The Exposure Triangle Is Not a Triangle: Two Settings Gather Light, and ISO Only Amplifies

— ISO $\mathbf{1600}$ at $\mathbf{1/1600}$ s gathers a sixteenth of the light of ISO $\mathbf{100}$ at $\mathbf{1/100}$ s, cutting the signal-to-noise ratio by a factor of $\mathbf{4.011105}$, while raising ISO gains only $\mathbf{1.049336}$-fold — graininess is set by the photons gathered — [Paper 595]

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— *From thinking to syncing.* —

Abstract

Photographic exposure is often explained as a “triangle” with aperture, shutter speed and ISO at its corners.What this paper shows is that only aperture and shutter speed set the amount of light, that ISO adds not a single photon but only amplifies the signal gathered, and that the graininess of a dark photograph is set not by the amplification but by the number of photons gathered.No new theorem or law is claimed. First, two settings alone set the light a pixel gathers——the number of electrons gathered is proportional to the time the shutter is open and inversely proportional to the square of the f-number; ISO does not change it (Section 2). **Second, and this is the core.Taking a photograph of the same brightness three ways, the signal-to-noise ratio is set by the light——ISO 100 at $1/100$ s gives $\mathbf{70.457486}$, ISO 1600 at $1/1600$ s gives $\mathbf{17.565607}$, and ISO 100 at $1/1600$ s brightened sixteenfold gives $\mathbf{16.739737}$** (Section 3). **Third, the loss from less light and the gain from higher ISO differ in size——cutting the light to a sixteenth costs a factor of $\mathbf{4.011105}$ ($\sqrt{16} = 4$ from photon noise alone), while raising ISO gains $\mathbf{1.049336}$, the difference in read noise alone** (Section 3). **Fourth, gathering more light raises the ratio by its square root——twice the light gives $\mathbf{1.416748}$ times, four times the light $\mathbf{2.005383}$ times** (Section 3). **Fifth, generating photons and read noise at random gives the same——the ratio estimated from 200000 samples, photons Poisson and read noise normal, agrees with the formula to a relative 1.2×10^{-3}** (Section 4). **Sixth, the separator is whether a setting changes the number of photons gathered or the amplification afterwards——aperture and shutter speed do the first, ISO the second** (Section 5). **Keywords**: exposure, ISO sensitivity, shot noise, signal-to-noise ratio, photography.

Scope of this paper (scope note): **No new theorem or law is claimed——photon (shot) noise, read noise and the signal-to-noise ratio that combines them are all standard.Only a mid-grey pixel is considered.The numbers are representative——5000 electrons at the reference exposure, read noise of 6 electrons at ISO 100 and 2 at ISO 1600 (a sensor whose input-referred read noise falls at higher ISO).Dark current, pixel-to-pixel variation, quantisation and noise reduction are not included.Depth of field and motion blur are not treated——aperture and shutter speed each have a second role, but this paper looks only at the amount of light.No equipment is assessed.Relation to earlier papers**: **Paper 312 showed that some noise falls when you measure longer and some does not, and set aside the noise figure of amplifiers in its scope note——shutter speed here is the "measure longer" side that lowers photon noise, and ISO takes the amplifier's seat that 312 left open.Paper 358 showed that the depth of depth of field is a convention, not a measurement, and set aside equipment in its scope note——this paper looks at another setting of the same camera.Paper 300 showed that sharing a root is decidable——aperture and shutter speed move the same quantity (photons gathered) and share a root; ISO has a different root.**What is added is **setting the signal-to-noise ratios of three ways to take the same photograph side by side**, **separating in numbers the loss from less light and the gain from higher ISO**, **checking the formula against random samples**, and **placing the separator on photons versus amplification**.

1. Notation and the Question

Setting: **the number of electrons N a pixel gathers is proportional to the shutter time t and inversely proportional to the square of the f-number N_f.The photon count fluctuates with standard deviation $\sqrt{N}$; with read noise of σ_r electrons added by the readout circuit,**

$$N \propto \frac{t}{N_f^2}, \qquad \mathrm{SN} = \frac{N}{\sqrt{N + \sigma_r^2}}.$$

ISO is an amplification that sets how large a number N is reported as; it does not change N itself.

> **Observation 1.1**
>
> **photographic exposure is often explained as a "triangle" of aperture, shutter speed and ISO.Move one corner and the other two can restore the balance——whether the three are quantities of the same kind is another question.**

Question: **when a photograph of a dark scene is grainy, is that because ISO was raised, or because the light was short?**

2. Gathering Light

> **Observation 2.1**
>
> **the light a pixel gathers is set by aperture and shutter speed alone.Opening the aperture admits more light; a longer shutter time gathers for longer——ISO only sets how many times the gathered electrons are counted, and adds not one photon to the pixel.**

3. Three Ways to Take the Photograph

Computation 3.1: **a photograph of the same brightness taken three ways (a mid-grey pixel, 5000 electrons at the reference exposure).**

method	electrons gathered	read noise	SN ratio
A: ISO 100, 1/100 s	5000.0	6.0	**70.457486**
B: ISO 1600, 1/1600 s	312.5	2.0	**17.565607**
C: ISO 100, 1/1600 s, brightened 16×	312.5	6.0	**16.739737**

Cutting the light to a sixteenth costs A/B = 4.011105 ($\sqrt{16} = 4$ from photon noise alone); raising ISO gains B/C = 1.049336.From the ISO 100 reference, twice the light raises the ratio 1.416748-fold and four times the light 2.005383-fold.

> **Observation 3.2**
>
> **this is the core.B and C gather the same light, and their ratios, 17.565607 and 16.739737, barely differ; A and B are photographs of the same brightness, yet their ratios differ fourfold——what sets the graininess is neither the brightness of the photograph nor the ISO, but the number of photons gathered. Raising ISO gains only the 1.049336-fold that comes from lower read noise in the circuit.**

4. Checking with Random Numbers

Computation 4.1: **as a route separate from the formula, 200000 samples were generated with photon counts Poisson and read noise normal, and the ratio was estimated from their mean and standard deviation (fixed seed).B gives**

17.546460 (formula 17.565607) and C 16.719687 (formula 16.739737), agreeing to a relative 1.2×10^{-3}.

> **Observation 4.2**
>
> the formula comes only from photons fluctuating one by one.Random samples, built from photon counts and read noise alone, give the same ratios——amplification multiplies both fluctuations by the same factor and leaves the ratio unchanged.

5. The Separator

> **Observation 5.1**
>
> the separator is whether a setting changes the number of photons gathered or the amplification afterwards.Aperture and shutter speed change the photon count; ISO changes the amplification——the three corners of the triangle are not of one kind: two gather light and one changes how it is counted.

> **Observation 5.2**
>
> taking the seat left by Paper 312.It showed that some noise falls when you measure longer and some does not, and set aside amplifier noise figures in its scope note——shutter speed sits on the “measure longer” side that lowers photon noise, and ISO sits on the amplifier side that 312 left open.

> **Observation 5.3**
>
> beside Paper 358.It showed that the depth of depth of field is a convention——this paper looks at the light side of the same camera. The aperture has two roles, depth of field and amount of light.

> **Observation 5.4**
>
> under Paper 300, aperture and shutter speed share a root and ISO does not.Aperture and shutter speed move the same quantity, photons gathered——ISO moves a different quantity, the amplification factor.

Observation 5.5

what is not said.No equipment is assessed. The numbers are representative, and sensors differ in read noise and in how it falls with ISO——what is shown is the form of the formula: graininess is set by the photons gathered.

6. Roll Call and Closing

1. **light is set by aperture and shutter speed alone** (Observation 2.1): **ISO adds no light.**
2. **ISO 100 at $1/100$ s gives a ratio of $\mathbf{70.457486}$** (Computation 3.1): **the reference.**
3. **ISO 1600 at $1/1600$ s gives $\mathbf{17.565607}$** (Computation 3.1): **a photograph of the same brightness.**
4. **less light costs a factor of $\mathbf{4.011105}$** (Computation 3.1): **4 from photon noise alone.**
5. **higher ISO gains $\mathbf{1.049336}$** (Computation 3.1): **the read-noise difference only.**
6. **brightening afterwards gives $\mathbf{16.739737}$** (Observation 3.2): **the core.**
7. **twice the light $\mathbf{1.416748}$, four times $\mathbf{2.005383}$** (Computation 3.1): **rising as the square root.**
8. **random samples agree with the formula to 1.2×10^{-3}** (Computation 4.1): **two routes.**
9. **ISO takes the amplifier's seat left by Paper 312** (Observation 5.2): **that is where it sits.**
10. **the separator is photons versus amplification** (Observation 5.1): **the corners are not of one kind.**

Closing: **Photographic exposure is often explained as a "triangle" with aperture, shutter speed and ISO at its corners.Only aperture and shutter speed set the amount of light——ISO adds not a single photon and only amplifies the signal gathered. Taking a photograph of the same brightness at ISO 100 and $1/100$ s and at ISO 1600 and $1/1600$ s gathers a sixteenth of the light, and the signal-to-noise ratio falls from $\mathbf{70.457486}$ to $\mathbf{17.565607}$, by $\mathbf{4.011105}$. Shooting the same $1/1600$ s at ISO 100 and brightening it gives $\mathbf{16.739737}$, so raising ISO gains only $\mathbf{1.049336}$-fold. Twice the light gives $\mathbf{1.416748}$ times and four times $\mathbf{2.005383}$ times, and random samples agreed with the formula to a relative 1.2×10^{-3}.The separator is whether a setting changes the photons gathered or the amplification afterwards——graininess is set not by ISO but by the photons gathered; under Paper 300 aperture and shutter speed share a root and ISO does not.Placed among the earlier papers——ISO takes the amplifier's seat that Paper 312 left in its scope note, and shutter speed sits on 312's "measure longer" side; depth of field, seen in Paper 358, is the aperture's other role.To be honest——only a mid-grey pixel is considered, the numbers are representative, and dark current, pixel variation, quantisation and noise reduction are not included. Depth of field and motion blur are not treated, and no equipment is assessed.**

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