any exposure. Even with no noise reduction, a very high end camera can produce a much cleaner image, to a point that may even seem unnatural to a film photographer. Of course, some cameras may also abuse of noise reduction algorithms, and images can become very waxy indeed. Just choose your raw converter carefully.

Film industry struggled very hard to make films more sensitive, but they never really made it. Grain is acceptable at ISO 400, and some would argue, 800. But much above that, grain was a limiting factor. However, they also worked very hard to give the grain a nice looking and this also made the charm of some photographs, in particular for black and white (for instance the Kodak Tmax 3200, not measured in this study).

For dynamic range, results may seem more controversial but still confirm popular wisdom. Films have a very large dynamic range. Now 10 f-stops difference is huge, and film aficionados will hastily use this value as the proof that film is much superior. If you look at a traditional print from a film, it is very likely that you will not see such a difference. Indeed prints have a limited dynamic about 6 f-stops, because black pigments still reflect typically 2% of the incoming light. We applied quite a sophisticated process to make sure that we got the most information from the films we tested: multiple HDR scans, measurement with no lens…

Also the threshold value for defining the dynamic range (0dB) is clearly too low for decent image quality if no efficient noise reduction is applied, which was probably the case on pictures twenty years ago. If we define the dynamic range with a higher threshold, the difference between film and sensor is smaller and sensors eventually become better than film. These values are summarized in Table 2. If we choose this threshold such that the film DR with our protocol matches the DR values traditionally calculated from the film characteristic (say 12 f-stops), we observe that film and sensors are very close.

Table 2. Values of dynamic range for Nikon D3x and Kodak Portra 160NC for different values of acceptability threshold. When the threshold becomes more demanding, the film DR decreases faster than sensor DR.

Acceptabilty SNR threshold	DR Nikon D3x	DR Kodak Portra 160NC
0dB	14	24
10dB	12	16
20dB	10	8

We also experimented some flare and veiling glare (despite an excellent lens), clearly limiting the dynamic on the input signal itself on the sensing device. Of course, these optic flaws also apply to digital sensors, but it turns out that the effect becomes really annoying for a scene with at least 14 f-stops dynamic, which is the order of magnitude of the DR of the best DSLRs to date.

For a casual photographer, a very good dynamic is useful for better exposure latitude, at least for negative films. For positive films, the dynamic is much lower (we actually measured it to be similar to digital sensor), and it is very hard not to burn highlights or underexpose the shadows. For digital cameras, some tools (as auto-exposure, live view histograms, easy digital tone mapping) can help to use sensors at their best potential, but there are some cases (back lit, light source in the image field) beyond the limit of a single shot.

5. CONCLUSIONS

At first sight, comparing recent digital sensors with decades old film technology may seem matter for geek at best and pointless at worst. However, the argumentation is slightly more subtle as film can be considered in a more modern workflow. Shooting pictures is merely a first step and pictures are then digitally scanned. Once the image has gone digital, it makes sense to compare digital images coming from a digital sensor and a scanned film. In this paper, we studied the potential of these two images in terms of potential image quality offered by the two sensing devices for graininess and dynamic range. Concerning grain, modeled by the signal to noise ratio, the film has long been beaten by the sensors. However, chemists had to cope with this low sensitivity, and transformed an apparent drawback in a special look, by giving the shape and color of the grain a particular aesthetic (in the same way optical designer can give bokeh a beautiful shape.) As far as dynamic is concerned, the negative film has potentially a clear advantage. If we apply the definition of dynamic range used for digital sensor (range for which the SNR is larger than 0dB), the difference is a huge 10 f-stops. For casual photographers, larger dynamic mainly means larger exposure latitude that can compensate for bad exposure. More advanced photographers can actually get more and reveal more details in shadows and highlights than it is possible on a single digital shot. However, we also discussed that this threshold is questionable since 0dB can be viewed as a visibility threshold but it is certainly not enough for good image quality. When we increase the acceptability threshold to 10 or 20dB, the difference of dynamic range between sensor and film decreases very fast and sensors eventually perform better. Therefore, the difference is in practice much less than the 10 f-stops of the ideal case measured in this paper between the Nikon D3x and the Kodak Portra 160 NC. Moreover, the gain is eventually limited by optical problems as flare or veiling glare, although the optical flare and hard copy print limitations apply equally to both digital and film captured images. It is also worth noting that positive films do not have the same very wide dynamic and the performance of digital sensors is ahead in all aspects. Also, regular scanners may not have a wide enough dynamic to cover the film in a single scan and several bracketed scans may be necessary. To be perfectly fair, bracketed shots can be acquired with a digital sensor to also increase the image dynamic, so the advantage of the film in terms of dynamic will keep on decreasing. Faster frame rate and faster embedded image processing will also make exposure bracketing easier to use in practice, and high dynamic range (HDR) photography may become the rule.

Of course, other image attributes are also very important for image quality, as resolution, or tone and color rendering. The two latter are very difficult to evaluate from an objective point of view, since it is well known that preference does matter a lot for these attributes. Moreover, with digital processing, it is virtually possible to mimic any tone and color rendering. Therefore, it is not clear whether it is relevant to compare films and digital sensors on that aspect. As for resolution, this is indeed an interesting topic and it requires further work.

REFERENCES

[1] Schonfelder A., “Do todays digital image sensors out perform photographic film?”, http://www.lightandtime.co.uk/tech/Digital-vs-Analogue.pdf
[2] Clark Jones, R. “Information capacity of photographic films,” J. Opt. Soc. Am., 51, 1159-1171 (1961).
[3] Clark Jones, R. “New method of describing and measuring the granularity of photographic materials,” J. Opt. Soc. Am., 45, 799-808 (1955).
[4] Naderi F., Sawchuk, A.A., “Estimation of images degraded by film-grain noise,” Appl. Opt., 17, 1228-1237 (1978).
[5] Yu, F., “Information capacity channel of a photographic film,” IEEE Trans. On Information Theory, 16:4, (1970).
[6] Kodak, “Print grain index,” Technical publications (2000).
[7] ISO 9236-1: 2004, “Photography – Sensitometry of screen/film systems for medical radiography – Part 1: Determination of sensitometric curve shape, speed and average gradient.”
[8] ISO 10505:2009, “Photography – Root mean square granularity of photographic films – method of measurement.”
[9] ISO 15739: 2003, “Photography – Electronic still-picture imaging – Noise measurements,” currently under revision.
[10] Ferguson B. (Editor), “Basic photographic sensitometry workbook”, Eastman Kodak (2006).
[11] EMVA 1288, “Standard for characterization of image sensors and cameras,” www.emva.org.
[12] Dxomark.com.