# Digital Photography: Towards Ultimate Performance

*Rodney Shaw*
*Hewlett-Packard Research Laboratories*
*Palo Alto, California*

## Abstract

The recent widespread acceptance of digital photography within the consumer marketplace has brought renewed interest to questions of overall performance and image quality. The generic comparison with traditional analog photography is naturally of great interest, as is the inter-comparison between competing digital systems. But relatively little attention has been given (at least in the open literature) to the inherent digital limitations which govern performance, and the future increased performance expectations as technological advances are made. The present study attempts to identify some of the salient features of digital systems, and to emphasize those aspects which are likely to lead to the opening up of new areas of quality and performance as technological advances continue.

## Introduction

For several decades the concepts of ultimate imaging performance have been used within the photographic context as a tool to explore the technical parameters that limit the pathway between original scene and final print quality. Analog photography is now almost completely understood within this context, its primary limitations being centered around the binary nature of the silver-halide grains and the wide spread of quantum efficiency from grain to grain. These limitations have been translated into the influence on all important aspects of imaging performance, from camera speed, dynamic exposure latitude, tone reproduction, and print sharpness/noise characteristics, and within these inherent limitations analog photography can be said to be optimized. Likewise there is exhaustive knowledge of the those areas of silver-halide technology from which future incremental imaging improvements might be derived by future advances.

Whereas digital photography is subject to its own set of technical limitations, with evidence that from a fundamental viewpoint these are considerably less restrictive on imaging performance than those of silver halide, the digital community as a whole has not clearly articulated the relationship between these limitations and overall photographic performance in terms of contemporary technology (although at least two reviews are of historical interest in this context.[1,2] Clearly this has been largely due to factors such as the competitive rush to market and perhaps a pervasive intuition that more sensor pixels will sweep aside all remaining performance problems. But as the field matures it is appropriate to step back and examine digital systems as a whole, and to question the role of each step in the end-to-end digital system, and especially its limitation on achieving ultimate photographic performance. In order to do this it is first necessary to identify the most important components and parameters in the end-to-end digital system, and also to establish the key performance parameters with which to track their influence.

## Digital Systems Parameters

During recent conferences in this series the author has presented various calculations based on an end-to-end parametric model of a digital photography system[3-6]. Shown below are examples of system variables incorporated into the model:

**Sensor Parameters Used In Scene Detection**

- Geometry
  - absolute pixel dimensions
  - pixel x,y-array size
- Primary quantum efficiency
- Pixel well-depth
- Pixel dark-current

**Sampling and Processing Parameters**

- Sampling function
- Sampling levels
- Sampling (read) noise
- Mapping function to printer

**Printer Parameters Used To Display Image**

- Geometry
  - absolute pixel dimensions
  - pixel x,y-array size
- Distinguishable ‘gray-levels’ per pixel
- Min and max pixel ‘grays’

Essentially these parameters consider the digital system within three phases of the end-to-end system, namely, image capture, image processing and image display. Although this list of parameters is not exhaustive, it includes the most important factors governing the transfer of signal-to-noise-ratio, and other factors not included explicitly (eg, those controlling color reproduction) can be thought of as an implicit sub-set.

## Performance Evaluation Parameters

A critical set of performance parameters is readily assembled from those used to describe signal-transmission within the general field of imaging, and more specifically those which have evolved over the years to define 'photographic' space within the domain of conventional (analog) silver-halide photography. These can be thought of as falling into two main categories, namely those governing the reproduction of large-areas (mean-level) and those governing the reproduction of fine-detail (fluctuations about the mean). The former is most easily dealt with, since a rich literature exists within the field of analog photography. However this does not imply the adoption of conventional standards without distinguishing between those which relate back to 'how analog photography works' (eg, four-quadrant scene-to-print tone-reproduction curves) and those that are based on the fundamental laws of governing image reproduction and perception.

The parameters describing the reproduction of fine detail fall into two sub-categories, namely those concerned with the reproduction of signal and those describing the attributes of noise. These categories naturally lead themselves to combination in overall information-theoretic based concepts that describe the ability to transfer signal-to-noise ratio from scene to image.

For simplicity we summarize some of these key evaluation parameters below:

**Large-Area Scene-Brightness Reproduction**
- Average scene brightness
- Minimum and maximum brightness levels
- Functional sampling of brightness range

**Fine-Detail Reproduction**
- Signal reproduction
  - Digital sharpness index
- Noise reproduction
  - Digital noise scale

**Overall Evaluation Parameters**
- Image SNR (NEQ/spatial-frequency/exposure)
- Speed-to-Grain (DQE/spatial-frequency/exposure)
- Information Capacity

Two of these fine-detail evaluation parameters have been recently described by the author[7] as extended specifically to the digital domain from previous well-established Fourier-based analyses. Summaries only are given here.

## Digital Noise and Sharpness Scales

Digital noise may be expressed on the *DNS* as

$$DN = \sqrt{\left\{ \iint WS_R(u,v)\, VTF^2(u,v)\, du\, dv \right\}} \,.$$

where $WS_R(u,v)$ represents the Wiener Spectrum of the noise fluctuations measured in units of reflectance, and $VTF(u,v)$ denotes the transfer function associated with human vision. With the power spectrum expressed in absolute print reflectance units the calculated digital noise is such that the typical photographic range falls within *1* to *10* on the scale.

An equivalent methodology may be used in developing a digital sharpness scale, namely adopting the same standard visual transfer function as assumed for normal print viewing conditions. This is cascaded with a transfer function based on the pixel geometry which defines the sharpness limitation of the digital system, typically a sinc-function. The expression for digital sharpness thus becomes of the form

$$DS = \iint TF_{PIX}(u,v)\, VTF(u,v)\, du\, dv \,.$$

## Performance Criteria

Having established a sufficient set of performance parameters and likewise a sufficient set of technical variables for the digital system under review, it remains to establish the relationship between the two and also the reasonable practical ranges for these multiple variables. The previously-mentioned end-to-end model establishes this relationship, and we are left with the task of defining the appropriate ranges and limits. On the one hand reasonable ranges for the system technical parameters depend on contemporary capabilities and likely future technical advances, and on the other hand reasonable ranges for the performance parameters can best be benchmarked in terms of equivalent analog performance characteristics, since the latter have long been established in the photographic domain.

**Table 1. Empirical descriptors for the perception of image noise according to levels on the digital noise scale.**

| DNS | Photo-Grain |
|---|---|
| 10 | off-scale |
| 8 | very coarse |
| 6 | coarse |
| 5 | moderately coarse |
| 4 | medium grain |
| 3 | fine grain |
| 2 | very fine |
| 1 | extremely fine |
| <1 | microfine |

Given the existence of absolute sharpness and noise scales, and their translation into analog photography, the performance criteria based on these scales are perhaps the easiest to establish. Existing empirical descriptors for photographic grain fall on the *DNS* as shown below in Table 1, implying a gamut of physical values in the range *1* to *10* for practical photography and experience shows that to achieve high-quality photographic prints calls for the image noise to be below *2* on this scale.

A simple model for the image noise associated with ink-jet printing may be approximated on the digital noise scale in terms of *ppi* (resolved pixels per inch in the print) according to

$$DN(max) = 12{,}700 \,/\, (m\ ppi)$$

where *m* denotes the number of available gray-levels expressed in reflectance-space.

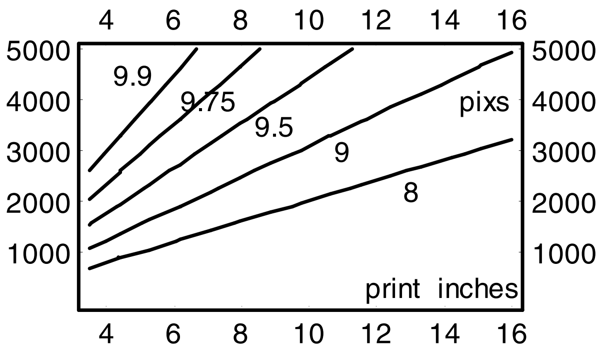


*Figure 1. Relationship between number of sensor x-pixels and print x-dimension in order to conform to the range of sharpness values typical for analog photography.*

According to the sharpness model the acceptable photographic range falls within *8* to *10* on the sharpness scale, with high-quality photographic prints being around *9.5* or higher. Since the digital criteria for achieving such sharpness levels is mainly based on geometry (pixel in sensor 'enlarged' to pixel in print), Figure 1 provides an overall summary of these fundamental geometric requirements.

Of the overall parameters, the most straightforward parameter to specify is that of *DQE*, since a wealth of knowledge exists of the practical range for conventional photography, where it directly controls the important speed-to-grain ratio. Further, and most obviously it has an absolute upper limit of *100%*, and it is in this domain that the importance of quantum-efficiency and multilevel versus single-level recording is most strikingly demonstrated.

Questions of large-area scene-brightness reproduction are less amenable to a simplification for comparative specification purposes, but at the most recent conference in this series the author specifically addressed this question in terms of an end-to-end systems mean-level linearization strategy[6] which is simple yet yields a desirable criterion for large-area reproduction, namely that differences in absolute reflectance in the print are proportional to the square-root of differences in the original scene, as expressed in lux.

## Towards Ultimate Performance

In view of the number of system parameters on the one hand and performance criteria on the other, only a selective illustration will be given here, in the form of summary before-and-after performance attributes. The *before* example is based on a set of parameters typical of contemporary consumer digital photography, while *after* is representative of those potential technical improvements which may reasonably be anticipated in the near future. The performance criteria are based on a high-quality *8x10"* print. Typical values for CCD quantum efficiency, pixel and array dimensions, well-depth and dark current, and printer resolution and gray-level capability, as used previously by the author[3-6], are replaced by an equivalent set (for example a *2*-megapixel sensor is replaced *4*-megapixels, the primary quantum efficiency increases from *0.1* to *0.25*, the printer capabilities change from *32* distinguishable gray-levels at *160ppi* to *64* at *230ppi*, etc).

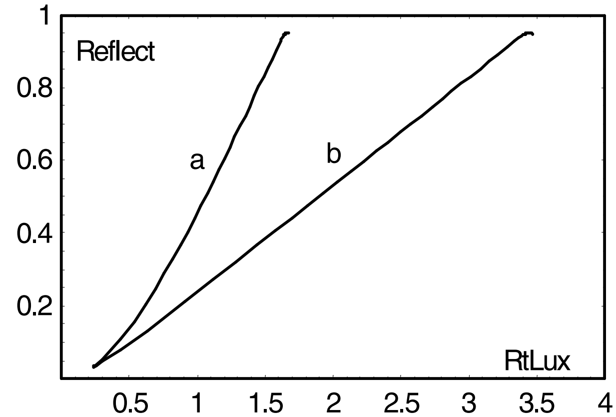


*Figure 2. Mean-level input relationship: a). For typical parametric set, and b) for parametric set representing future advances.*

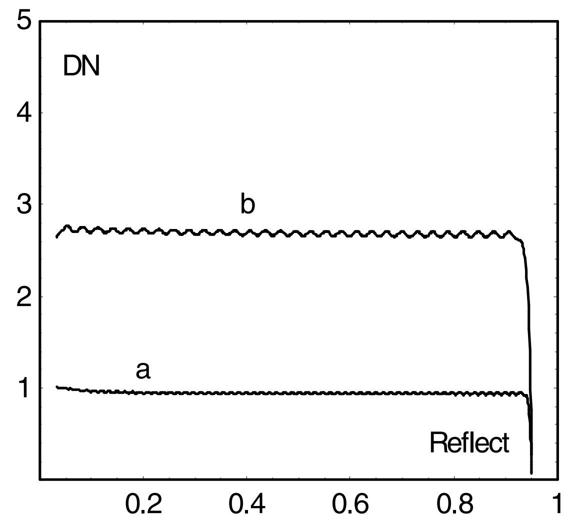


*Figure 3. The noise/print-reflectance characteristics corresponding to those of Fig 2.*

Figure 2 shows the influence of this change of parameters on the mean-level scene-to-print characteristics, with desirable and substantial increase in dynamic recording latitude (the arguments for linearity in this domain have been made previously[6]).

The sharpness implications of these parametric changes are simple to calculate and express, depending no more than on geometrical detector-to-print considerations as expressed in Figure 1. In this example a prior sharpness index of *7* (somewhat below the normal range for reasonable-quality conventional photography) is replaced by a value of *8.2* (comfortably within range). This not surprising conclusion underlines the need for even further future increases in array size, although of course the assumption of smaller, say *3x5"* prints, would allow photographic sharpness criteria to be met.

The accompanying decrease in noise, according to the digital noise scale, is less intuitively obvious than that of sharpness. Figure 3 shows the old and new print-noise/print-reflectance characteristics, with *fine-grain* (*DN=3*) being replaced by *microfine* (*DN=1*). In other words, the fundamental noise level is now within the high-quality region of conventional photography (the independence of the noise over the operating print reflectance region is a desirable outcome of the overall scene-to-print mapping function).

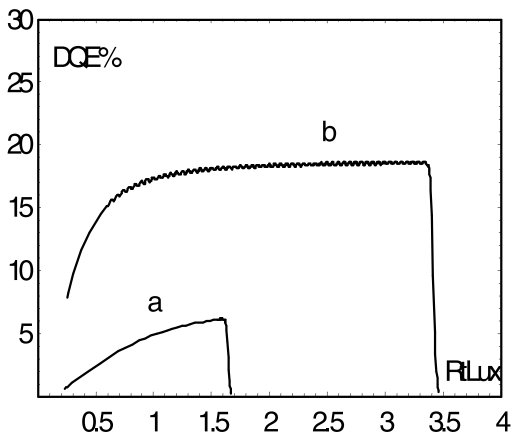


*Figure 4. The DQE-exposure characteristics corresponding to those of Fig 2.*

Finally, and perhaps of greatest significance, the changes in *DQE* characteristics are shown in Figure 4. In context we recall that according to this comprehensive overall measure, conventional silver-halide photography falls at best in the *1* to *3%* region, and then only within a very limited region of the exposure scale due to its inherently non-linear, single-level mode of detection. A value approaching *20%* for digital photography would open up hitherto inaccessible speed/grain regions of photographic space, which has translated in this example to the calculated *microfine* level of print noise. This would leave fundamental resolution/sharpness issues to be addressed separately via array-size considerations as already discussed.

## Conclusions

Some questions of the ultimate performance of digital photography have been addressed using an end-to-end systems-performance model. Reasonable simulations based on existing and potential technical sets of scene-capture and print parameters have indicated the capability of future advances that will open up new areas of overall photographic performance. In this respect the role of the primary quantum efficiency associated with scene detection and the size of the CCD pixel-array are definitive.

## References

1. "Towards the ultimate speed in photography" Conf. papers and summary, J.Phot.Sci., 9, 1961.
2. L. J. Thomas, "Photographic systems analysis" Procs Japanese Soc. Phot. Sci. & Tech. pp 291-313, Dec 1980.
3. R. Shaw, p 335, Procs IS&T 50th Ann Conf, 1997.
4. R. Shaw, p 165 Procs IS&T PICS Conf 1998.
5. R. Shaw, p31 Procs IS&T PICS Conf 1999.
6. R. Shaw, p 55 Procs IS&T PICS Conf 2000.
7. Ibid p71.

## Biography

The author received his PhD from Cambridge University. After several research and teaching positions in the UK and Europe 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 image processing and digital systems modeling. *rodshaw@hpl.hp.com*