

Signal-to-Noise Ratio of Digital Photographs

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Abstract

Information-theoretic metrics based on signal-to-noise ratio have long been established as providing an overall assessment of image quality, and more recently have been applied in the context of digital photography and digital printing. Such metrics are in fact ideally suited to the overall evaluation of imaging systems where the chain from scene-capture to final print may be a complicated one involving diverse technologies. This present study considers the signal-to-noise requirements for high-quality digital prints, and by consideration of the entire imaging chain accounts for signal-to-noise ratio (SNR) loss due to each significant component in this chain. By these means it is possible to distinguish the respective roles of the capture and print technologies and establish the fundamental imaging requirements for high-quality prints.

Introduction

At recent NIP meetings the author has described an absolute scale for print noise[1], and an overall quality scale for digital photographs[2] which takes into account the properties of both the scene-capture and image-print components and which is based on well-established signal-to-noise-ratio metrics. Both scales lead to ease of comparison between different imaging technologies and have previously been applied to a range of applications, including the quality associated with conventional (analog) photographic systems. The print-noise metric was in fact scaled to existing practical numbers which had previously been generated specifically within the context of the psychophysical response to the physical noise in photographic prints under controlled viewing conditions.

Whereas the ability to make such comparisons is a beneficial outcome of such studies, the main purpose of this work is to serve as an optimization exercise; ie, to identify those components within the end-to-end digital-photography chain which place practical limitations on the final signal-to-noise ratio in the image, and to quantify improvements which would accompany the optimization of all such interacting components. Within this general framework the purpose of this present study is to make use of these metrics to perform an absolute accounting for the signal-to-noise ratio of a digital photography system based on CCD-image-capture and TIJ-image-printing. As an aid to this investigation, it should be noted that separately a detailed model for CCD detection has been developed[3], and applied to various comparisons between the fundamental efficiencies of scene-detection for analog and digital systems[4-6]. These CCD-detection parameters, tied together with the appropriate mapping function to the printer and the technical parameters associated with printing, provides the end-to-end signal-to-noise ratio model appropriate for the present investigation. Since details have been previously described, only a summary will be given here.

The SNR Model and Evaluation Parameters

The SNR model for the CCD-detection stage is based on accounting for the photons which constitute the exposure as they generate electrons which in turn are sampled to provide a digital output. This output is then mapped to appropriate printer states to form the printed image. Prior to detection the SNR is that associated with the statistics of the photons themselves. The *noise-equivalent* number of quanta (NEQ) is then used to track the flow of SNR through the various stages, where specifically the SNR is measured by square-root of the noise equivalent number of quanta, since there is consistent evidence that this absolute physical measure of performance also provides a satisfactory surrogate for perceived image quality when the image is presented to the perceptual process in an optimum way (which in itself is a lengthy topic beyond the scope of the present study). After mapping to the print, and as a consequence of the magnitude of the SNR, the tone reproduction characteristics are accompanied by a certain level of image noise. Since the important question of digital tone reproduction is a separate though not unrelated issue, here we investigate the absolute noise level in the image, since this is a crucial driver of image quality.

The print-noise model is characterized by a *digital noise scale* (DNS), essentially defined by the low-spatial frequency value of the Wiener (power) spectrum of the digital noise fluctuations in reflectance, and it has previously been demonstrated that DNS lends itself readily to image noise modeling in terms of, on the one hand, dominant printing parameters such as *dpi* and number of gray levels; and on the other hand, the role of the incoming noise from the scene as transducd via the CCD and digitization processes.

Of course the spatial-frequency spectrum (rather than the low-frequency or scale value) associated with the SNR is of great importance in defining image quality, as is the full spectrum associated with the image noise. However in the digital domain these spectra are dominated by the role of the physical dimensions of the pixel, and specifically enlargement of the CCD pixel into the print domain. Here the image spatial frequency spectrum is tracked only by a *sharpness index* (SI) obtained by merely constructing a frequency-weighted integral over the product of the visual transfer function and a *sinc-function* based on the pixel dimension in the print. In analog photography the phrase *photographic space* is sometimes used to describe the boundary of the practical speed-resolution-contrast-granularity space, and with the addition of a sharpness index, we have now constructed an equivalent digital space to this conventional analog space. With this, and the previously-discussed end-to-end model, it is possible to account in quantitative manner for most of the significant mechanisms which reduce the SNR between scene and print.

CCD + TIJ Digital Photography Model

For the purpose of illustration a set of parameters have been chosen to describe detection by the CCD and printing by thermal ink-jet (TIJ) in the print. We may think of these as the base set from which variations over a prescribed range for technical parameters are accompanied by model calculations of the accompanying variations in imaging performance.

CCD Parameters

A pixel size of 7microns is assumed and an array size of 1024x1280 pixels. The primary quantum efficiency is 0.25, the dark current 6 electrons per square-microns per sec at 25^{o}C, with an exposure of one-sixtieth of a second at this temperature assumed standard. The saturation level (well-depth) corresponds to 300 electrons per square-microns, ie approximately 15000 electrons for a 7 microns pixel.

Digitization Parameters

The separation between read-levels is assumed to take place according to a fixed 2-sigma total-noise separation-criterion, with a fixed contribution to this noise from the read-noise itself of 30 electrons.

Print Mapping Function

The CCD sensor array is mapped geometrically to a 3.5"x5" print, implying a linear magnification of approximately 12*x*, with the seven micron pixel in the array thus mapping to around 84 microns in the print. The mapping from is linear from digital-level to print-reflectance.

Printer Capabilities

At the required resolution level (ie 84 microns) the printer is capable of 32 distinct, linearly-spaced, reflectance levels between minimum and maximum values of 0.01 and 0.85 respectively, implying a basic capability of 32-levels at an effective 300dpi.

Incorporation of the above values as system parameters into the existing SNR and DNS models now allows calculation of these important image performance criteria. Note that above parameters have already defined the image sharpness according to a sharpness index based on an 84-micron image pixel of SI = 8.8 on a scale of 1 to 10. Again it should be stressed that this set of values, although believed reasonable, is for illustrative purposes only, and not naturally representing any specific practical system.

Model Performance Calculations

Figures 1 and 2 show the image quality characteristics as calculated according to the overall model for the system parameters identified above.

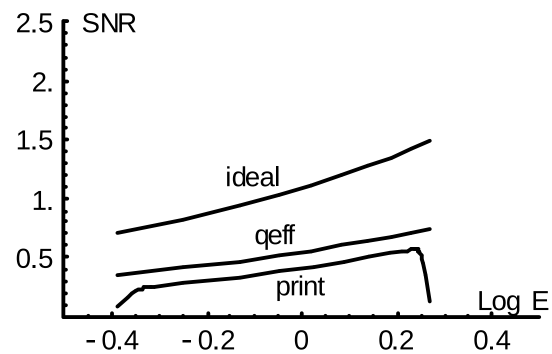

Figure 1. Image SNR, compared to the ideal case.

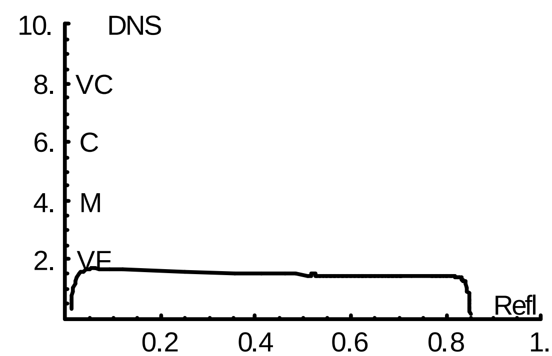

Figure 2. Print noise on the Digital Noise Scale.

The image SNR is expressed here in terms of root-NEQ per square-microns in the print, and the exposure scale is in terms of lux. The ideal case represents that where the exposure quanta and the noise-equivalent number exactly coincide, ie, for a hypothetical ideal system limited only by the incoming photon statistics. The curve labeled *qeff* shows the SNR following the conversion of photons to electrons via the primary quantum efficiency. The influence of the latter is easy to illustrate in these terms since the SNR as defined simply various as root-quantum-efficiency. With the above assumption that the quantum efficiency is 0.25, the curve representing its influence will thus be everywhere one-half that of the ideal case.

Other factors influencing overall quantum efficiency (eg additive color filter arrays for color reproduction, not considered here) will have similar implications on the overall image SNR.

The numerical DNS scale is as described previously, where the descriptors shown are the equivalent ones from analog photography (VF, very fine; M, medium; C, coarse;

VC, very coarse), and it is concluded that the SNR characteristics of Figure 1 can thus lead to an absolute print noise level well within the normal range found in conventional silver-halide prints.

As is the case with analog photography, the implications of sensor format and the size of the print (and more specifically the degree of geometrical enlargement between the two) play a dominant role in defining the signal-to-noise ratio and absolute noise level in the print. Recalling that the parameters listed above imply a 12*x* enlargement, we now consider the cases whereby a) the sensor area is doubled (four times the number of pixels) and the print area is halved, yielding an enlargement of only 4*x*; and b) *vice versa*, implying an enlargement of 48*x*. Note that the assumptions of a) and b) yield values of SI= 9.95 and 2.76 respectively, indicating that in the practical case the latter would be ruled out by sharpness considerations alone. Figure 3 shows the SNR for these two cases compared to the standard case, while Figure 4 shows the corresponding noise characteristics.

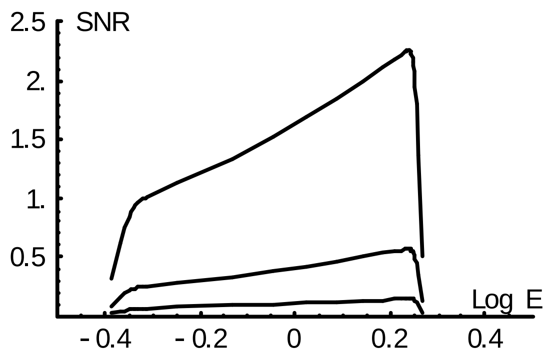

Figure 3. SNR variation with sensor-to-print enlargement: upper 3x, middle 12x, lower 48x.

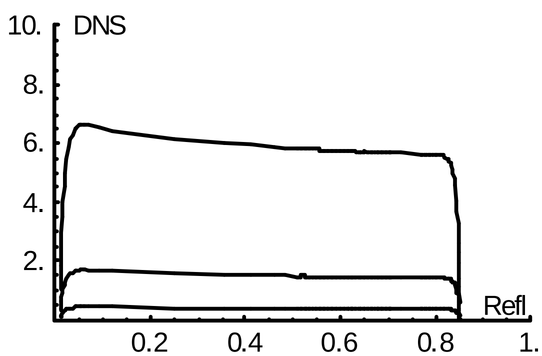

Figure 4. Print noise dependence on degree of enlargement: upper 48x, middle 12x, lower 3x.

It is intuitively satisfying to note that both the SNR per unit area and the print noise have a linear dependence on degree of enlargement, and of course change in opposite directions with change in enlargement (more enlargement, less SNR per unit print area, more print noise). It is also interesting to note that the range of parameters considered above leads to a range of noise levels on the digital noise scale which approximately covers the complete normal range of noise levels in conventional photographic prints (and perhaps a somewhat greater sharpness range).

From the viewpoint of the printing technology an important SNR question involves the influence of increases in the number of distinguishable gray levels at a fixed resolution limit (print pixel size), and specifically the accompanying ability to sense and print a greater number of distinguishable levels from the original scene. To explore the influence of levels we now consider a halving and doubling of the original assumption of 32 levels, and Figures 5 and 6 show the results of the model calculations.

Extending the number of levels captured in the scene (while maintaining the same functional translation of levels to bits) is of course seen to extend the SNR to greater exposure levels, and assuming that the printer has the capacity to print these levels, this in turn drives down the absolute print noise. In fact under these idealized conditions the print noise level will scale exactly with the reciprocal of the number of levels. Of course in the present case the print resolution (and hence sharpness index) remains unchanged.

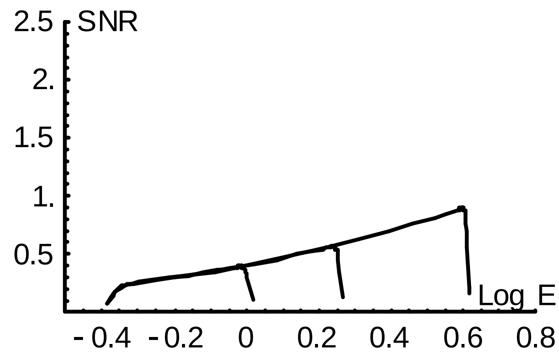

Figure 5. Print SNR as a function of scene levels detected and printed: left,16; middle, 32; right, 64.

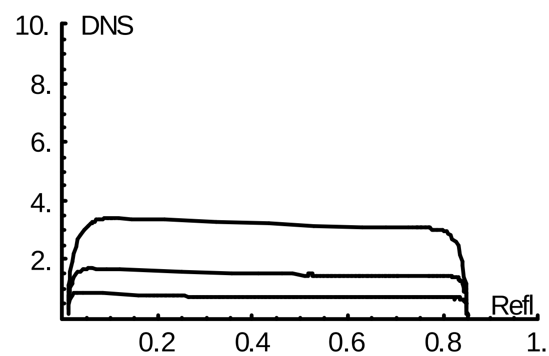

Figure 6. Print noise dependence on scene levels detected and printed: top, 16; middle, 32; bottom, 64.

Whereas the noise associated with the incoming scene (photon-noise) is inherent to the detected signal, noise sources due to the detection and digitization processes might be reasoned to be entirely harmful. Here we consider a comparative example calculated according to model conditions whereby these latter sources are on the one hand removed completely, and on the other significantly enhanced (by doubling the read-noise to 60 electrons rms).

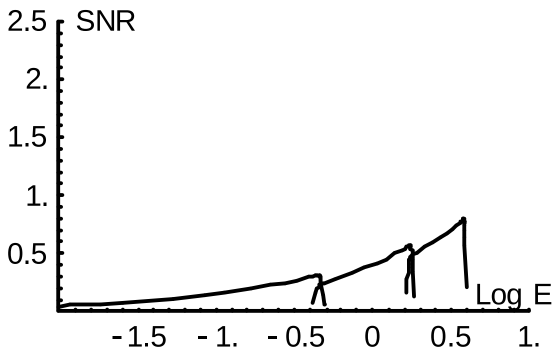

Figure 7. Influence of noise sources: left, noise-free case; middle, base noise; right, double read-noise.

Figure 7 shows the influence of these various noise assumptions on the calculated SNR. The accompanying changes on the absolute print noise level are not shown here since they are in fact too small to differentiate on the digital noise scale. At first this seems counter-intuitive, until Figure 7 is considered in more detail. In fact to obtain the same number of distinguishable levels to print in each case, with increasing detection noise it is necessary to use increasingly higher exposure levels (ie, more photons) in order to offset this spurious noise. Thus the imaging penalty is one of system sensitivity, or photographic speed, rather than any change in fundamental print quality. There are of course associated tone-reproduction implications, but these are beyond the present scope.

Conclusions

A series of model calculations have been presented in order to show some of the more important system factors which influence the final image quality in digital-photographic prints. The influence of some of these factors is intuitive based on similar relationships in analog photography (eg, format and enlargement). The influence of others (primary quantum efficiency, number of distinguishable scene/print levels) is also intuitive although arising from basically mechanisms than those in analog photography. Finally, the influence of others (eg, detection and digitization noise-sources) is less intuitive.

This report, while attempting to present a comprehensive overall SNR analysis, has ignored several important practical effects which may further significantly influence the print SNR. For example, the overall reduction in the effective quantum efficiency (plus the introduction of variability in quantum efficiency) associated with color filters arrays, may impose a significant limitation on the overall SNR and the absolute print noise level. Further reports will consider these and other important practical factors.

References

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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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