Quantum Efficiency Considerations in the Comparison of Analog and Digital Photography

Rodney Shaw
Hewlett Packard Labs, Palo Alto, CA

Abstract

The accelerating pace of digital photography into the consumer marketplace leads to a need for the reexamination of the old question of the ultimate performance of digital systems when compared on a like basis with traditional analog systems. It has long been understood that, in principle, quantum efficiency and multilevel recording properties afford digital systems a competitive edge. This present work revisits this aspect of comparative performance from a signal-to-noise viewpoint, and uses quantitative models for both analog and digital systems in order to illustrate the importance of these quantum efficiency issues.

Introduction

Following a lengthy period of speculative promise, digital photography has finally come of age, as witnessed by the current availability of a range of products and a general consensus that the consumer market will expand dramatically over the coming years. On the one hand CCD imaging arrays are finding increasing application as the image-acquisition component in a variety of digital-imaging contexts, including consumer photography, and with the trend towards the availability of larger, high-resolution arrays (and declining cost of manufacture), it might be anticipated that this trend can only accelerate. On the other hand the image quality associated with inexpensive digital printing devices (eg, thermal ink-jet) has increased dramatically in recent years, to the extent that comparison with the quality of traditional photographic printing has become a question of practical relevance. The combination of these digital image acquisition and printing technologies thus offers the opportunity of a competitive photographic system capable of overall performance comparable with that of traditional silver-halide based analog systems.

Whereas it is widely accepted that digital photographic systems offer striking advantages of convenience in the context of the computer-based information age, it is perhaps less well understood that digital acquisition systems offer a fundamental technical advantage compared with silver-halide. Stated generally, the inherent binary/error-prone nature of the silver-halide detection process represents a technical barrier which has proved resistant to decades of intensive research, and this barrier constrains analog photography to a region (so-called photographic space) in the trade-off between camera (acquisition) speed and print (display) granularity which has expanded only marginally in recent times. Stated more specifically, the DQE for silver-halide detection is perhaps the order of a few percent at best, with limited prospects for significant improvement. Indeed, while several decades ago a lively discussion took place on this topic within the silver-halide community, including contemporary measurements and interpretive models (for a review see reference 1), the contemporary silver-halide literature is now largely silent on this topic, indicative perhaps of a general frustration associated with the decades-old identification of an intransigent limiting factor (ie, binary, error-prone detection).

It is well known that multilevel modes of photo-detection afford the possibility of significantly higher values of DQE than those associated with binary detectors. The hypothetical ideal (100% DQE) photon-counter would essentially be a multilevel detection process, extending over exposure-space as far as any limitations imposed by the existence of threshold and saturation mechanisms[2]. In this respect CCD imaging arrays, while having their own inherent limitations, more closely approximate to ideal multilevel recording than do silver-halide grains.

The purpose of this present study is to illustrate these comparative advantages of CCD imaging arrays by the use of simple models for both digital and analog photographic acquisition systems, and therefore to demonstrate the potential expansion of photographic space which becomes possible with multilevel detection processes.

Photo-detection: Silver Halide Grains

Measured DQE values for film can be more or less completely explained by existing models of image formation. DQE values which are highly non-linear with exposure and peak, at best, in the region of two to three percent are speculated as representative of contemporary silver-halide processes. These values arise naturally according to models based on parameters such as those which follow.

It is assumed that film grains within the photographic layer have a spread of (binary) quantum thresholds which may be represented by a two-parameter negative binomial distribution[3] (parameters assumed here to be based on 3 absorbed quanta required for latent image formation, but only a random 10% chance of any absorbed quantum making a contribution to this number).

Figure 1 shows the proportion of (binary) grains having the lowest quantum requirements, as predicted by this probabilistic model, while Figure 2 shows the entire probability distribution. From Figures 1 and 2 it is concluded that whereas a very small proportion of grains require only three quanta for image formation, the peak of the distribution falls at around 20 quanta, and the least responsive grains require in excess of 100 exposure quanta.

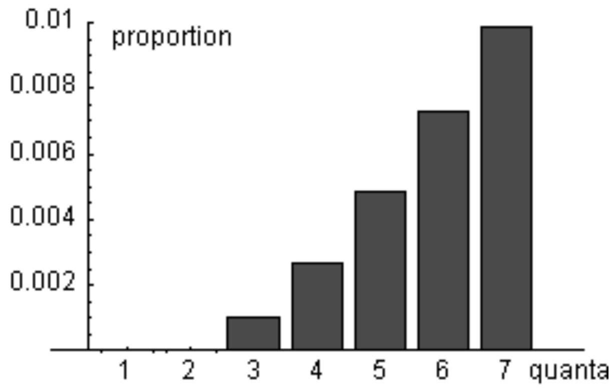

Figure 1. Quantum requirements of most sensitive grains.

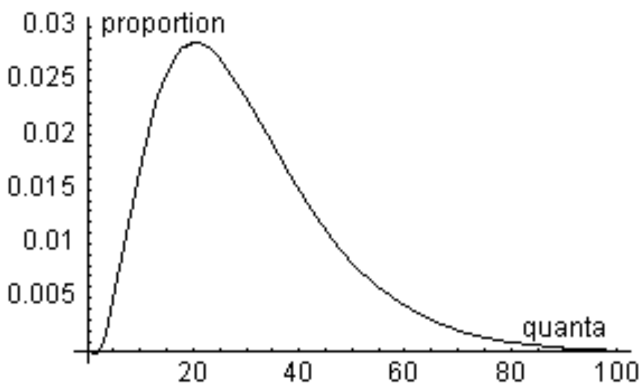

Figure 2. Overall distribution of quantum requirements.

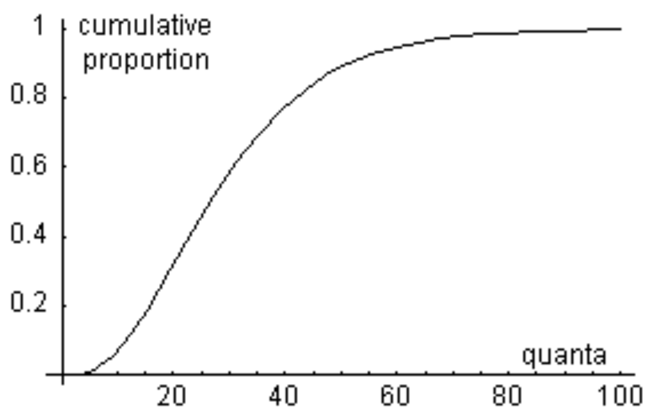

Figure 3. Cumulative proportion of grains made developable in terms of the grain quantum exposure.

From a signal-to-noise viewpoint the probability distribution of Figure 2 is in effect an equivalent noise source to the read-error in digital acquisition systems, and from this viewpoint can be thought of as entirely harmful, ie, as a situation wherein a binary 20-quantum (mean) detector is subject to an error described by an appreciable variance. However from a traditional photography viewpoint this error-spread has become to be regarded as a positive advantage, since it plays a major role in providing an acceptable degree of system exposure latitude.

The role of the quantum sensitivity distribution in defining the exposure latitude is more explicitly demonstrated via the cumulative probability distribution associated with Figure 2. This cumulative distribution is shown below in Figure 3, where the dynamic response of the grain population is shown in terms of the range of exposure levels per grain. Figure 3 should not be confused with a characteristic curve as such, since the latter also takes into account the spread of the quantum exposure among the grains, as determined by the Poisson statistics. In the form of Figure 3, however, the dynamic grain response is in a convenient form for comparison with that of a digital detector, as for example, a CCD imaging array.

Photo-detection: CCD Imaging Arrays

A signal-to-noise based model of a CCD imaging array has been discussed elsewhere, and this multilevel model[4] is in the same basic form for making quantum efficiency comparisons as is that for the analog silver-halide process described above. We assume that the primary quantum efficiency for transfer of photons to electrons is 30%, and that subsequently the electrons are converted linearly to digital form by quantization every 20 electrons. Figure 4 shows schematically the first several pixel count levels in terms of the number of pixel electrons.

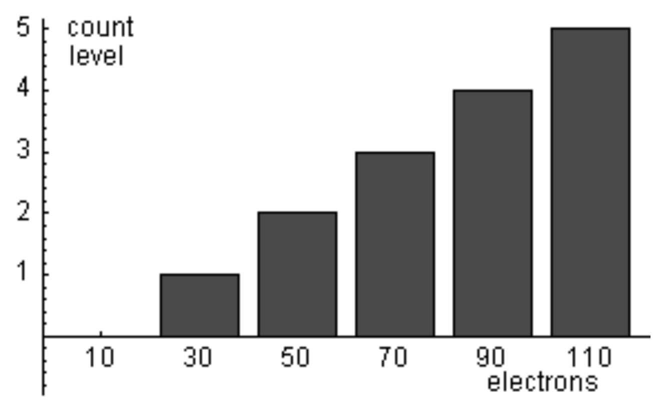

Figure 4. First count levels in terms of pixel electrons.

At this stage we ignore the effects of background noise and read-error, but in order to make the comparison absolute it is necessary to make assumptions concerning the count dynamic-range and the pixel size. Assuming 128 output count levels implies an electron range up to 2,560, which in turn implies a linear exposure range up to approximately 8,500 photons per pixel. If in addition the pixel size now defined, it is possible to translate the characteristics of Figure 3 into the same terms as the response characteristics for CCD imaging. We assume the pixel size is 7 microns, and that an equivalent pixel of this size in the analog case would include 128 grains of size 1 microns (ie, nominal grain/area coverage of around 2.5, similar to that in practice). These assumptions lead to the comparative characteristics shown in Figure 5, where for silver halide the output count refers to the mean number of grains in a 7 microns pixel.

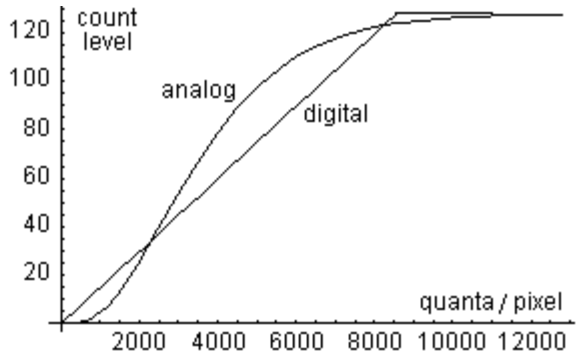

Figure 5. Comparative count level characteristics.

Whereas Figure 5 now provides an absolute comparison for the availability of count levels in analog and digital photography, and has been arrived at using quite reasonable mutual quantum efficiency parameters, although interesting it is not in itself an indicator of overall signal-to-noise ratio or of implicit image quality. It does however demonstrate a similar availability of count levels over a similar range of quantum exposures, at least according to the assumed parameters. However in the silver halide case these count levels correspond to discrete grains, while the image output is usually measured and expressed in terms of an analog function such as the mean image density level. Further the role played by the noise statistics must be taken into account, implying in the silver halide case the availability of a much lower number of *distinguishable* count levels. In the CCD case the assumed upper exposure level is in fact quite low - equivalent to around 2,500 electrons - as compared to typical practical electron well-depths several times higher than this assumed value. These and other technical details must of course be taken into account in carrying out a balanced practical comparison, but the best road to such balance is in terms of the mutual signal-to-noise ratios associated with photo-detection, as we shall now explore.

Comparative Signal-to-Noise-Ratio Models

Having established that, according to the construct of Figure 5, digital and analog photographic processes may have similar nominal capacities and latitudes for the acquisition of images, we now invoke appropriate signal-to-noise-ratio models, in order to establish their overall utility.

In the case of the CCD imaging array we use a previously–described model[4], with quantization as above (ie, at every 20 electrons). Associated with this quantization scheme we introduce a background noise of approximately 100 electrons and a read-error function as shown below in Figure 6. These noise values are based on realistic parameters as estimated for 7 microns pixels and a quarter-second exposure time, and under these conditions Figure 6 may be thought of as the equivalent digital multilevel source of error as that defined by the analog binary error of Figures 1 and 2.

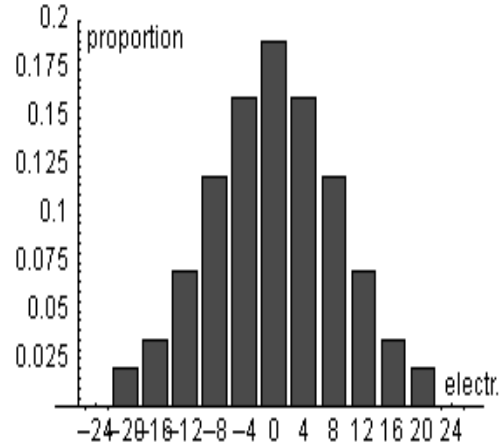

Figure 6. Error function (normalized) for electron read-out.

In the silver-halide case we assume that the detected signal-to-noise ratio is limited only by distribution of binary quantum thresholds as described in Figure 2, noting that this is flattering to analog photography since in practice there are typically other sources which reduce the detected signal-to-noise ratio, including spread of grain sizes, fraction of quanta not absorbed by grains, presence of fog grains, emulsion-layer grain-shielding effects, and so on.

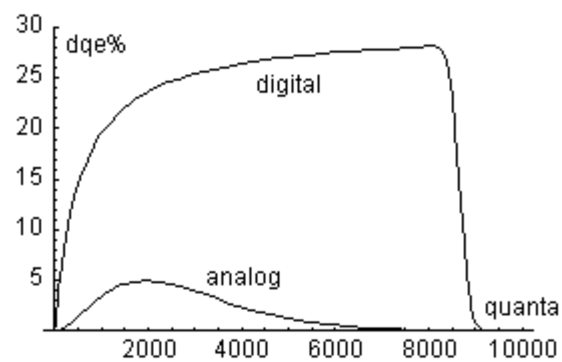

Figure 7. Model DQE values for analog and digital detection.

Figure 7 shows the DQE functions calculated according to the above respective models. The analog and digital systems are now clearly separated in their efficiency of transfer of signal –to-noise ratio. In spite of the presence of significant read-error the DQE for CCD imaging array approaches the limiting upper value of 30% based on the assumed primary quantum efficiency of 0.03, while the silver halide efficiency peaks at around 4% at an exposure level corresponding to the peak of the quantum sensitivity distribution. Due to the multilevel response the digital system is approximately linear over a significant exposure region, while the analog system falls off rapidly with exposure. The conclusion is that multilevel detection is tolerant of appreciable inherent error while binary detection is on the one hand limited by its inherent error yet dependent on it for exposure latitude (binary error-free 3-quantum grains have significantly less exposure latitude than that shown for the silver halide case in Figure 7).

One aspect not considered in this comparison is that of the respective mechanisms whereby analog and digital systems reproduce color rather than gray-scale. In general, silver-halide color processes are so-called *subtractive* in nature while CCD imaging arrays are typically used in *additive* mode. In DQE terms the implications here for the extension to color is that while the DQE values remain unchanged for silver halide, those for CCD-based imaging might be reduced to around one-third of the values shown in Figure 7. However, even with this modification the resulting DQE would approach 10%, and maintain this level over an appreciably higher exposure range than that calculated for silver halide.

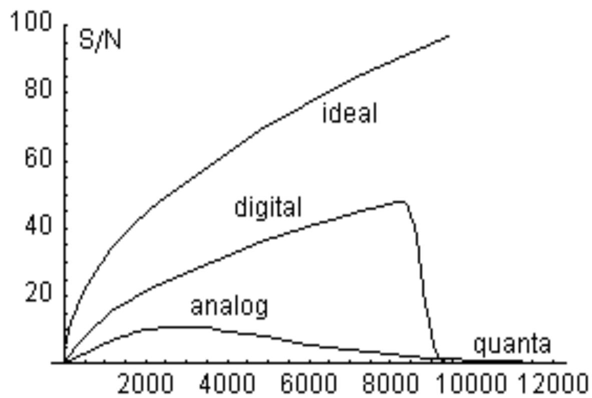

Figure 8. Comparative S/N ratios, including ideal detector.

The detected signal-to-noise ratios associated with the DQE levels of Figure 7 are shown in Figure 8, where for additional comparison the signal-to-noise ratio which would be acquired by an ideal loss-less detector is also shown. Here the signal-to-noise ratio is defined by the square-root of the number of acquired noise-equivalent quanta (NEQ) , which in turn is defined by the product of the actual number of exposure quanta and the DQE. Although not the topic of this present study, it has been established that in this form the signal-to-noise ratio provides not only a satisfactory metric for acquired image capture, but also one for final print quality if the detector and print are coupled in an optimum way for viewing. This coupling of course must include the appropriate signal-to-noise scaling which takes place during format-enlargement from detector to print - a factor which at this stage of the technical evolution of practical CCD imaging arrays is usually favorable to silver-halide. This aside, and in view of the already mentioned modification of these results which may be appropriate for color rendition, one further advantage associated with multilevel detection calls for elaboration. We recall that the number of quantized levels assumed in Figure 5 was only 128 (7 bits), with an associated well-depth of only around 2,500 electrons. Doubling the number of levels and even doubling again leads only to 8 and 9 bit quantization schemes, with required well depths of around 5,000 and 10,000 electrons respectively - values quite commonplace in digital photography.

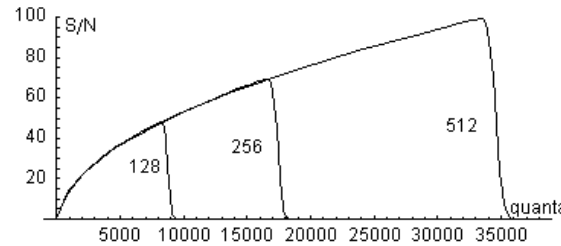

Figure 9. Digital S/N latitude as a function of count-levels.

Figure 9 shows the extension of response in S/N terms made possible by extensions of the count levels as shown, again stressing the importance of extension of latitude via extension of multilevels rather than by introduction of noise in a binary system.

Conclusions

A quantitative study has been made to illustrate the comparative signal-to-noise limitations in analog and digital photography, and the manner in which these are determined by the respective quantum efficiency characteristics. By the use of simple models it has been demonstrated that multi-level image detection in the presence of noise is capable of inherently higher signal-to-noise than is binary acquisition in the presence of similar noise (or the greater noise which may be necessary for satisfactory latitude). In this context digital systems based on (multilevel) CCD imaging arrays would appear to have the capability of closer approximation to the ultimate limits imposed by the incoming photon statistics than is possible for (binary) detectors such as those associated with silver-halide systems.

References

1. J. C. Dainty & R. Shaw, *Image Science*, Acad. Press, 1974.
2. R. Shaw, *Phot. Sci. Eng.*, **16**, 192 (1972).
3. R. Shaw, *J. Phot. Sci.*, **21**, 25 (1973).
4. R. Shaw, *Procs. IS&T 50th Annual Conf.*, 335 (1997).