Noise in Digital Cameras

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FOREWORD

Noise in the field of digital photography refers to a random discrepancy between the digital output of a photodetector on successive “shots” of the same exposure, or over the multiple photodetectors subject to the same exposure in a single “shot”. This article identifies the mechanisms of various contributors to this noise and how noise is quantified. It also discusses the closely-related matter of the dynamic range of a digital camera.

Extensive background is given in various important technical areas.

1 INTRODUCTION

1.1 “Shot”

Proper terminology would refer to the taking of a single photograph as an “exposure”. However, since the term “exposure” has two other important meanings in this article, I will use the more colloquial term, “shot” for the taking of a single photograph, to avoid any confusion.

2 QUANTIFYING NOISE

2.1 In electrical engineering

I’ll start with a parallel concept in electrical engineering. The instantaneous voltage of an sinusoidal AC-only signal (v) varies about zero, and has a mean (average) value of zero.

Its overall “potency” is quantified as the *standard deviation* of the instantaneous voltage. This is reckoned by taking the square of the instantaneous voltage, averaging that (taking its mean) over perhaps one complete cycle, and then taking the square root of that value.

Thus, this is actually spoken of in that field as the *root-mean-square* (RMS) measure of the voltage of that AC signal.

That measure is important because an AC signal with an RMS voltage of, say, 10V will create exactly the same average power in a certain resistive load as would a DC signal (which has a constant instantaneous voltage) with a voltage of 10V.

That happens because, instantaneously, the heat generated in that resistive load is proportional to the square of the instantaneous voltage.

If we had an unintended random discrepancy between the noted instantaneous voltage value of, say, an audio waveform, and its proper instantaneous value, due to some source of "noise", we isolate that noise, take its standard deviation, and report that as the *RMS voltage* of the noise.

And in fact, the perceptual impact of the noise to the "listener" is essentially proportional to the RMS value of the noise.

2.2 In digital imaging

Consider a delivered photographic image (on a print, perhaps) that is being viewed, and which contains a significant amount of noise. Broadly speaking, the viewer's perception of the "seriousness" of the noise in any region of the image is proportional to the ratio of (a) the RMS value of noise in the luminance of that region to (b) the average luminance, the signal-to-noise ratio (SNR), where noise is defined as he RNS value of the extraneous component).

So mathematically, this turns out to be the same notion as for the quantification of noise in an electrical signal.

3 THE ISO SETTING

3.1 Introduction

The "sensitivity" of the sensor system (that is, the inverse of how much photometric exposure is needed to cause a certain response by the sensor system) is controlled by what I will refer to as the "ISO setting" of the camera). This section gives some background on the meaning of that.

3.2 In film photography

The very same matter is of interest in film photography, where we recognize that the amount of photometric exposure required to produce a certain result (perhaps a certain density in the developed film) varies between different kinds of film.

If film B has a greater sensitivity than film A, then, for a given scene luminance, and using a lens with the same aperture, the shutter speed needed for a "proper" exposure with film B will be less than for film A. That is, film B responds "faster" than film A to the accumulating photometric exposure. Thus the sensitivity of film came to be known as its “speed”.

Many different schemes of quantifying film speed came into use. Eventually, the American Standards Association (ASA) developed a standard quantitative metric and a standard procedure for determining it. The “film speed’ (yes, that was the term) was to be expressed thus: “ASA 64”, and appeared thus on film boxes, film data sheets, and the like.

Corresponding work was none on other countries (notably Germany, although there the film speed was expressed differently).

Eventually these different standards were reconciled and consolidated in an international standard published by the International Organization for Standardization (ISO). The “ISO film speed’ (yes, that was the term) was to be expressed thus: “ISO 64”, and was to appear thus on film boxes, film data sheets, and the like.

3.3 In digital photography

As digital photography emerged, there was of course a comparable need to quantify the sensitivity of a digital camera’s imaging system. The definition used for the “ISO speed” of film could not be applied directly, so a new standard needed to be developed.

But one of the criteria for a new scheme, for digital cameras, was that the free-standing exposure meters operating, under to the ISO standards involved (including the ISO film speed standard) would still give the “appropriate” photography exposure recommendation with a digital camera.

The result was an ISO standard for determining and stating the sensitivity of a digital camera imaging system. but out of historical inertia, that measure was called the “ISO speed” of the digital camera.

3.4 Terminology

One of the controls on a digital camera is for the sensitivity of the imaging system. This was originally commonly in terms of the ISO speed. But rather than speaking of this setting as the ”ISO speed setting”, it became almost universal to speak of only as the “ISO”. This is of course not handsome since “ISO” by itself identifies an organization.

As a compromise with common ptacice, I will generally speak of this setting as the “ISO setting”.

3.5 Another metric

The underlying premise of the original ISO speed measure for film provided a “1/2 stop headroom”, in the case of a fictional “typical scene”, as a margin against overexposure when the scene was not “typical”. This of course carried through into the ISO speed definition for digital cameras.

But modern digital cameras are ordinarily operate with their internal automatic exposure systems, and these use clever techniques to avoid overexposure over a range of scenes. Thus it was attractive to “burn the headroom” in the interest of a more attractive photographic exposure setting for any scene.

However it was considered important that for, for example, an “ideal” test scene, the exposure recommendation of a free-standing exposure meter be the same as would be enacted by the camera’s internal automatic exposure system.

The only way to “burn the headroom” under this set of constraints was to have the ISO setting of the camera based on a lower value than would be determined as the “ISO speed” of the camera, for that setting, under the ISO standard—about “1/2 stop lower” (0.707 of the actual determined value).

That did not seem “proper”, so eventually the ISO added to the standard an alternative measure of the “sensitivity” of a digital camera, called the “ISO standard output specification” (ISO SOS), a different metric than the “ISO speed”.

And today, the sensitivity of a digital camera, set to a certain “ISO” number, will most often be the *ISO SOS* value, not the *ISO speed* value.

Note that my preferred term for this setting, “ISO setting”, accommodates this metric as well as the original “ISO speed” metric.

4 TWO KINDS OF NOISE

4.1 Introduction

Noise in a digital camera is of two general natures.

4.1.1 *Temporal noise*

This is a random variation in the digital output from a single photodetector in successive shots (which happen of necessity at different times, thus the name).

4.1.2 *Spatial noise*

This is a random variation over the outputs of multiple photodetectors all of which are subject to the same photometric exposure (as if regarding a uniform-luminance test target). This variation is *stationary*; that is, while random over the various photodetectors, the pattern would be consistent over exposures taken in succession.

5 SOURCES OF NOISE

There several sources of noise, each having their own mechanism, which collectively contribute to the two kinds of noise described just above.

5.1 Photon noise

5.1.1 *Introduction*

What be think of as a continuous "stream" of light of a certain fixed "potency" can also be recognized as consisting of a stream or particles called "photons". While it is tempting to assume that in the "constant light" case mentioned above that these arrive at a regular rate, in reality they arrive at random times, that being well-described by a statistical distribution called the Poisson distribution.

This kind of noise is often described as "shot noise", that term being taken from the name of the scientist Walter Schottky, who first completely characterized such nose (and coined that term himself).[1]

5.1.2 *Variation with luminance*

If, in a single shot, with a certain photometric exposure, the mean (over multiple shots) number of photons that strike a particular photodetector is N, then the standard deviation of N (and thus the measure f the noise in that exposure), σN is given by:

$$\sigma N = \frac{N^2}{\sqrt{N}} \qquad (1)$$

which can of course be written as:

$$\sigma N = \sqrt{N} \qquad (2)$$

[1] Sorry for the ambiguity between this use of "shot" and my other use of shot here to mean "the taking of a picture".

Thus as exposure increases, the photon noise increases, but more slowly than the exposure, so if we considered the signal-to-noise ratio (SNR) to only involve photon noise, it will increase with exposure (that is, the image will be less perceived as corrupted by photon noise with greater exposure).

5.1.3 *Variation with ISO setting*

Photon noise (as noted in the digital signal) increases in proportion ton the ISO setting (because that setting controls the amplification of the photodetector output before it is digitized, and of course the noise is amplified just much as the signal proper.

5.2 Read noise

5.2.1 *Introduction*

This in an umbrella term for the noise that appears in the course of observing, amplifying, and introducing to an analog-to-digital converter (ADC) the voltage that is developed by a photodetector as a result of its exposure during the shot.

5.2.2 *Variation with exposure*

At least to the first order, the amount read noise is not affected by the actual photodetector voltage (thus, by exposure).

5.2.3 *Variation with ISO setting*

The amplification is changed by changes in the ISO setting of the camera. Exactlty what effect those changes have on the magnitude of the read noise depends on the details of the organization of the amplifier chain and the input section of the ADC. All we can say for sure is that typically the read noise increase with an increase in the ISO setting.