Systems Linearity Considerations for Digital Photography

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Abstract

End-to-end system studies in digital photography inevitably lead to the question of setting goals in order to achieve overall linearity. But this itself poses the specific question of which key print/display variables should, in ideal circumstances, be linear with which key scene-acquisition parameters. Within the digital context, intuitive answers gleaned from traditional analog approaches to this question can vary from the confusing to the misleading, and digital attempts at direct emulation of analog systems may in fact off-set the potential advantages implicit in the newer digital technologies. The author has used a digital end-to-end signal-to-noise ratio model to consider some aspects of this linearity question, and to offer solutions based on the appropriate combination of SNR optimization and the human visual-response characteristics. Some results and conclusions are discussed here, especially those relating to the optimum digital strategy for scene-acquisition.

Introduction

As digital photography comes of age, witnessed for example by both widespread consumer application and technical scrutiny, it is generally accepted that fundamental questions remain of achieving acceptable levels of image quality. These questions are usually couched in terms of equivalent quality levels in traditional (analog) silver halide photography, with goals for digital often set in terms of these existing levels. That analog photography provides the image-quality standard for digital photography arises not simply from the familiarity of widespread prior usage, but the technology-specific detail that silver halide grains, (the basic detection unit) are one the scale of a micron or less. Image quality as such has thus not been a prime technical problem in traditional photography for the last century, although the associated problem of sensitivity, or speed, has been a constant challenge due to fundamental quantum efficiency problems associated with silver-halide during the detection process.

A further more-subtle problem still to be satisfactorily addressed in digital photography is in fact also intricately connected with these questions of image quality, speed and quantum efficiency as relevant to the digital domain. This pertains to the question of overall systems linearity, and the precise manner in which the input (acquired scene) is transported to the output (print) so that the impression is conveyed that the original has been optimally reproduced. In analog photography a wealth of phenomenological solutions have been erected around this important question, without necessarily grasping the fundamental issue. Further, emulation of analog recipes in the digital domain may lead to unsatisfactory results, or at best inhibit the natural advantages offered by digital acquisition technologies. To understand this again requires a full appreciation of the basic technological differences in the detector properties of sensitivity and quantum-efficiency and how these tie-in to the fundamentals of scene-detection, in addition to knowledge of those pertinent aspects of the visual-response to original scenes and printed versions of these scenes.

In brief, silver-halide photography makes use of a negative and a positive in order to achieve so-called overall satisfactory tone reproduction, but in doing so attaches separate characteristics to both components, and tracks both separately as well as jointly in their ability to reproduce the scene. Experience has shown that by and large the image quality and tone-reproduction properties of the negative are definitive, and are tracked to the positive via enlargement considerations in the case of image (detail) quality, and via joint linearity considerations in the case of overall tone reproduction (as for example, in terms of familiar four-quadrant-diagram representations). The negative is itself typically interrogated with light and evaluated in terms of its densitometric properties. In digital photography there is no negative as such in the image-chain conversion from photons to electrons to bits to print elements, and only the properties of the latter are considered to have relevance in the visual context. How therefore are systems linearity properties and goals to be compared on an objective basis between analog and digital systems?

The situation is further complicated by distinctive differences between the quantum efficiency characteristics of analog and digital scene acquisition. Both are lossy in the quantum-efficiency sense, but the former is essentially a single-level process, while the latter is a multilevel process, and this distinction leads to quite different scene-transfer characteristics.

In view of these differences in operation and the consequential complications to both absolute and comparative evaluation, the path forward might seem obscure. However when the analysis of digital photography is seen not as an evolution of analog techniques, but starts from the fundamental basis of information and signal-detection theories, and this approach is coupled to the appropriate pragmatic aspects of visual science, considerable clarification arises both in general understanding and in detailed evaluation techniques. Further this approach readily embraces both image quality (sharpness, grain, detail rendition) *and* tone reproduction/linearity considerations as a comprehensive whole, rather than an asserted set of *ad hoc* parameters.

A significant literature exists in this field spanning the past half century or so (see for example references 1-17), including the application of these techniques to the evaluation of analog photography. Over recent years the author has attempted to illustrate the potential of these techniques in a series of studies concerning signal-to-noise analysis and comparison of digital photography systems (see for example references 18-24). These studies have described an end-to-end DQE model (signal-to-noise-transfer) from scene to print, and specifically included most of the key parametric variables in a CCD+TIJ digital capture/print combination, and their relationship to the most important image outcomes in the print.

During the course of these studies the author has developed the concept of the ideal linear end-to-end system in terms of constant-DQE performance (as opposed to a DQE which is highly variable with scene exposure-level in the case of silver halide), including linear representation of significant visual differences in the original scene as equivalent significant visual differences in the print.

The purpose of the following examples of this model is to demonstrate the concept of digital end-to-end linearity. For more details of the construction and implicit assumptions of the model, readers are referred to the previous series papers, since space prohibits full repetition here.

Scene-to-Print Digital Linearity

Initially we consider an unrealistic but illustrative set of parameters. The (scene) exposure is detected with 10% conversion efficiency from photons to electrons. Digitization then follows, with digits subsequently mapped linearly into print reflectance. Figure 1 shows the resultant DQE characteristics for a series of digitization schemes.

These digitization schemes are based on statistical separation of the levels according to the underlying (assumed Poisson), and have been set at 1, 2 and 3σ respectively. For simplicity a fixed and restricted exposure range has been considered, implying, 100, 20, 10 and 6 levels respectively for the above cases. Figure 2 shows the corresponding mean-level (reflectance scaled to 10) and absolute digital noise[30] characteristics, as plotted on the same exposure scale, the top curve representing digitization at every electron count, and in descending order the 1, 2 and 3σ level-separation criteria. Based on complex arguments beyond the present scope, linearity of these mean level characteristics is assumed optimum, along with minimum digital noise in the print. According to these assumptions the 2σ-criterion appears to meet an optimum compromise between digital-economy and the linear transfer of signal characteristics - a familiar result from the field of signal sampling.

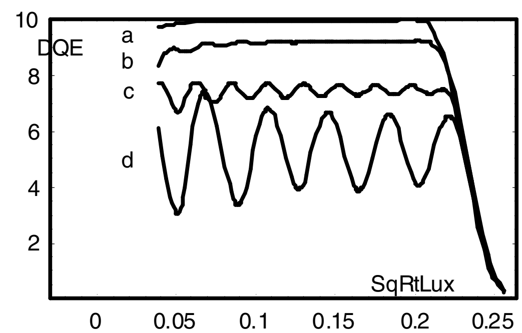

Figure 1. DQE-exposure characteristics for four digitization schemes. a) every electron, b) 1σ; c)2σ; d) 3σ -criterion.

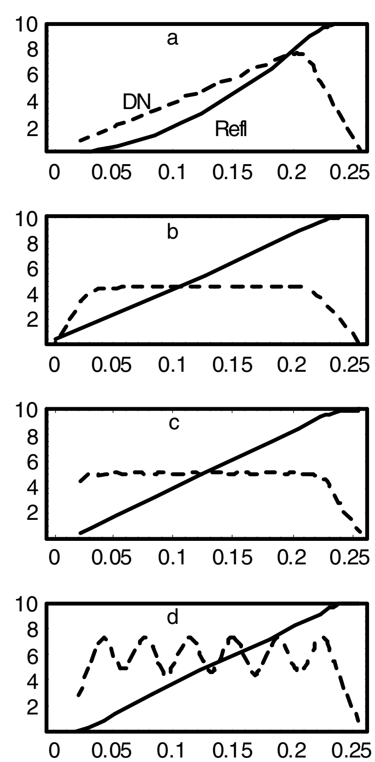

Figure 2. Reflectance (solid) and noise (dashed) characteristics corresponding to DQE characteristics of figure 1.

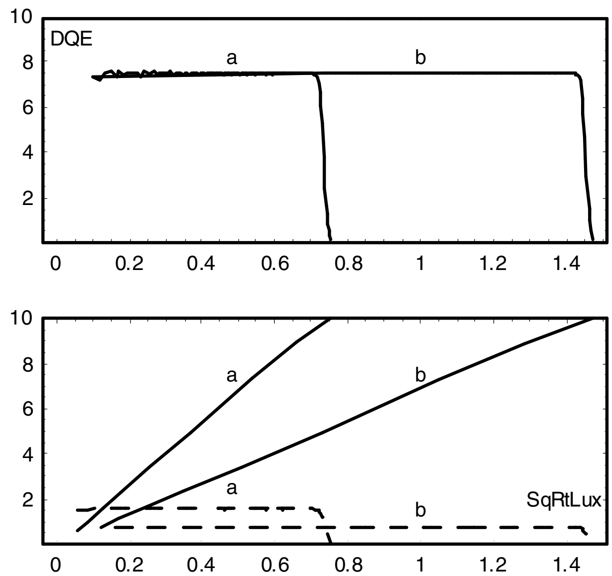

Figure 3. DQE (top) and reflectance (solid) and noise (dashed) characteristics (below) for 2σ sampling criterion, with a) 32, and b) 64 levels sampled.

This result implies that a first order strategy is to sample the scene at enough 2σ-digitized levels to produce a print with sufficient exposure latitude, and noise low enough to yield satisfactory image quality. Figure 3 shows examples based on a doubling of levels while maintaining the same separation criterion. The longer exposure needed will then imply an accompanying lower noise level, but the overall efficiency of transfer will remain constant (DQE around 8%) and the linear mean-level characteristics will be maintained.

The situation becomes more complex from a statistical viewpoint when spurious noise sources are present at some stage in the acquisition/digitization process, in addition to the natural noise inherent in the statistics of the scene quanta. In such practical cases end-to-end linearity in the sense discussed above is still an essential condition, but the definition of distinct scene levels will now change due to the presence of this spurious noise. While the general solution to this problem may be difficult, the following simple example can provide insight into the general solution.

We suppose that a scene is to be sampled at 32 levels, and that spurious additive noise sources (eg, dark-current, read-noise) are present to the extent of 32 rms electrons per CCD pixel on average (perhaps typical for pixel sizes used in contemporary use[23]). Figure 4 shows three scene-sampling strategies that might be considered. The first of these ignores the presence of the spurious noise, and is still based on the 2σ-criterion calculated according only to the photon noise. This is represented by curve a, while curve c represents an offset of the sampling sufficient to maintain the functional nature of the conversion. Curve b represents maintenance of the 2σ-criterion.

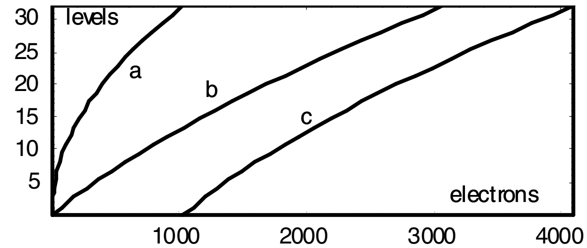

Figure 4. Sampling function, electrons to digits. a) 2σ criterion, photons alone, b) overall 2σ criterion applied, including spurious noise, c) sampling offset according to spurious noise.

The various DQE implications of these assumptions are demonstrated in Figure 5. In all three cases the DQE linearity has inevitably been modified with DQE approaching the limiting case of that of Figure 3 upper, that is, only at higher exposures where the relative contribution of the fixed spurious noise has become small compared to that inherent in the scene photon statistics. Note however that curve b (2σ-criterion applied overall) exhibits the essential virtues of both separate cases, a and c. This may be demonstrated by calculation of the accompanying mean and variance characteristics, as shown in Figures 6 and 7.

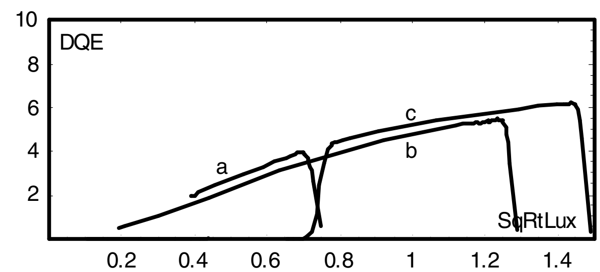

Figure 5. DQE-exposure characteristics corresponding to three sampling schemes of Figure 4.

The mean-level (print-reflectance) characteristics of Figure 6 indicate the anticipated straight-line relationship in the case where the photon statistics alone dictate the sampling scheme, and also where the off-set is applied according to the spurious noise. The significant exposure penalty of the latter is also apparent, the new straight-line relationship being an exposure-scale translation from the old scale. However in the case where the 2σ-criterion is maintained on a joint statistical basis, it is seen that the mean-level curve now spans the other two, with a slight bowing of the curve in essence resulting from one set of statistics within the criterion merging into the other.

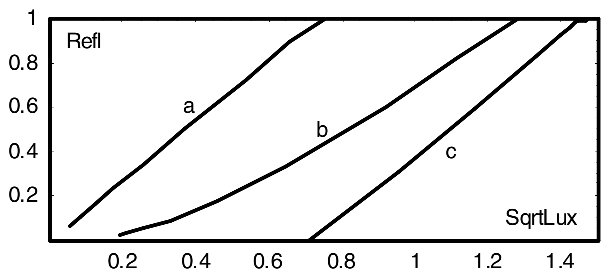

Figure 6. Reflectance-exposure characteristics corresponding to three sampling schemes of Figure 4.

The desirability of these mean-level characteristics must also take into consideration the accompanying levels of absolute print noise which will result, according to all the system-assumptions which have been made, and the corresponding noise curves are shown in Figure 7. The specific nature of this scale and the practical quality levels associated with it have been discussed elsewhere[25,26], suffice it to say here that absolute values in the region of 1 to 2 represent quite satisfactorily low levels of photographic noise.

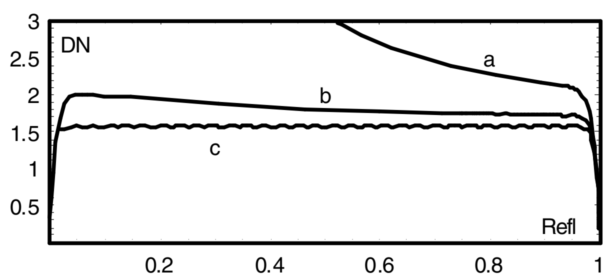

Figure 7. Absolute digital noise characteristics corresponding to three sampling schemes of Figure 4.

In the case where scene–sampling takes place based on an unmodified photons-only 2σ-criterion, the noise becomes disproportionately high at the low-exposure (low print-reflectance region). This follows intuitively from the presence of the spurious noise source. When the latter is combated by using either sampling schemes b or c the noise approximates the absolute level and straight-line characteristics dictated by the photon noise in the scene and the binomial statistics of the discrete print image levels. There is only slight additional noise resulting from use of an overall 2σ-criterion. In light of the associated significant increase in speed and latitude, and print reflectance characteristics remaining close to the desirable linear goal, the attraction of general adoption of this criterion is strong. As practical levels of extraneous noise fall due to rapid technical advances, and as the inherent scene (photon) noise becomes the dominant noise source, this conclusion becomes even more persuasive, leading to a significant simplification in overall linearity goals.

Conclusions

Use of an end-to-end SNR model for digital photography has demonstrated that considerable insights into overall scene-reproduction goals are possible. Further, these reproduction goals implicitly span the essentials of both macroscopic and microscopic image properties. The central premise has been that of sampling the scene according to well-know signal-detection principles.

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Biography

Rodney Shaw received his PhD from Cambridge University. He came to the USA in 1973, and following research appointments at Xerox and Eastman Kodak was Director of the Center for Imaging Science at RIT. He joined H-P Labs in 1994, and his current interests are in digital photography and systems modeling.
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