Camera Dynamic Range (DR)
and Signal to Noise Ratio (SNR)

There are several ways to view dynamic range (DR). At base ISO the sensor can record the highest useful value or signal. If we increase the exposure we will pass the "full well" capacity of the sensor.

The useful range means that we can easily get a linear response from the sensor as we reduce the exposure. Once the signal is no longer proportional to the amount of light being recorded the camera is at its maximum analog limit. The bottom of the analog range might be a way to define the DR.

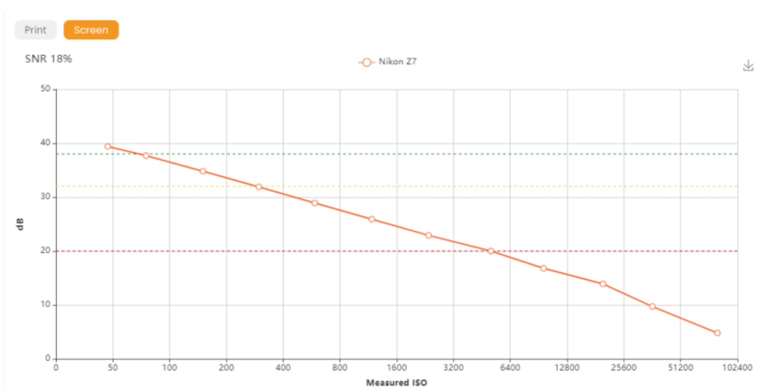
With the lens cap in place, there will be no useful signal, only dark current or residual noise. By the time we reach that level we will probably have passed the point where a linear response is possible. We could also define DR based on that lower limit but by then the amount of noise will be quite visible.

The level of visible noise we can tolerate is subjective. So we can also define DR as the range from the brightest to the darkest image that is, not only linear, but also above the noise level that is acceptable.

Each of these definitions of DR is different but they all start at base ISO. Increasing the ISO does not change the DR of the camera.

When we raise the ISO setting above base we no longer record the largest possible signal. To keep the digital value from exceeding the binary upper limit (16383 for a 14-bit raw file) the exposure needs to be limited. This reduces the signal and amplifies the noise. The signal to noise ratio drops.

Many of us use measurements compiled by DXOMARK (DXO) to see how a camera reacts to changes in ISO. Here is an example for the Nikon Z7:

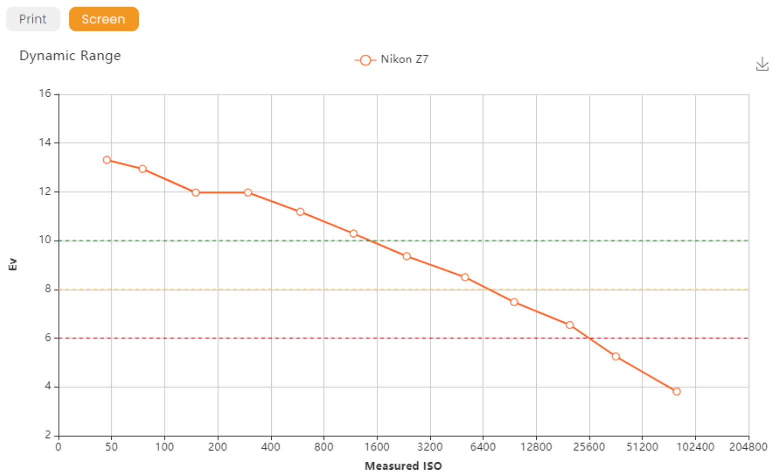


[1]

The vertical scale is in decibels (dB). Note that the change in SNR is almost linear.

But SNR is not the same as dynamic range. It is the ratio of the signal, in this case 18% gray (EC+0), to a particular level of noise. If we know the signal that produces 18% gray (close to raw 1024 at base ISO or 2^10) then we can calculate the noise at that level.

A DR plot shows similar results but the vertical scale is in base 2 logarithms, Ev.



2

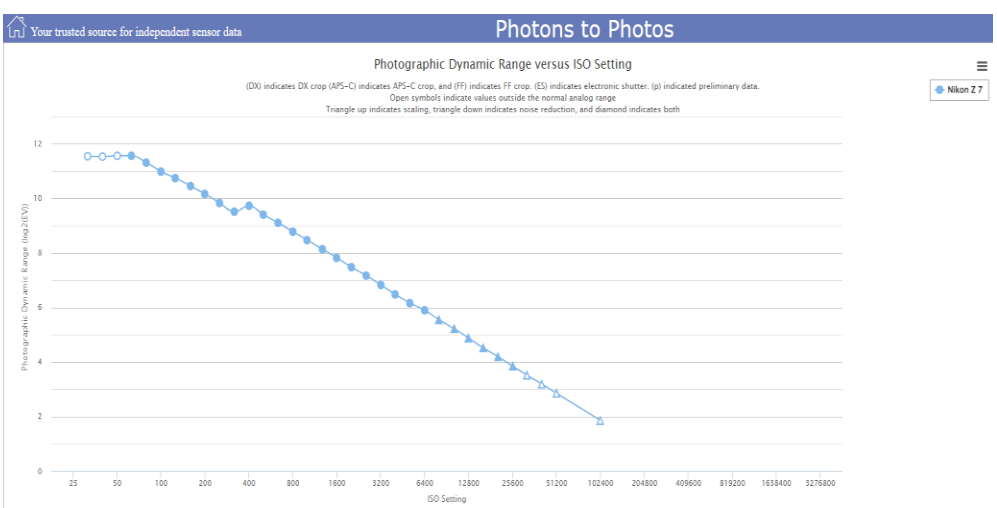
The dB and Ev scales are directly proportional, 1 Ev equals 3.0103 dB.

This appears to show that something is happening in the camera due to a change in how the gain is handled for low and high ISO ranges. But this gain change is not reflected in the SNR plots. It does not affect the signal or the noise used for SNR.

The horizontal scale shows a progression of ISO steps. The DXO label is "Measured ISO"for the plotted points. The manufacturer's ISO is actually higher. The relevance of DXO 's measured ISO is not clear.

There is also something different about the two DXO DR plot for the Z7. It is not strictly linear. It has a break in continuity between ISO 200 and 400.

A more precise presentation of DR can be found at [Photons to Photos] (P2P) which displays values in 1/3 stop increments. The dynamic range is calculated a little differently. The points are plotted at the manufacturer's ISO setting. The solid points are for the normal analog range. Open points above or below the normal range are manipulated to artificially extend the results.



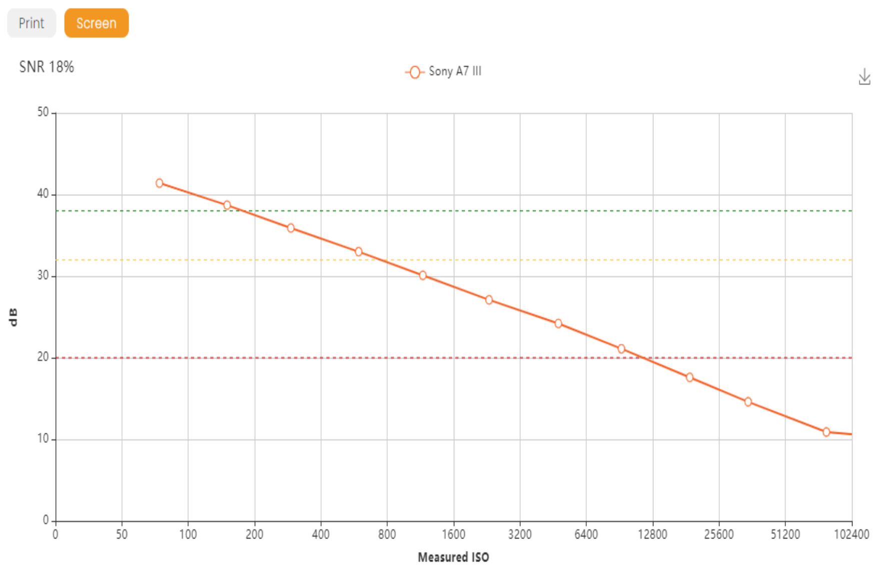
3

The P2P plot narrows down the break in linearity to between ISO 320 and 400.

The information displayed by P2P is based on data compiled by DXO.

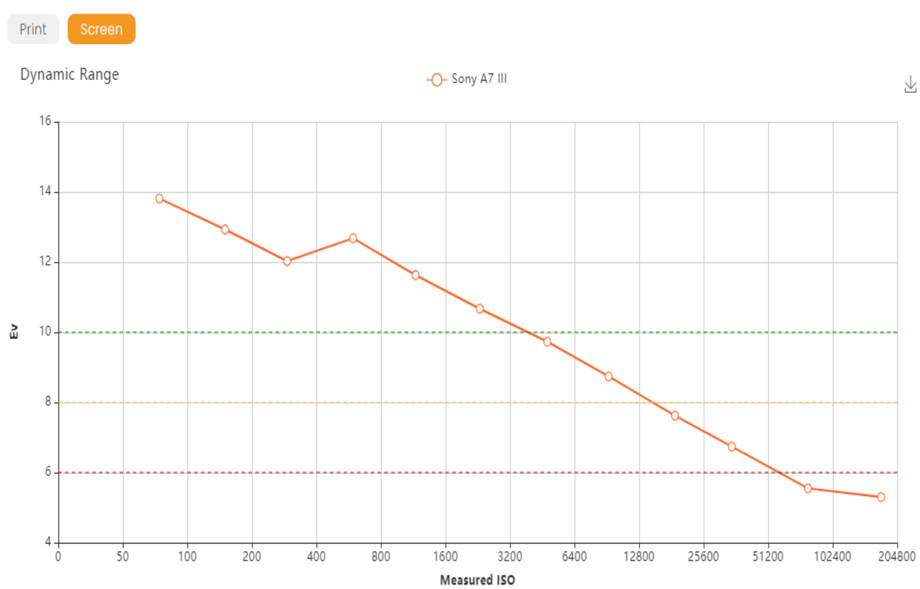
P2P also provides a wealth of information about what is happening under the covers as the information recorded by the sensor is saved as a digital record.

Here is another example for a Sony A7 III:



4

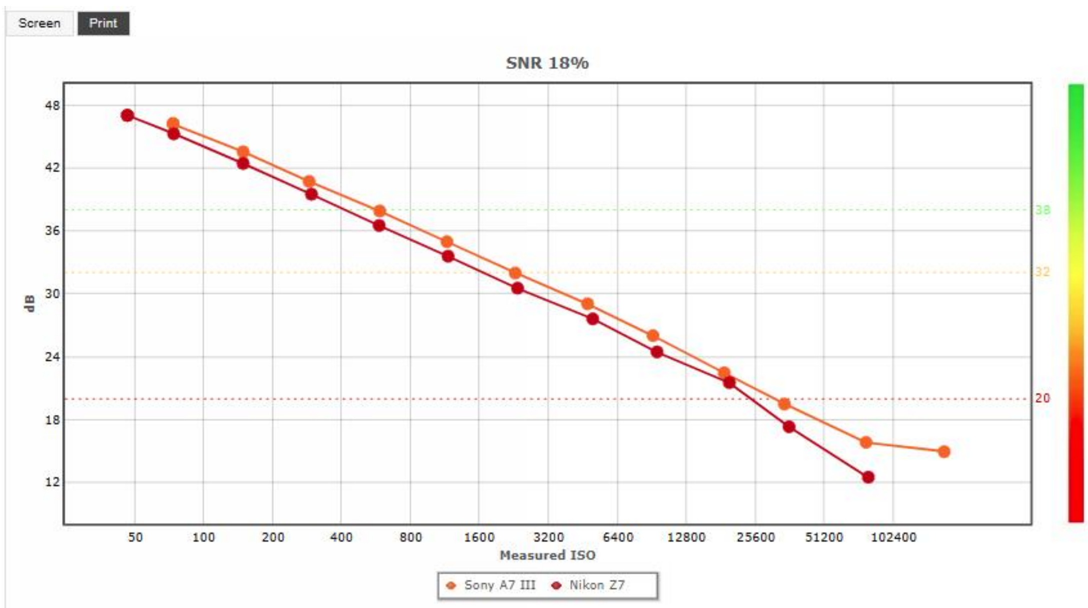
There are no discontinuities in the SNR plot. Since both the signal and SNR lines are straight, the noise line must also be straight, almost constant. Nevertheless:



5

The DR plot might show a discontinuity for cameras with dual gain processors.

The primary purpose of these plots is to provide a simple way to compare the performance of two or more cameras. Here are two comparisons from for the Nikon Z7 and the Sony A7 III. By selecting the "Print" tab the cameras with different resolutions can be fairly compared.



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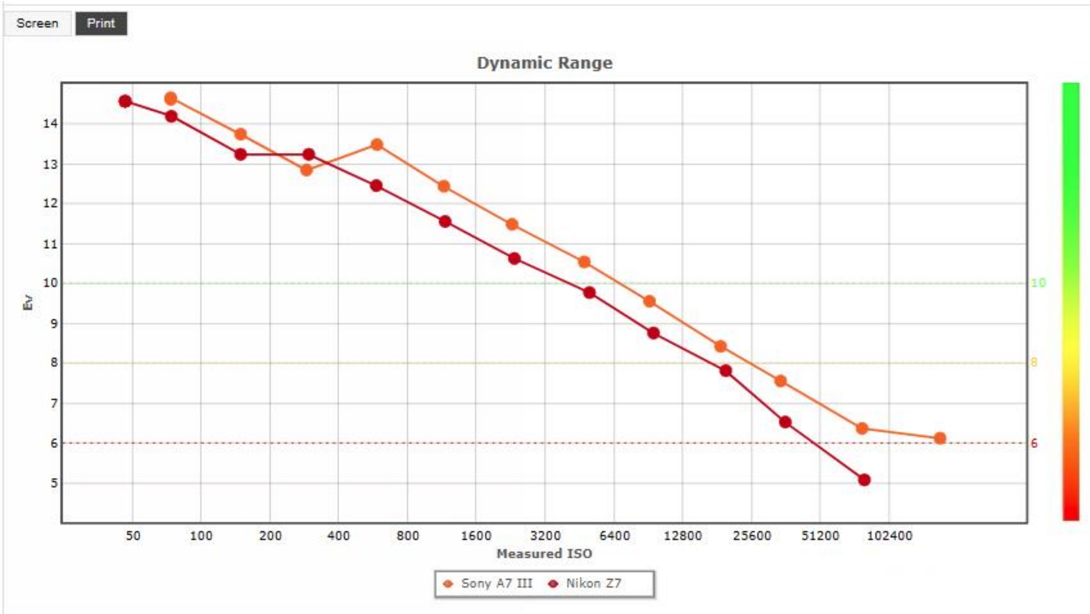
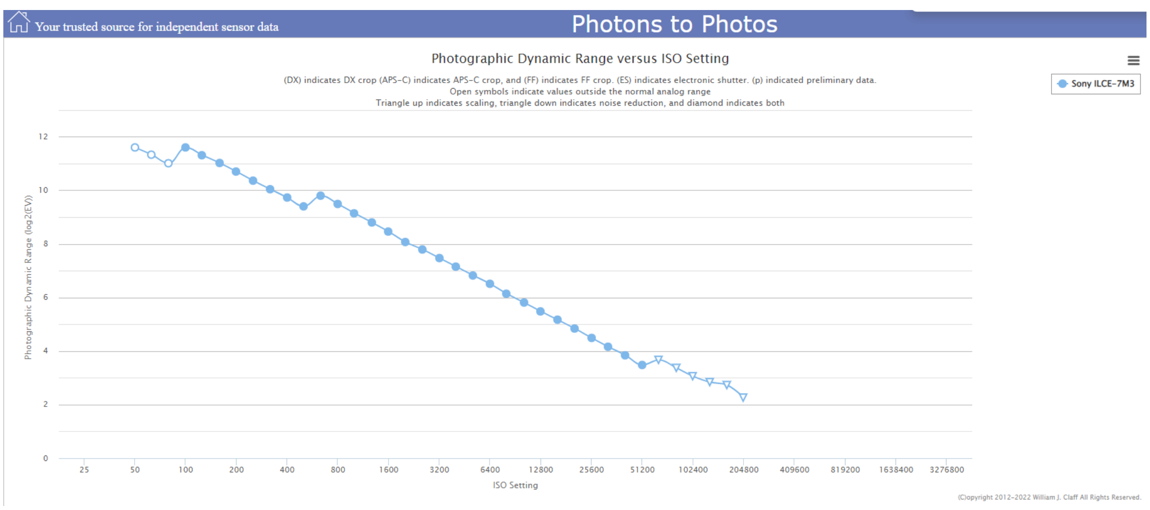
The 24MP Sony clearly shows a better SNR performance than the 45MP Nikon.

But the DR comparison shows something different:



7

Here is the DR information from P2P for the A7 III:



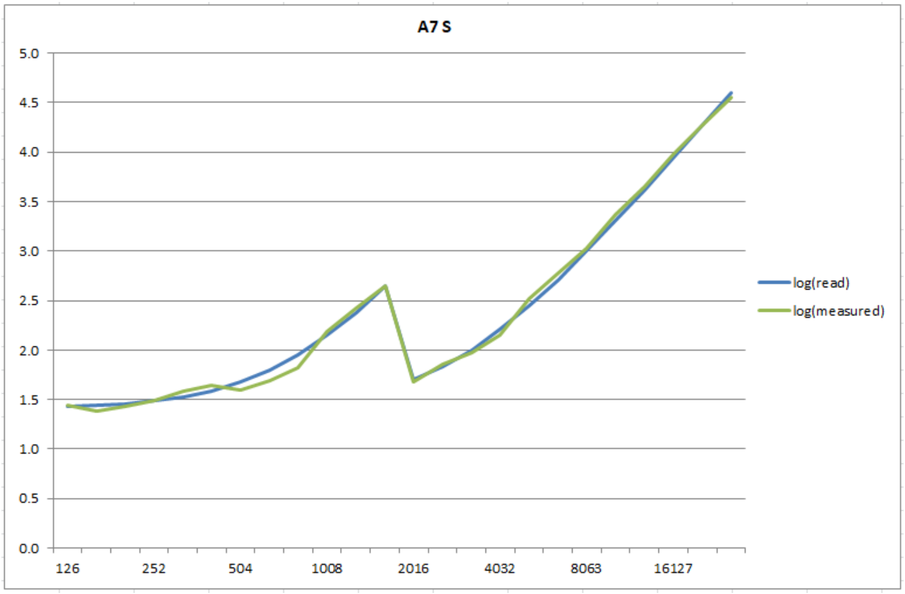
8

In P2P the discontinuity happens between ISO 500 and 640.

P2P only shows DR, no SNR information. The P2P definition of DR is not the same as DXO's.

A sudden change in read noise may not translate into a discontinuity in the DR. As an example, see [Sony A7S DR-Pix Read Noise (photonstophotos.net)]

The article illustrates how read noise changes between ISO 1600 and 2000.



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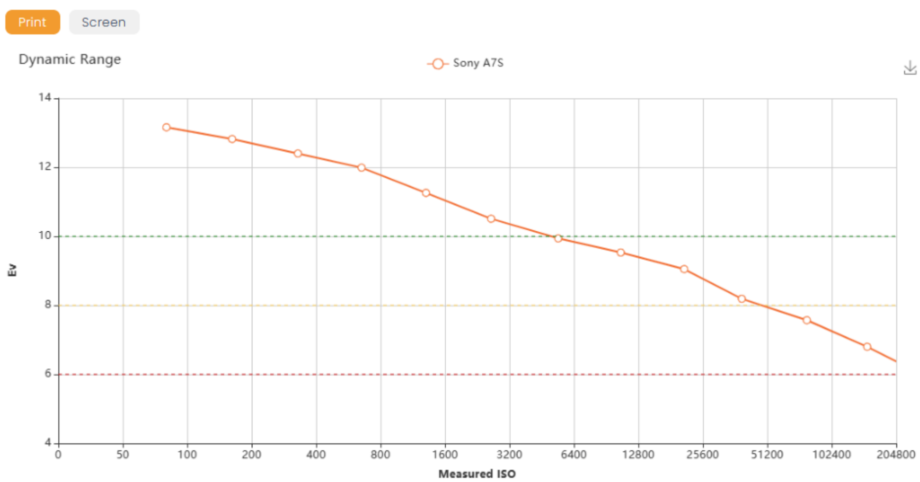
Yet DxO does not show a significant discontinuity.



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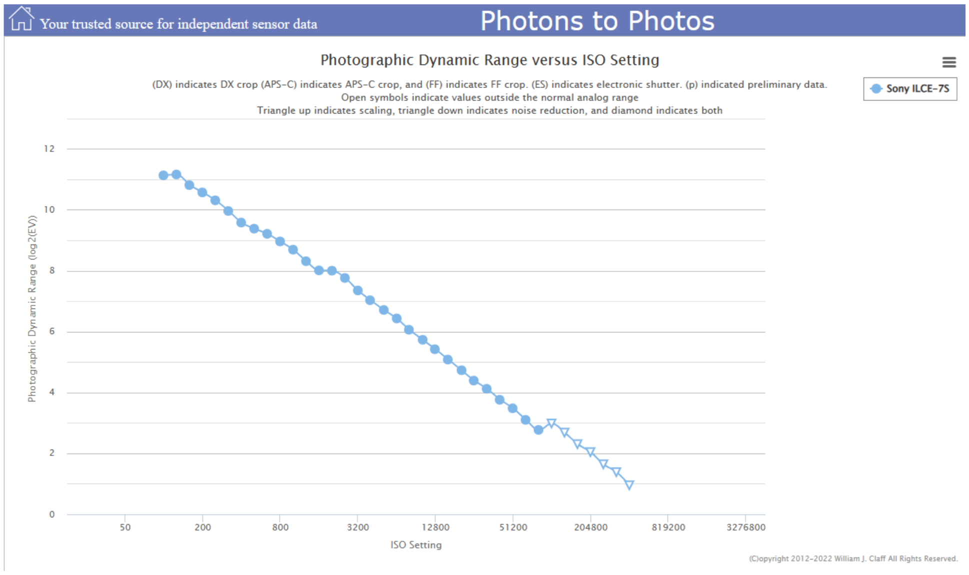
The DXO data is used by P2P.



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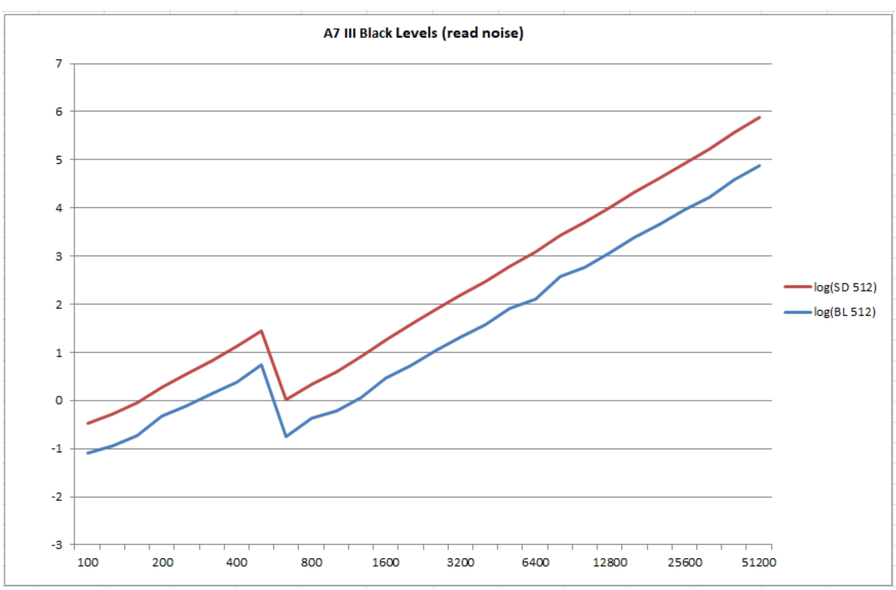
The large change in read noise does not result in much change in DR.

Reason for Discontinuities in the DR Plots

The explanation for the discontinuities shown in DR for the Z7 and the A7 III is that both cameras use dual gain sensors with a different gain for low ISO settings than for high affecting the read noise.

There are no discontinuities in the SNR plots or in the actual final values stored in the raw file. They only appear in the original DR plots.

But the black noise shows a distinct change where the gain is switched in the camera. The black noise is measured with the lens cap in place and the camera shielded from light.



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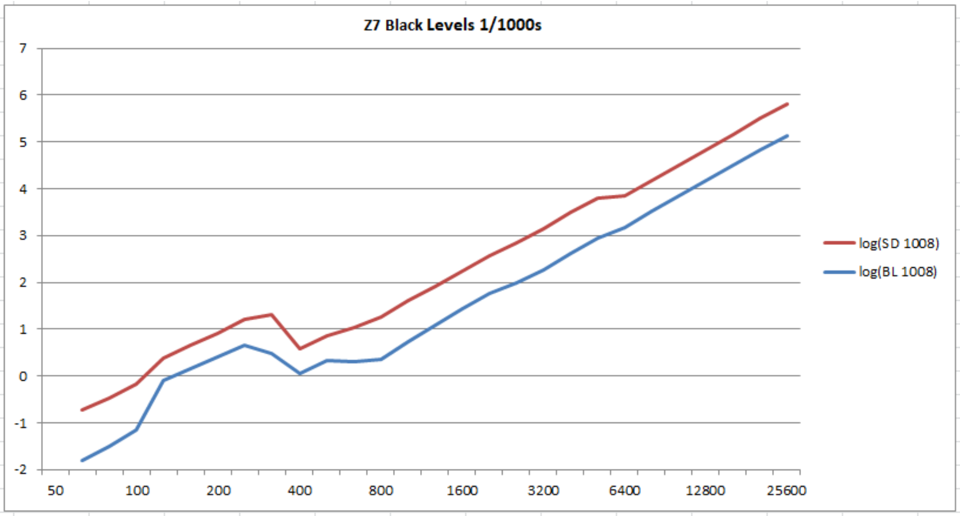
The change is also visible for the Z7. It's smaller but there are also some peculiar things happening at other places on the lines.



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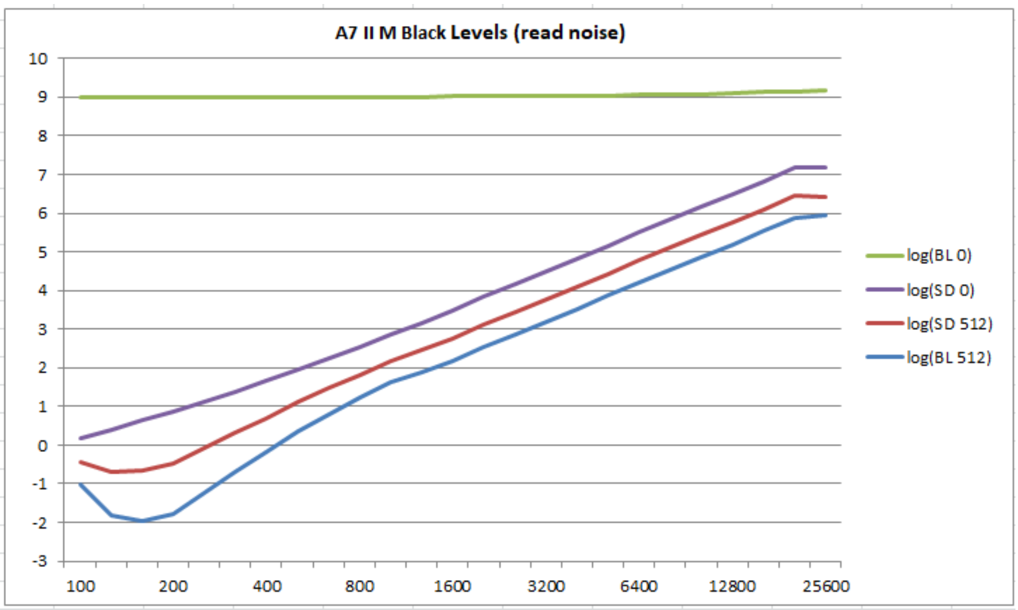
We can see why DxO and P2P DR plots display discontinuities.

Here is a plot for the A7 II which does not use dual gain.



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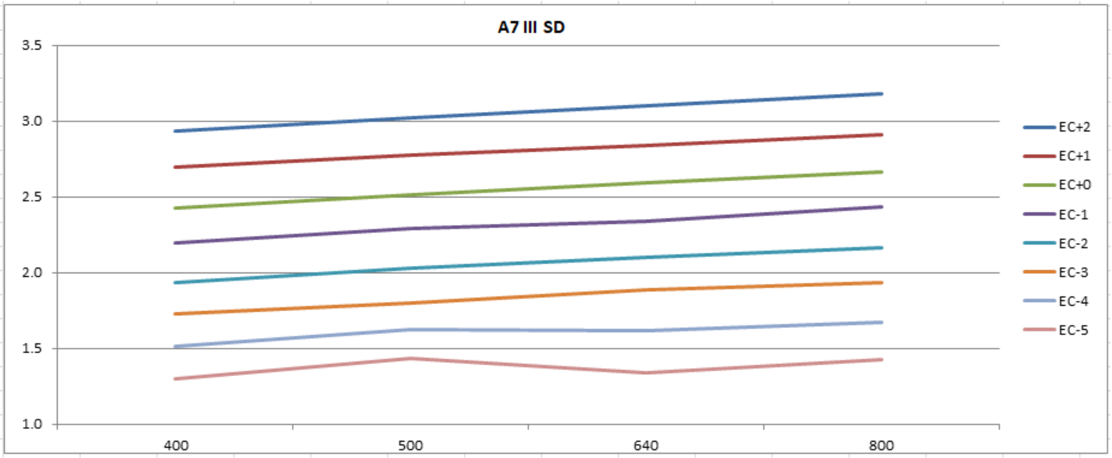
There is no discontinuity but there is something else happening at the low ISO range. The SD value is higher than the average value after subtracting 512 for the black level. The distribution of noise around the average is not a normal SD bell curve because the raw values (not the log values) cannot go below 0.

By over and underexposing the target we can obtain these results to plot of the SD for the A7 III:



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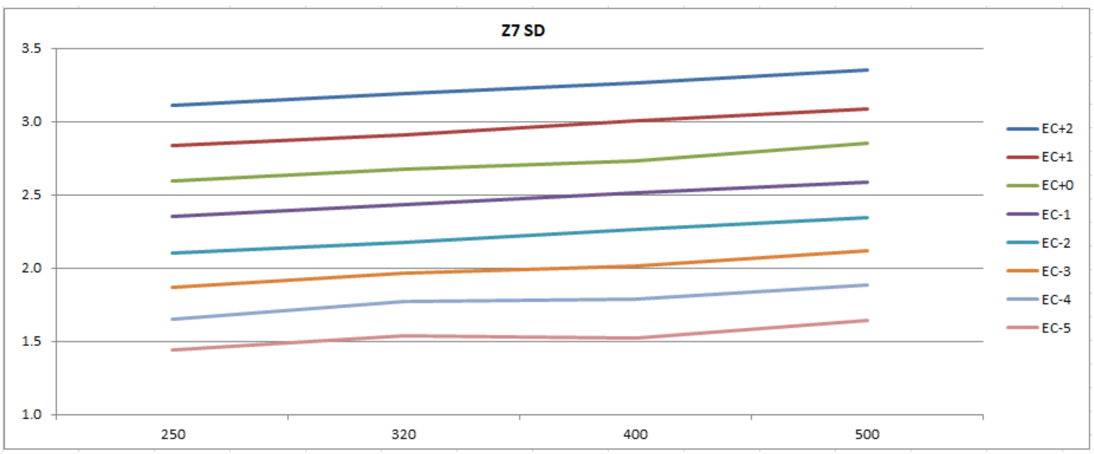
It’s harder to show for the Z7:



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These are plots of the standard deviations. Discontinuities do not show up in a plot of the signal.

In both cameras the DR does not show a significant discontinuity until EC-5. That’s five stops lower than middle gray. There are still about 3 stops above middle gray before the raw highlights blow out. Since each stop represents a range of +/- ½ of a stop this covers an overall range of nine stops.

We don’t reach the black level itself until EC-9. At that level the image contains nothing of value.

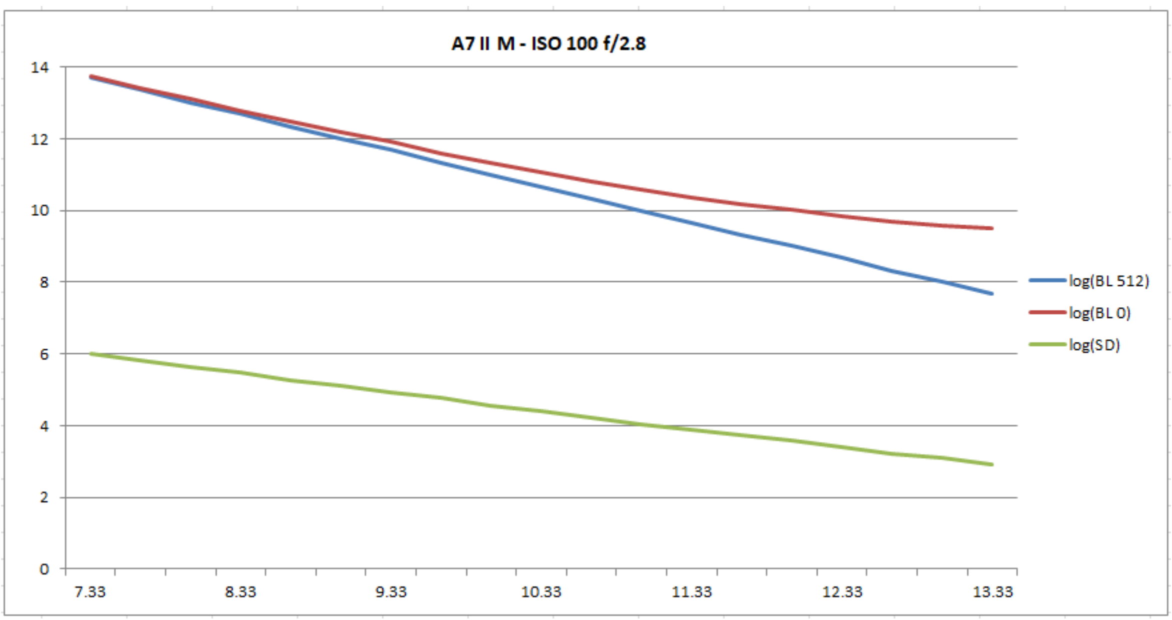
Even at EC-5 the unadjusted image is almost pitch black. It is only during shadow recovery that the really low raw values can be lightened enough for the noise to be seen. But the problem with shadow recovery is that it lightens everything else below middle gray proportionately.

Signal to Noise Ratio

We can plot the raw values at base ISO while varying the exposure, converting them to base 2 log values.

ISO 100 f/2.8	LV	ss
1	7.33	20.16
2	7.67	25.40
3	8.00	32.00
4	8.33	40.32
5	8.67	50.80
6	9.00	64.00
7	9.33	80.63
8	9.67	101.59
9	10.00	128.00
10	10.33	161.27
11	10.67	203.19
12	11.00	etc.

Here is a plot of raw values for the A7 III.



The log(SD) shows the standard deviation for the exposure values.

The log(BL 0) represents the sensor recorded levels including the black level over a six stop range.

The black level is not the same as the dark noise which is measured with the lens covered.

BL is an arbitrary integer used to facilitate the recording of dark values with more precision than would be possible if they were stored directly. For example, the two A7 bodies use a BL of 512 (2^9) and the Z7 BL is 1008 (almost twice as high). Neither BL value has anything to do with DR. Some older cameras (D610, Df) use a BL of 0. The dark parts of their analog ranges are less precisely recorded in the raw file. This might look slightly noisier. The use of the BL value can make it easier to recover shadow information.

When you subtract the black level (512) you end up with a straight line, proportional to the light value (LV). A wider range of exposures do not change the fact that the blue and green lines essentially remain straight although very low exposures they might deviate a little.

Sony (and Nikon, etc.) deliberately keep the signal proportional to the exposure as expected to conform to the exposure triangle. They have also concentrated on keeping the noise down so that it does not become visible until the exposure is drastically reduced.

Regardless of how ISO is set, SNR is more useful than DR when it is calculated correctly.

As stated in the opening paragraph, DR for the sensor is defined at base ISO. All other values within the normal analog range of the sensor are something other than dynamic range.

How to Measure SNR

The DXO data may have been compiled by putting the camera on aperture priority.

A series of images can be captured with EC set to 0. The target should have a smooth tone with a controlled brightness. A white display on a calibrated monitor works well. To avoid any unwanted patterns, the camera should be focused at infinity and the camera held close to the screen. Images should be recorded using spot metering. Measurements should be taken for a small selection at the center of the image using the green channel since they represent half of the Bayer color array (a little more for X-trans).

As the ISO is increased the shutter speed gets shorter to keep middle gray at the same raw and JPEG level. It is primarily *the reduction in exposure* that drops the SNR making the noise more visible.

We are familiar with the progression of ISO settings in whole stop increments – 100, 200, 400, 800 … But what about 1/3 stop increments? They are ISO 100, 126, 159, 200, 252, 317, 400 … The intermediate steps are not whole numbers since they are based on 100x(2^(n-1)/3) where **n** can be any integer, even 0 or negative.

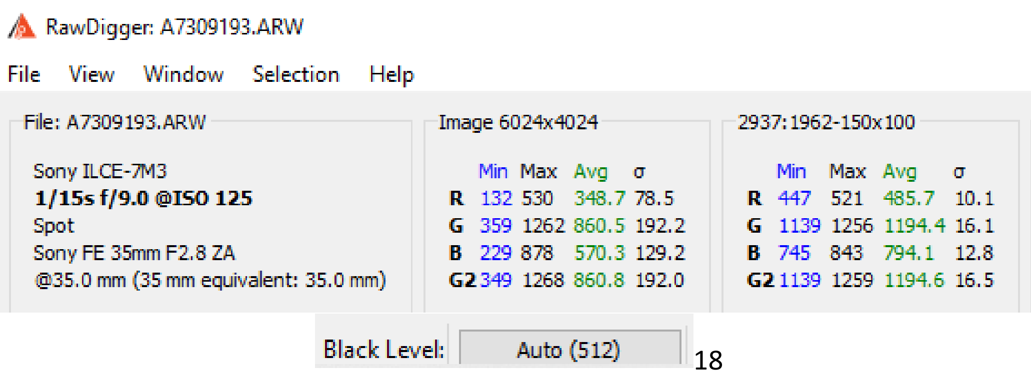
We may also be familiar with the progression of shutter speeds in seconds – 1, ½, ¼, 1/8, 1/15, 1/30 and 1/60 … The last three are actually 1/16, 1/32, 1/64 … The intermediate steps are also based on powers of 2 in 1/3 step increments. Here is a typical sequence for ISO and shutter speed:

#	ISO	1/ss
1	100	12.70
2	126	16.00

3	159	20.16
4	200	25.40
5	252	32.00
6	317	40.32
7	400	50.80
8	504	64.00
9	635	80.63
10	800	101.59
11	1008	128.00
12	1270	etc.

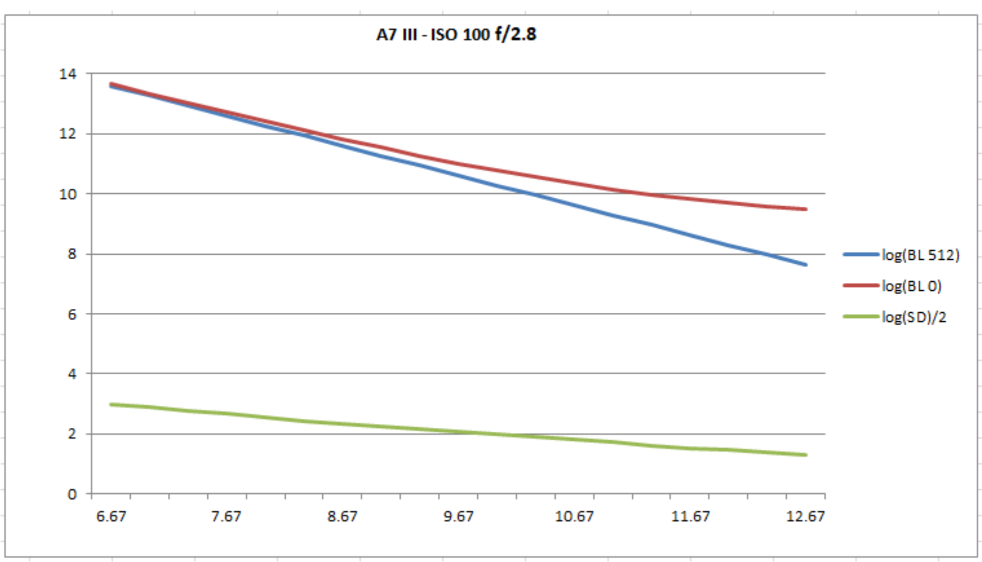
These values were used to test the A7 III and Z7 using a standard target spot metered to render a middle gray value at the center of the image.

Measurements were made using a 150x100 pixel selection from the center of the target image viewed in RawDigger:



[18]

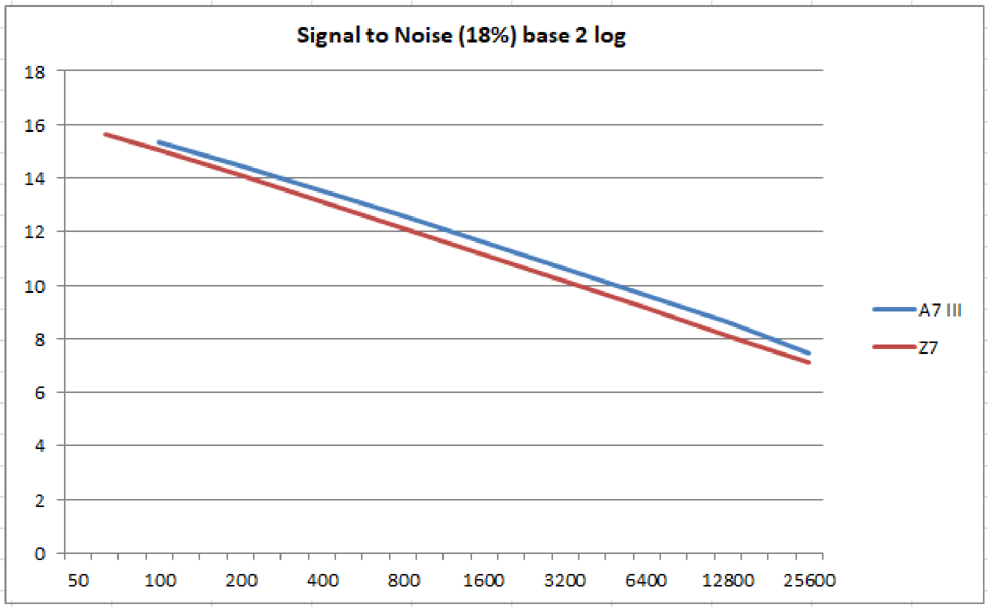
The average raw values and standard deviations (SD, σ) were recorded for the two green channels. The test was run at base ISO by varying the shutter speed.



[19]

The blue line is the plot of base 2 logarithm for middle gray after subtracting the black level of 512.

DxO shows the SNR for middle gray in decibels (dB). Converted to base 2 logarithms:



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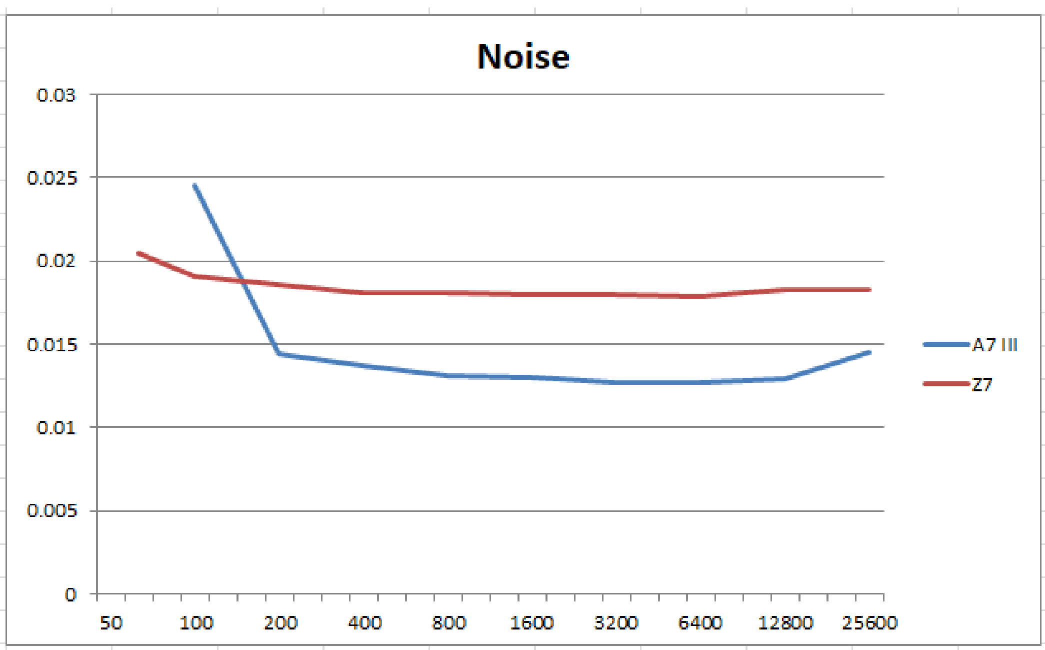
If we use the signal from the middle gray value (not shown) and the SNR from DxO we can get an estimate of the noise assumed by DxO.



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It implies that the noise does not change with ISO except at the top and bottom of the ISO analog range. It bears no resemblance to the plot of the black levels for the two cameras in images 12 and 13.

Conclusion

Both DxO and P2P do a good job comparing two or more sensors if we assume that the cameras being compared were tested with the same methodology and logic. But the methodology can change over time (compare the 2014 A7S and the 2020 A7S III on both sites).

DxO does not use the same definition of noise to compute the SNR as is does for the DR.

P2P does agree with the way that DxO determines DR. Both appear to be placing a lot of weight on the presence of dual gain sensors in determining DR.

Neither of them addresses the aesthetic value of noise levels in determining DR or SNR.