Digital Camera Exposure Indices

Radu Corlan

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1 Introduction

The fundamental specifications of a digital camera (either CMOS or CCD) fully define it's response to light. For a camera with linear response, these are: *pixel size*, *responsivity* and it's spectral distribution, *full well capacity* and *readout noise*. Knowing these, and the amount and spectral distribution of light falling on the focal plane, it is possible to calculate both the magnitude and uncertainty (noise) of the camera's response to that light.

A photographer using the cameras is more likely to be interested in obtaining a good exposure index for the camera rather than intricate spectral and noise calculations. When evaluating cameras, it is desirable to express sensitivity by a single number.

An exposure index (ASA or ISO number) serves these two purposes: to guide the user in selecting a good exposure; and as a basis for camera comparisons. These two sides of the exposure index are sometimes conflicting.

The existing ISO standard for specifying digital camera sensitivity allows no less than three different ratings for a given camera. Furthermore, adjusting camera settings will change some of those ratings. So while useful for choosing exposures, one has to be careful when using ISO numbers for making camera comparisons.

This paper presents some methods used to give an ISO rating to digital cameras, and some of the measurement methods and assumptions behind these numbers.

2 Saturation-based sensitivity

The amount of light needed to just saturate the camera is a natural choice for a sensitivity specification. It has the advantage that is both unambiguous and reasonably easy to measure. A stable light source is pointed at the camera's focal plane. The exposure the camera gets is varied until the image just begins to saturate, either by varying the intensity of the light source or the exposure time of the camera. The product of the illumination produced by the light source and the exposure time is the *photometric saturation exposure* H_{sat}, which is measured in lux seconds.

2.1 Calculating the exposure index

Naturally, the exposure index is inversely proportional to the saturation exposure; the constant of proportionality determines the exposure index

Light Source	x	y	H_{sat}(lux·s)	S_{sat}(ISO)
3000K tungsten	0.443	0.417	0.0674	1157
D65-filtered tungsten	0.312	0.330	0.0507	1538
D65 LED	0.313	0.329	0.0486	1604

Table 1: Saturation exposure and saturation-based iso sensitivity for a color Phantom v7, using different light sources.

scale. The particular constant specified in the ISO12232:1998 standard is 78, so

$$S_{\mathrm{sat}} = \frac{78}{H_{\mathrm{sat}}} \tag{1}$$

This particular constant was chosen with the intention of keeping the ISO sensitivity scale for digital cameras in sync with the film exposure indices. When a scene is illuminated according to the ISO saturation-based speed, an uniform diffuse reflecting medium with 100% reflectance will generate a camera output that is 70% of saturation, assuming the camera has a linear response. Values above the 70% level constitute “headroom” for specular reflections etc.

An object with a reflectance of 18%, which is the accepted value for “average” scene reflectance, will then generate a camera output of 12.7% of saturation.

2.2 Spectral composition of the illuminant

The spectral response of most cameras differs from the spectral response of light meters, the CIE *photopic spectral luminous efficiency function.* Because of this, the color and spectral composition of the light source will affect H_{sat} and the exposure index. The difference can be significant, especially between light sources of markedly different color temperature (e.g. tungsten vs. daylight), as shown in Table 1.

2.3 Adjusting the exposure index

Saturation-based exposure indices can be varied by adjusting the dynamic range of the camera. If the top half of the dynamic range is discarded while the lower half is “stretched” to fill the whole output range, the EI for the camera is doubled, and so on — same thing as applying gain in the camera.

The image quality decreases as more gain is applied.[1]

2.4 White balance

When color imagers are used, the red, green and blue channels will generally have different sensitivities that are dependent on the color temperature of the light used. H_{sat} is then defined as the light level at which the first channel begins to saturate. In general, this will be lower than the saturation point for light that matches the native white balance of the camera. The saturation-based exposure index increases when large white-balance compensation gains are required.

3 Noise-based sensitivity

With most cameras, the best image quality is obtained by exposing to a camera's lowest sensitivity setting. However, in many cases the amount of light avalable is limited, so it is desired to use a lower exposure. As shown above, the saturation-based exposure index can be adjusted by reducing the camera's dynamic range, with a corresponding increase in image noise.

The obvious question is how much can EI be increased before the image is degrades "too much". And what would a good way of measuring and specifying this be.

3.1 Image signal and noise

Let's take a uniformly-reflective surface (for example a 18% gray card, which is representative for the "average" scene reflectance). We illuminate it and take a picture of it with our camera.

The average level of the image across the card's surface minus the black level of the camera is the "signal", which of course varies with illumination.

If we now take several successive pictures of the same card, taking great care to keep everything else (illumination, exposure, distance) constant, we will find out that values of individual pixels change between images — the effect of noise. To measure the noise, we measure the standard deviation of the value of each pixel on the card across the several images; we obtain the *rms temporal noise* of each pixel, which we then average across the card's surface to obtain a single number for "noise". If we repeat the above

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[1] Most still photography digital cameras set their ISO sensitivity this way. In many cases, after the first 2-3 stops of gain, increasingly aggresive noise-reduction algorithms are applied on the image.

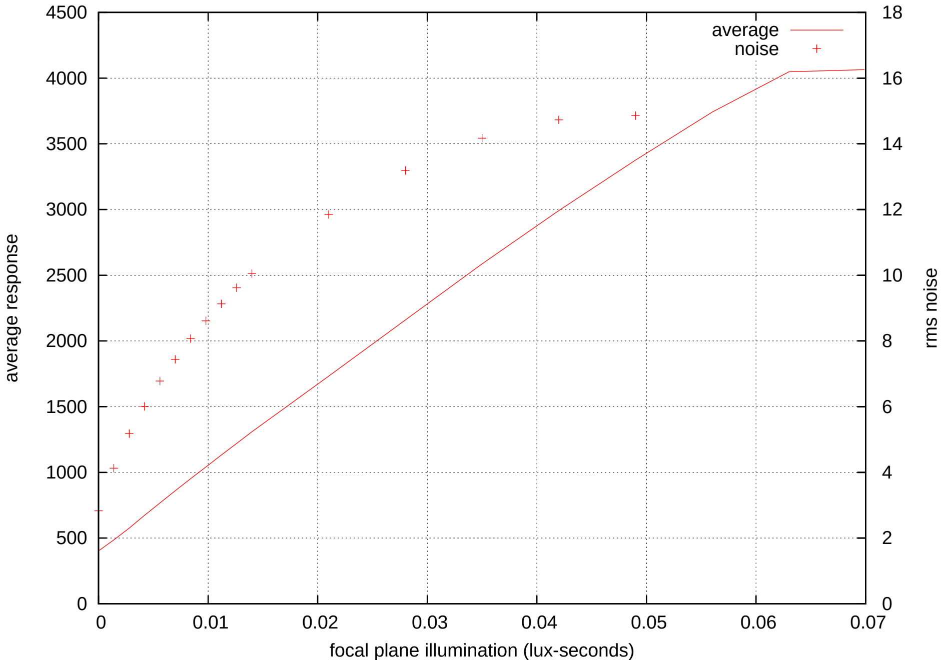

Figure 1: Response and noise of a monochrome v10 vs focal plane exposure levels.

at different illumination levels, we will find that noise also changes with illumination.

A typical plot of average response and noise for a Phantom V10 mono is shown in Figure 1. We see that the response saturates a bit above 0.06 lux·s.[2] The dark level is at 400 counts, so the saturation signal is 3696 counts. Noise in the darkness, also called *readout noise* is 2.8 counts.[3] Noise increases as the square root of light level, which is characteristic of *photon shot noise* limited cameras.

3.2 Signal to Noise Ratio

A related plot is shown in Figure 2. This plot shows the ratio of signal (camera response minus black level) to noise for different illumination levels. Using this graph, we can determine the minimum exposure we need in order to capture a given object with the desired signal to noise ratio.

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[2] This translates into a saturation-based ISO at 1300.

[3] The dynamic range of this particular camera is 1320:1, or 62.4 dB

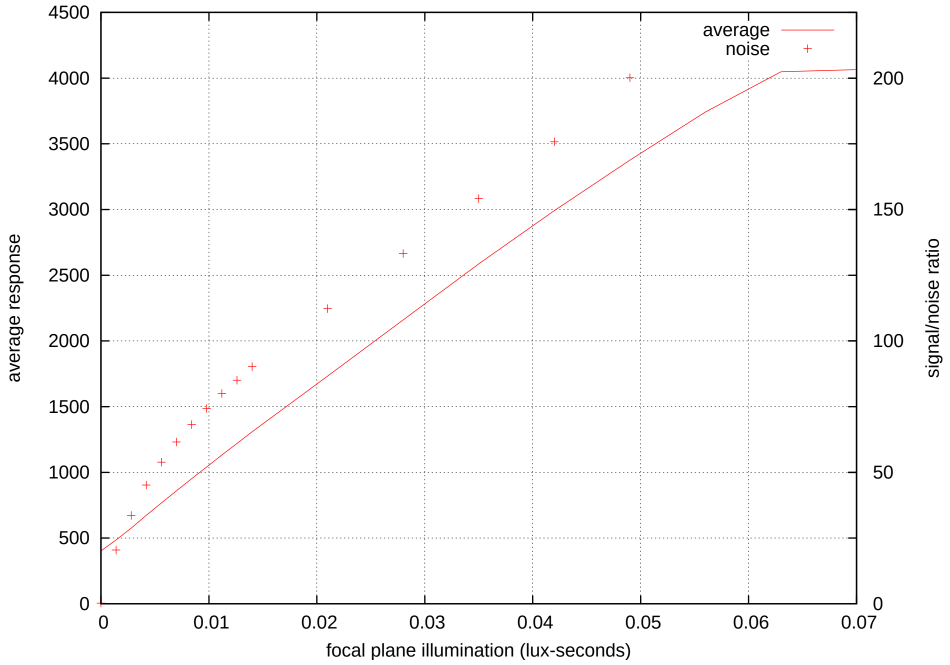

Figure 2: Response and SNR of a monochrome v10 vs focal plane exposure levels.

To establish a noise-based exposure index specification, it is necessary to decide what object to use as a reference, and what would the desired SNR be. The choice obviously depends on the application.[4]

For general photography, the ISO 12232:1998 standard specifies two SNR levels, both for the imaging of a 18% gray card: A SNR of 40 for "excellent quality" images, and a SNR of 10 for "first acceptable quality" images. These specifications were based on subjective experiments.

Knowing the focal plane exposures required for these levels of SNR, H_{noise40} and H_{noise10}, the corresponding ISO numbers are calculated using the following formula:

$$S_{\text{noise}} = \frac{10}{H_{\text{noise}}} \tag{2}$$

For our example camera, $H_{\text{noise40}} = 0.004$ and $H_{\text{noise10}} = 0.001$, so the two noise-based ISO numbers are 2500 and 10000 respectively.

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[4] As an extreme example, detecting the mere presence of a white rectangular object 10 pixels square on a black background requires a SNR of only 0.3 for a 0.1% error probablity.

4 Sensitivity of a v7.3

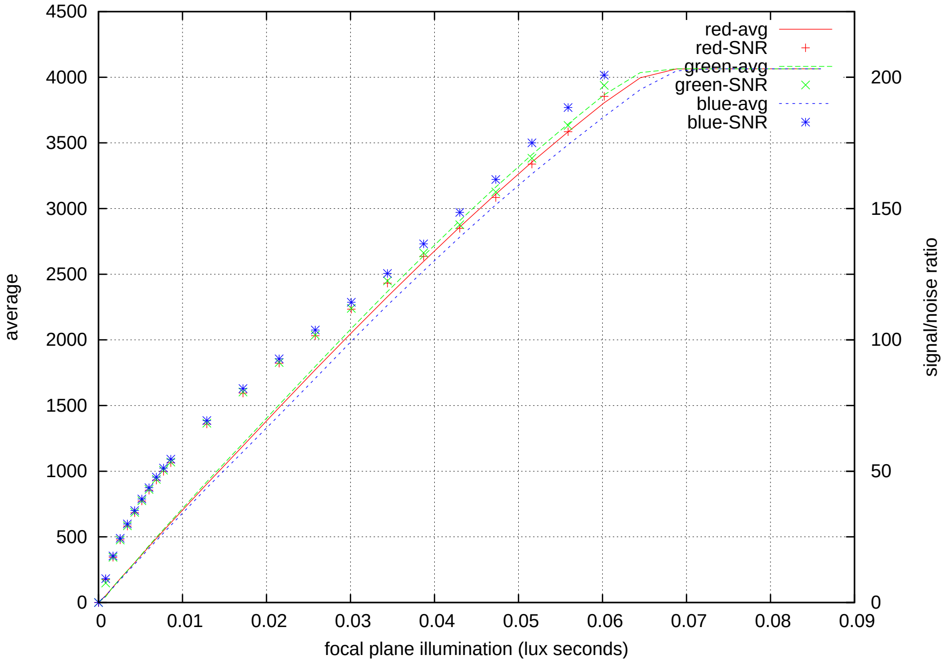

Figure 3: Response and SNR of a color V7.3 vs focal plane exposure levels.

ISO sensitivity	Method	SNR (18% gray)	Overexposure latitude
1200	Saturation	52	0.5 stops
1800	Noise	40	1 stop
2800	Noise	30	1.5 stops
5000	Noise	20	2.5 stops
11000	Noise	10	3.5 stops

Table 2: Summary of ISO numbers for a color Phantom v7.3

As a second example, we present the response and signal-to-noise measurements of a color Phantom v7.3. Figure 3 shows the response from darkness to saturation. The responses of the red, green and blue channels are quite similar, which implies that the light source matches the camera's natural white balance. The saturation exposure is 0.065 lux seconds, which gives a saturation-based ISO rating of 1200.

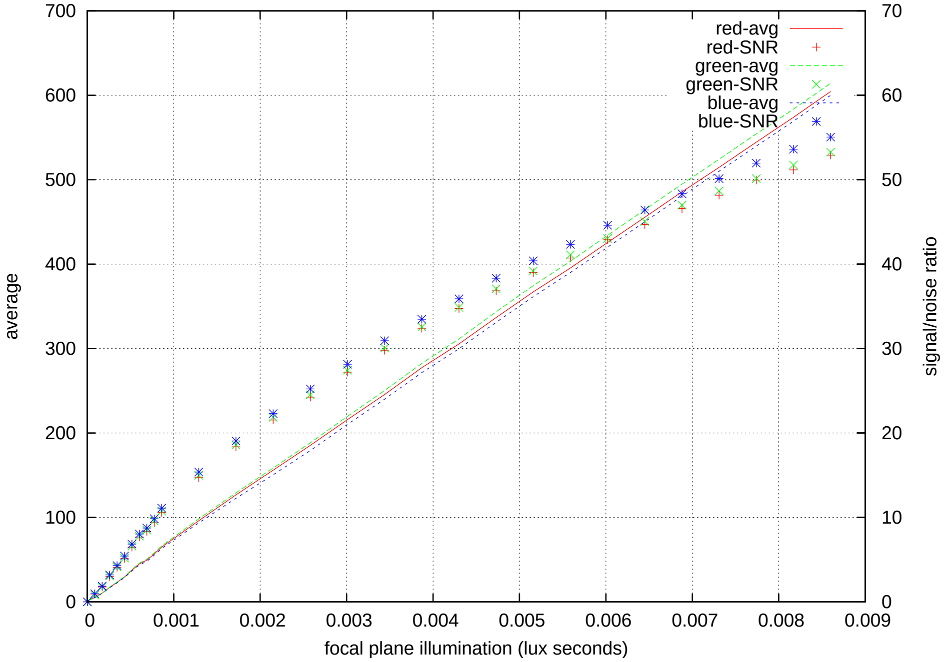

Figure 4: Low light Response and SNR of a color v7.3.

A second graph, shown in Figure 4 expands the response at low light levels, so that the exposure levels for low SNR values can be readily read. H_{noise40} is 0.0055 and H_{noise10} is 0.001, so the two noise-based ISO numbers are 1800 and 10000 respectively. Results are summarised in Table 2.

5 Conclusions

Two methods for determining exposure indices for digital cameras have been presented. The saturation-based method has the advantages of relative simplicity and general aplicability. It does not take into account variations in image quality. Noise-based determinations of sensitivity are more elaborate, but provide more insight for choosing an appropiate exposure for a given application.

It should also be apparent that it is not trivial to assign a single EI number to a digital camera; widely different values can be equaly "true".

Table 3 summarises possible ISO sensitivity specifications for a monochrome Phantom v10. The values were calculated using the methods described in

ISO sensitivity	Method	SNR (18% gray)	Overexposure latitude
1300	Saturation	65	0.5 stops
2500	Noise	40	1.5 stops
3700	Noise	30	2 stops
7200	Noise	20	3 stops
10000	Noise	10	3.5 stops

Table 3: Summary of ISO numbers for a monochrome Phantom v10

the ISO 12232:1998 standard, based on the SNR plot in Figure 2.

In addition to the ISO numbers and associated SNR values, the table shows the overexposure latitude afforded by each setting. Even when light is abundant, it is not clear that the "highest quality" EI of 1300 is better than the "excellent quality" EI of 2500. The increase in SNR from 40 to 65 is hard to even notice, and the latter setting is less prone to clipping the highlights. Lower exposures could be used in low-light, high dynamic range situations.

It should be noted that in order to take advantage of the higher dynamic range at low exposures, the camera must reach it's readout noise specification while capturing the full dynamic range (gain set to minimum). This implies that the image is saved using a large enough bit depth (at least 10 bits, prefferably 12). Applying gain before the image is saved does allow an increase in EI, but at the expense of overexposure latitude.

6 Sample Images

The images on the following pages illustrate the increase in noise that accompanies an increase in exposure index. The images were taken with the same v7.3 camera characterised in section 4. To obtain the images, the camera and lighting setup was kept fixed. Between two successive pictures, the lens was closed by one f-stop, except between the first two images, when the difference has been 1/2 stop. The images were "stretched" so they span the full output range. Unless otherwise noted, no noise reduction has been applied.

Figure 5: V7.3 color exposed for ISO 1200. Signal to noise ratio of the 19% gray patch (third from the right) is 60. Overexposure latitude is zero. With naturally-balanced light, at this EI the overexposure latitude would be 1/4 stops; however, balancing the for the test lighting (daylight) used up that latitude.

Figure 6: V7.3 color exposed for ISO 1400. Signal to noise ratio of the 19% gray patch (third from the right) is 47. Overexposure latitude is 0.5 stops. This would be the saturation-based iso setting when white-balanced for daylight.

Figure 7: V7.3 color exposed for ISO 2800. Signal to noise ratio of the 19% gray patch (third from the right) is 30. Overexposure latitude is 1.5 stops.

Figure 8: V7.3 color exposed for ISO 5600. Signal to noise ratio of the 19% gray patch (third from the right) is 18. Noise beging to be apparent on the darker patches. Overexposure latitude is 2.5 stops.

Figure 9: V7.3 color exposed for ISO 5600. This is the same image as the previous one, with a small amount of color noise reduction applied (20 in Adobe Camera Raw$^{\mathrm{TM}}$). Image sharpness is not affected, and noise is less noticeable.

Figure 10: V7.3 color exposed for ISO 11000. Signal to noise ratio of the 19% gray patch (third from the right) is 10. This is the “first acceptable” illumination level. Overexposure latitude is 3.5 stops.

Figure 11: V7.3 color exposed for ISO 11000. This is the same image as the previous one, with color noise reduction applied (33 in Adobe Camera Raw$^{\text{TM}}$). Image sharpness is not affected, and noise is less noticeable.

Figure 12: V7.3 color exposed for ISO 22000. Signal to noise ratio of the 19% gray patch (third from the right) is 4. Overexposure latitude is 4.5 stops.

Figure 13: V7.3 color exposed for ISO 44000. Signal to noise ratio of the 19% gray patch (third from the right) is 2. Overexposure latitude is 5.5 stops.

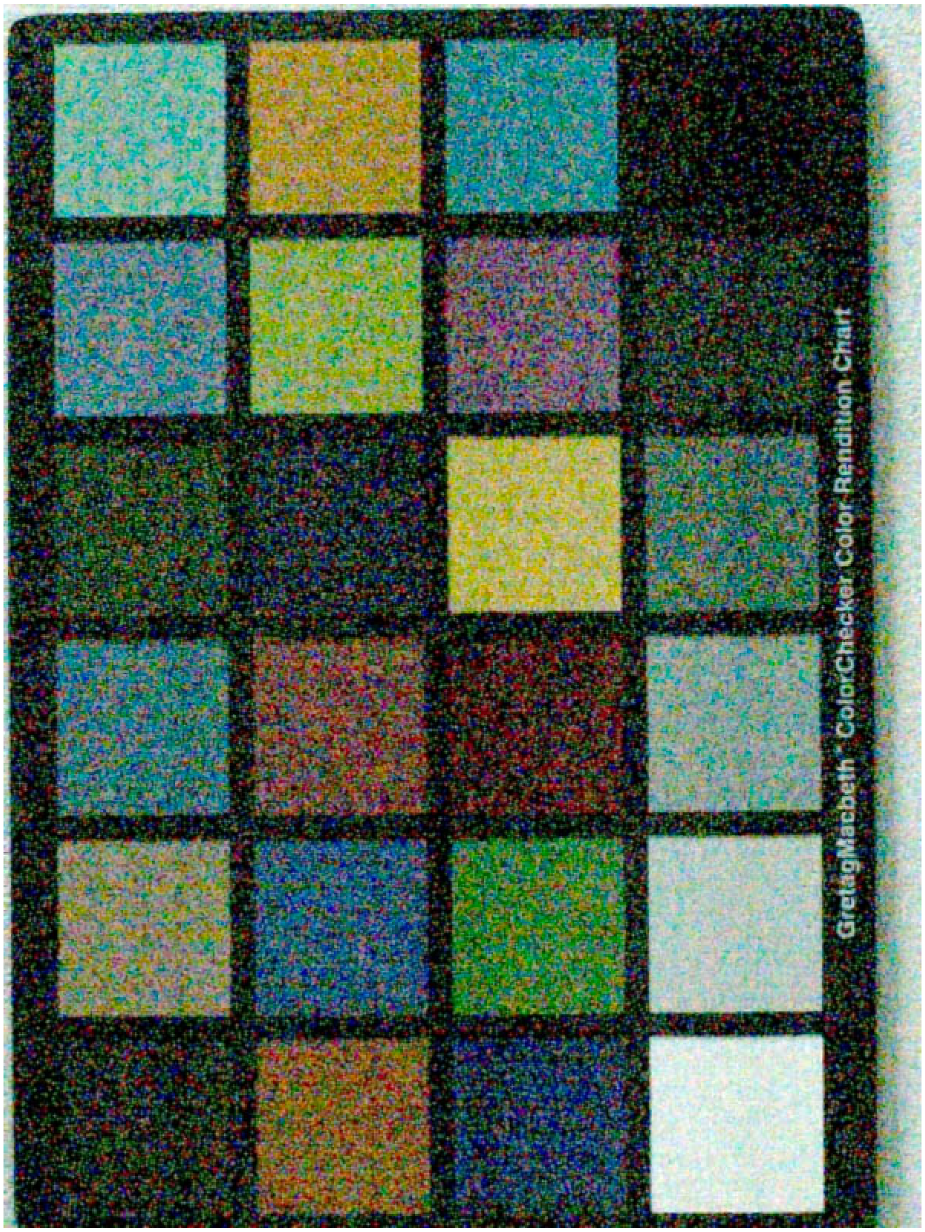

Figure 14: V7.3 color exposed for ISO 88000. Signal to noise ratio of the 19% gray patch (third from the right) is 1. Even at this high noise level, the contour of the patch can be easily discerned. Reading the small text on the chart is easy. The 9% patch (second from the right) reflects only 1/900 of the light needed to saturate the sensor.