ISO and the Camera's Meter

This study examines the way that the ISO value set in the camera affects its performance. Images were taken of a neutral target using Aperture priority with the camera's meter measuring a spot at the center of the image. Four digital cameras were used their full range of ISO values. The raw and JPEG values where then measured.

Background

The relationship between aperture and shutter speed Exposure Value (EV) is universally accepted. It is built in to the settings on Hasselblad film lenses and displayed on the backs of Rolleiflex cameras.

The relationship between EV and ISO is also universally accepted and described in the Exposure Triangle where the only controversy has been its name. But the name has stuck and nobody has come up with a better one.

The ISO and the exposure are in lockstep for all cameras set to Aperture, Shutter or Program mode and even when using Auto ISO. Every camera model behaves a little differently. That is the basis for the Sunny 16 rule (1/ISO seconds at f/16 for broad daylight).

There are physical limitations on the range of lens apertures, typically between 5 and 7 stops. Shutter speeds have a limited range and each camera offers a range of ISO settings. Program mode works within those limitations but the assumed light value might deviate by +/-0.3 stops. Auto ISO may not change the selected ISO unless the aperture or shutter speed comes close to a limit.

No camera can actually produce a perfect exposure but it can come very close. Reported values like shutter speeds, ISO and aperture values are rounded off and stated as conventional values. There may be two or three steps or more from one stop to the next.

	Set	Step	Log	Actual
1/sec*	125	3	7.000	128
f/	22.0	3	9.000	22.63
EV			16.000	
Filter	0	3	0.000	
ISO**	250	3	-1.333	252.0
LV			14.667	

Analog exposure meters use a dial to calculate the relationships among ISO, aperture and shutter speed.

This analog meter measures a light value (LV). You can rotate the dials to set the ISO and exposure value (EV) and calculate the appropriate combination of shutter speed and aperture.

Digital meters use the same logic. The [Exposure Triangle Calculator] shows how to use a calculator spreadsheet that can be [downloaded here]. For more information see also [Light Value (LV) 15].

ISO is used during the analog to digital (A/D) conversion of the impression captured by the sensor into digital data. The resulting digital raw data is linear. Each doubling of the signal yields a doubling of the numeric values.

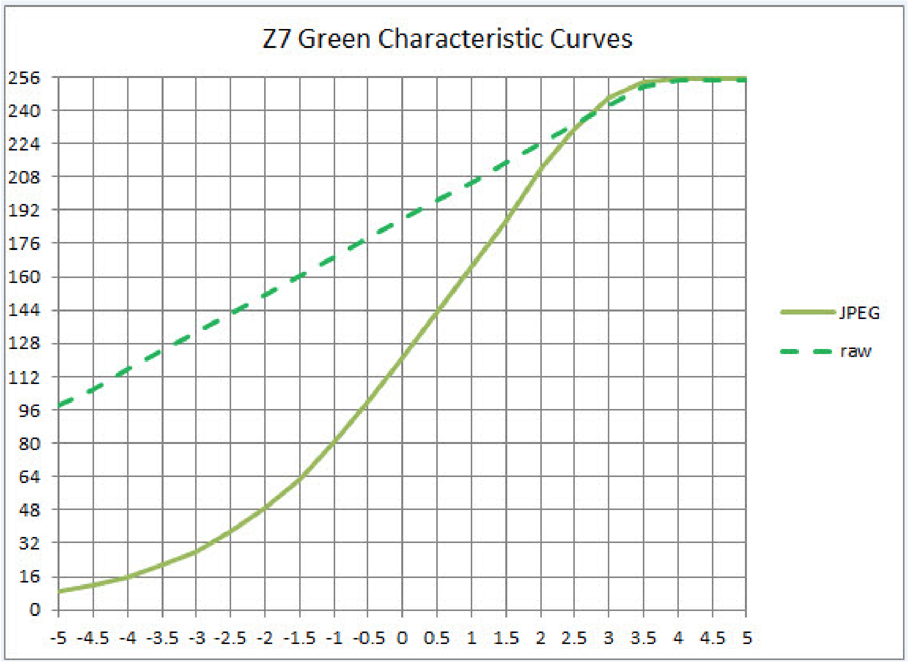
The raw data is then passed through a separate conversion step to produce an image. If you develop from raw on the computer this is considered post processing. What happens in the camera to create the image can also be viewed as post processing.

But the values in the image are created from a logarithmic conversion of the raw data, base 2 log(raw), plus an adjustment that gives the curve has an “S” shape with more contrast in the middle and less on the ends. The final results are values from 0-255 (black to white). How a particular camera model generates the raw file or the JPEG is entirely up to the manufacturer. The accuracy of the capture at different ISO settings depends on the precision of the shutter to and the lens aperture.

There is no consensus for the level where middle gray should end up in the raw file although all cameras leave about 3½ to 4 stops above that level to record highlights.

There is also no consensus on where middle gray belongs in the camera’s image.

Here is an example of the ranges used in a Nikon Z7:

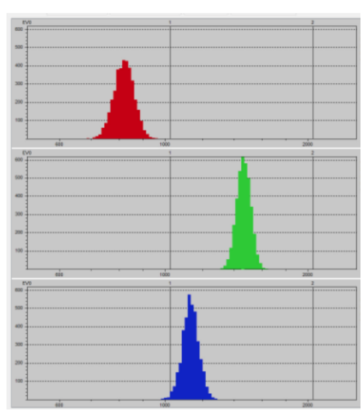


This information was compiled using a single ISO and aperture by varying only the shutter speed or exposure compensation (EC).

The raw values for a range from EC-5 stops through EC+5 stops (dashed lines) are linear, straight lines. The base 2 log values for the raw data (0-16383 for 14-bit raw) has been superimposed over the 8-bit JPEG scale (0-255) by multiplying the raw values by 256÷16384 (0.015625).

The JPEG values can be altered in the camera by overriding the default settings. Otherwise, the raw and JPEG values arrive at their upper limits at between EC+3½ and 4 stops above middle gray. Any additional exposure is “blown out”. That usually happens slightly sooner for the JPEG than for the raw file.

The green channel captures 50% of the luminance information (56% for an X-Trans array). When recording white or gray, the green the raw values are about a half stop higher than for blue and a full stop higher than the red channel.

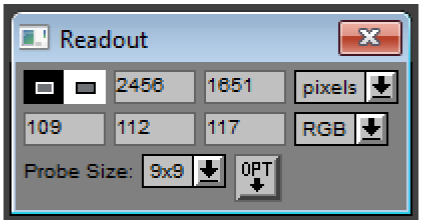


The Measurements

The goal of a camera's meter is to help produce an image in the camera that ranges from black to white with a midpoint at middle gray.

Middle gray can be close to half way between 0 and 255 but it can range from about 105 to 145. You can find out what it is for your camera with an editor that can display the value in the image.

Some editors will show the RGB (red, green and blue) values for spot in a JPEG or provide a window like this:

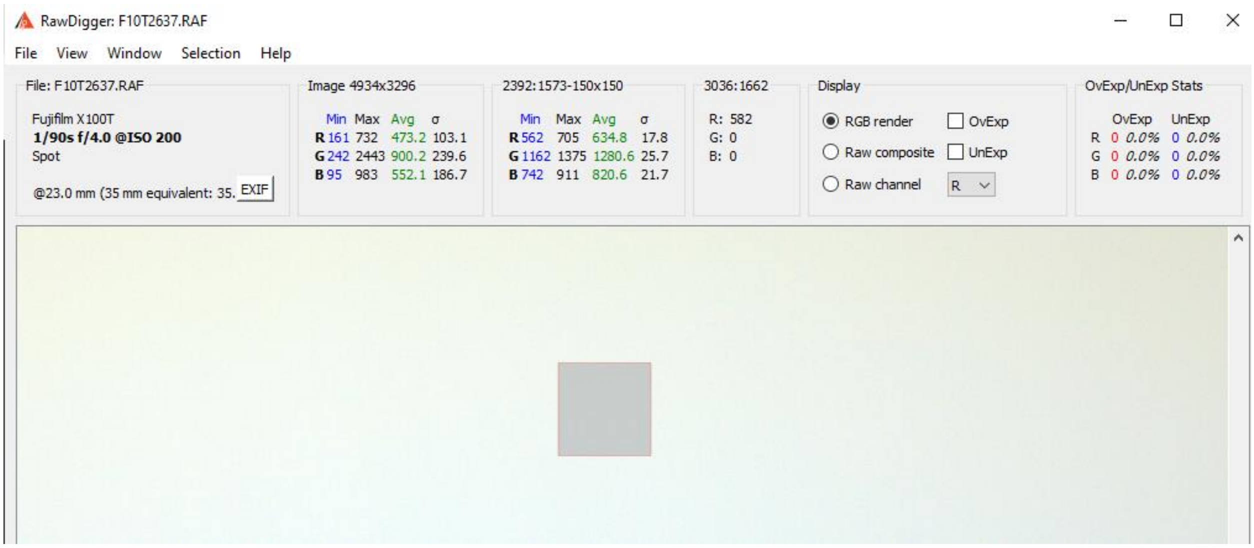


In this case the curser was over a point 2456 pixels from the left of the image and 1651 from the top. The three RGB colors may not match. We need the middle value, 112 from the G channel, since 50% or more of the pixels record green values.

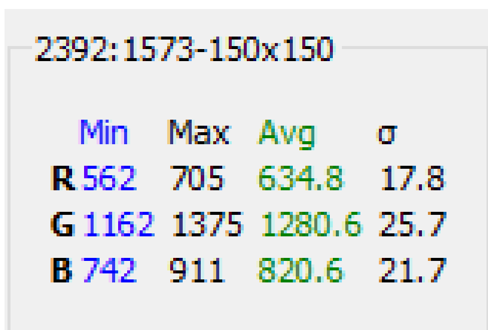
The results for each of four cameras were collected in a single pass with the ISO ranging from the minimum to the maximum possible setting. You can assemble a series with your own camera as follows.

1. Set the camera to its base ISO or a little higher.
2. Set the exposure mode to Aperture priority.
3. Set the metering method to Spot at the center of the frame.
4. Set the exposure compensation (EC) to 0.
5. Set the white balance to Auto.
6. If possible, turn off Autofocus and focus the lens at infinity (or ignore any out of focus warning).
7. Capture an image of a white or gray target. I use a calibrated high definition monitor displaying a white page because it's more reliable than a white or gray card.
8. Copy the image from the camera to your computer.
9. Open it in your editor and point to a spot in the center of the image.

We can use RawDigger (a bargain for about $20) to measure the raw values in a raw file. Here is an example:



The gray box is a 150x150 pixel selection from the center of a test image from a Fuji X100T. Its top left corner is 2392 pixels from the left of the image and 1573 pixels from the top.



It shows the average RGB values where the camera's spot meter measured the brightness to set the shutter speed for the Aperture Priority mode. The number we are interested in is 1280.6 (base 2 logarithm value 10.3226042. That's about 3½ stops below the maximum possible value of just below 14, usually between 13.90 and 13.95.

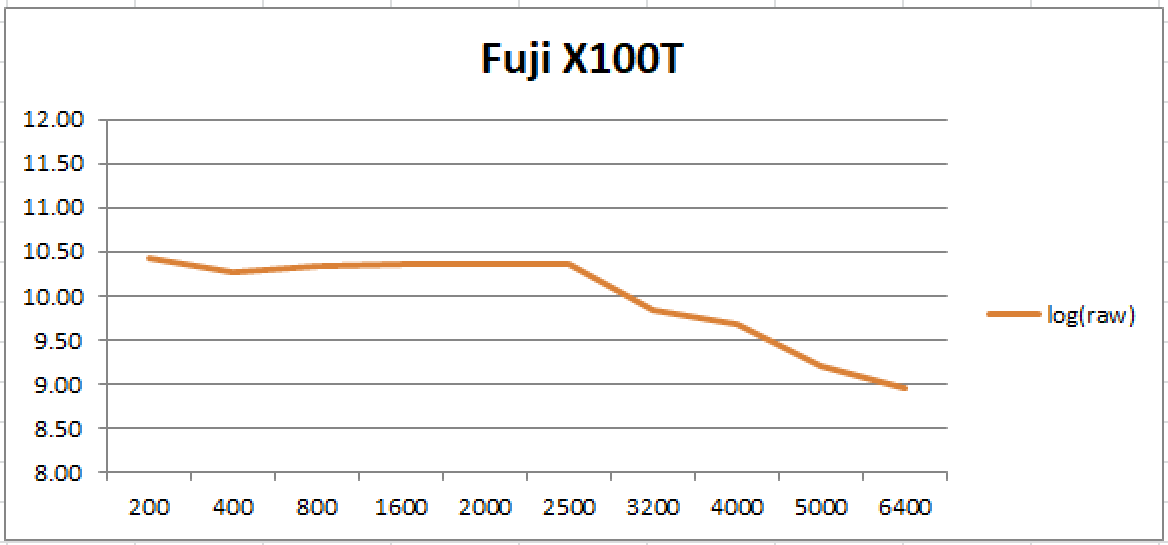
RawDigger can display raw histograms, blown raw pixels, etc. The RawDigger website is also a great source of technical information.

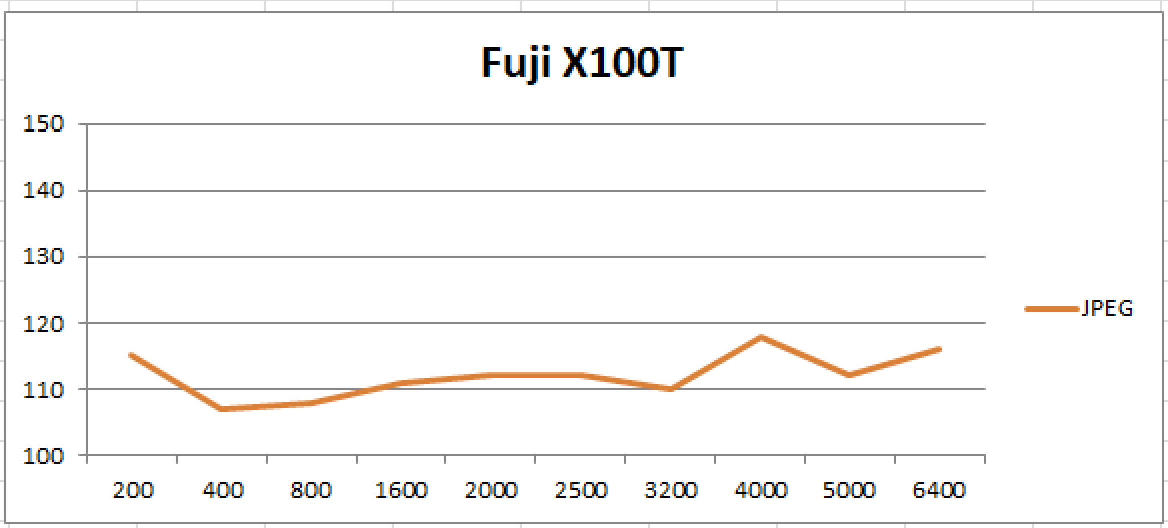
Fuji X100T (2014)

The X100T may not be representative of all Fuji models. It is a special APS-C sensor camera with a fixed 23mm lens (35mm full frame equivalent) and a leaf shutter in the lens and also an electronic shutter that is more precise. Like other APS-C Fuji models it uses an X-Trans color filter array (not a Bayer array).

Results measured for the X100T:

	ISO	1/ss	log(raw)	JPEG
Base ISO	200	90	10.42	115
	400	200	10.26	107
	800	350	10.33	108
	1600	750	10.36	111
	2000	900	10.35	112
Extended	2500	1000	10.37	112
	3200	1500	9.85	110
	4000	1700	9.68	118
	5000	2400	9.21	112
	6400	2900	8.95	116
		Average	9.98	112.1

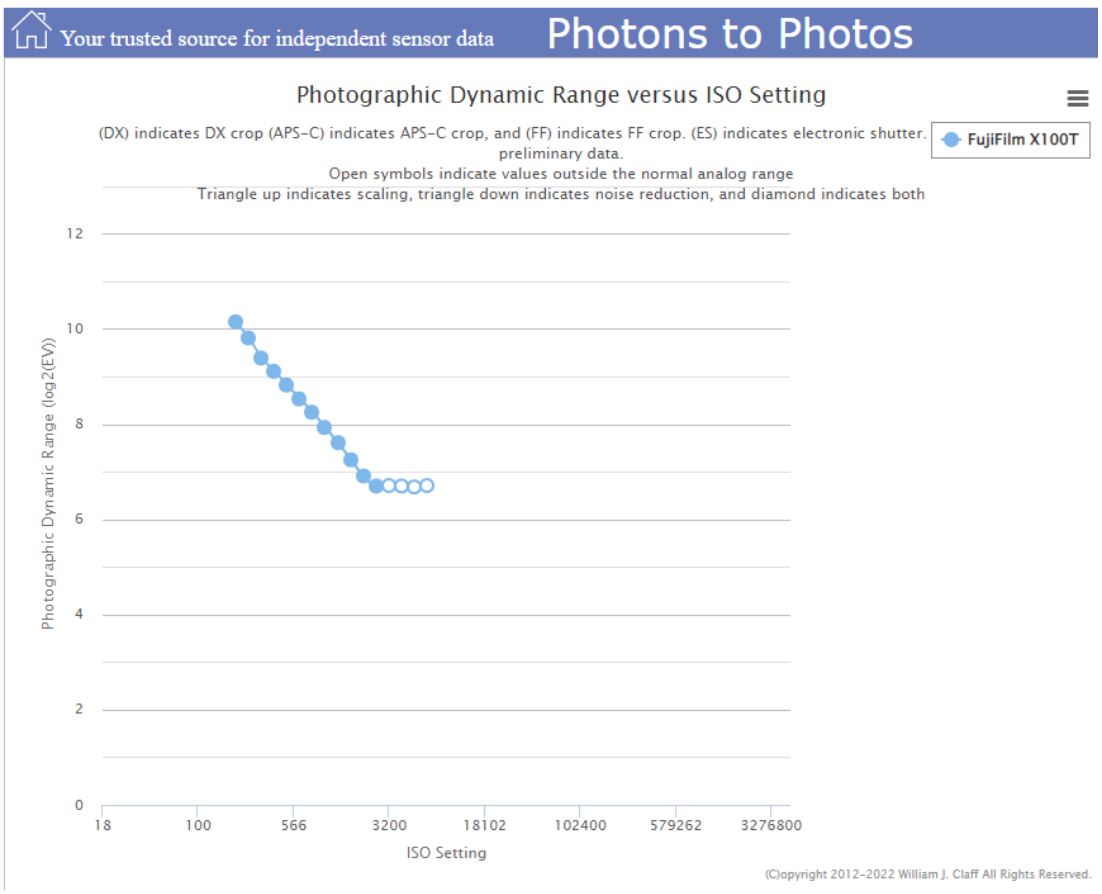




The first plot shows the base 2 log of the raw values recorded in the Fuji raw (.RAF) file.

Over the full range of ISO settings, each doubling of the ISO is offset by cutting the exposure in half (not always precisely). At the same time the signal from the sensor is doubled (analog gain changes) so that the recorded raw values keep pace with the change in ISO. This happens in the analog to digital (A/C) conversion. The raw values remain consistent up to ISO 2500. Starting at ISO 3200 the analog gain no longer increases. The gain used for ISO 2500 is applied from ISO 3200 through ISO 6400. Since the shutter speed continues to reduce the exposure as the ISO increases, the values in the raw file go down.

Here is a plot of the dynamic range (DR) for the X100T from [Photons to Phots](https://www.photonstophotos.net):



The solid symbols are for ISO settings within the normal analog range ending at ISO 2500.

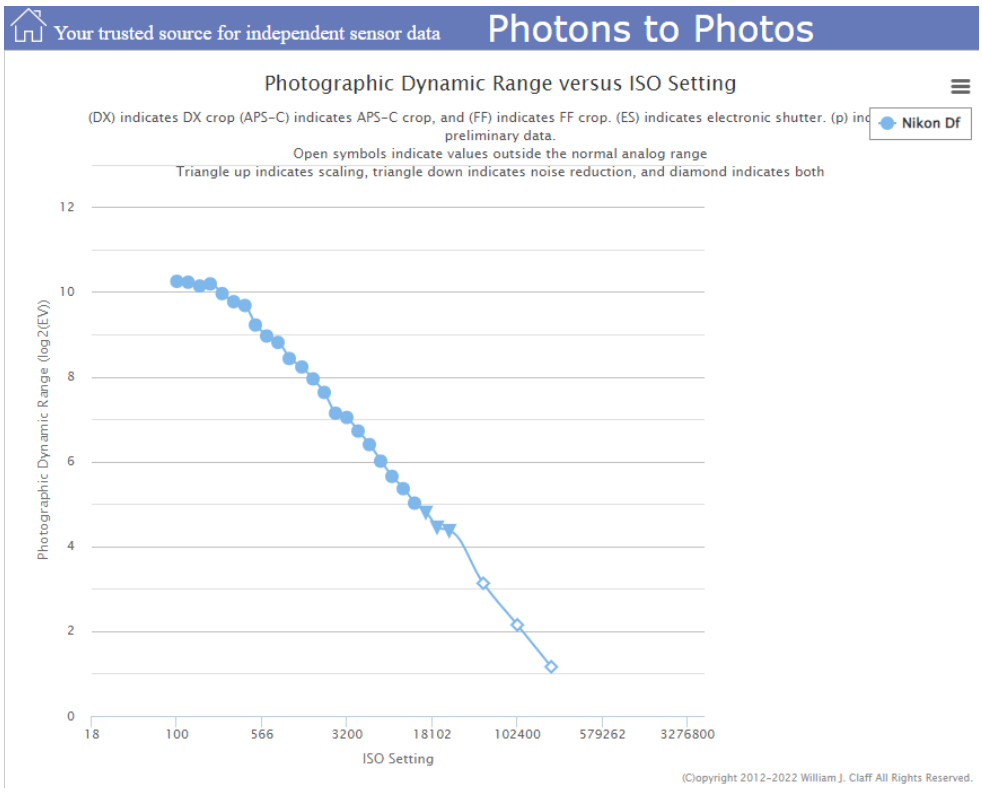
The JPEG values closely follow the raw values through ISO 2500. But they do not drop above ISO 2500 like the raw values. A second gain, digital gain, is applied during the raw conversion in the camera. It's the product of these two gains that place middle gray in the JPEG and tries to make it flat in our case:

[analog gain] x [digital gain] = [net gain used to produce the JPEG image]

If you copy the raw file to your computer to do your own processing, the digital gain may not yet be applied. The amount of digital gain needed is recorded in the raw file. Some raw converters (like ACR) use that value to apply to produce an image similar to the one produced by the camera. But if they don't you will immediately see that the image is too dark. The Exposure slider can make it lighter.

Nikon Df (2013)

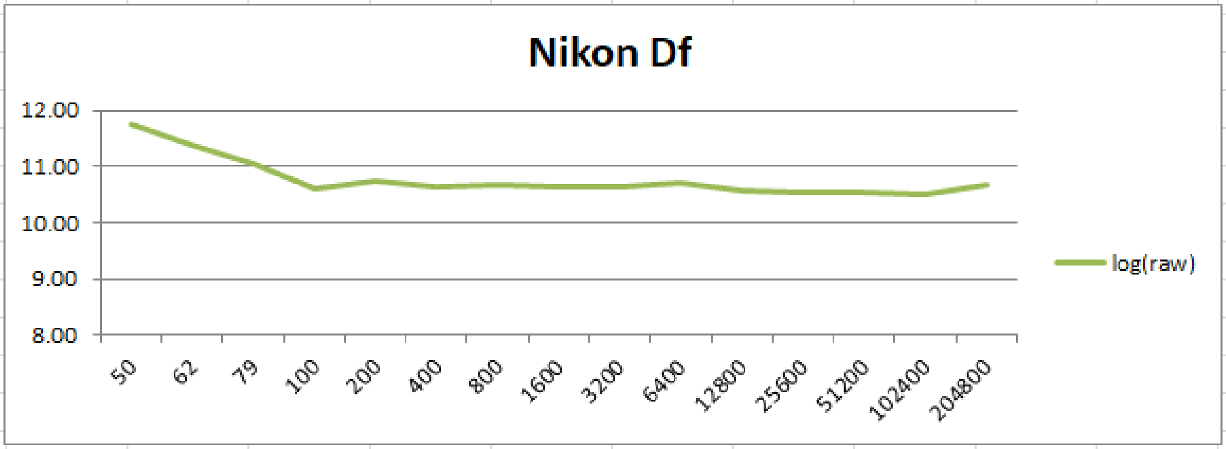
The Df behaves like other full frame Nikon DSLRs in the creation of the raw (.NEF) file and the camera's JPEG. It uses a mechanical shutter. Here is a plot of the DR:

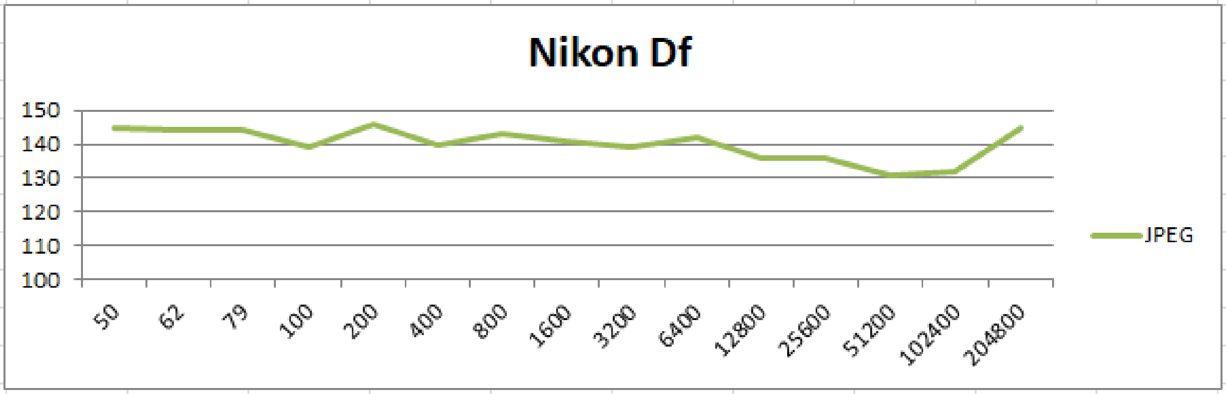


Unlike the X100T, the raw data uses only analog gain from the base ISO 100 through 204800, High 4. But it has an extended low range below base ISO that uses the analog gain for ISO 100 and applies a digital gain of about 0.84, 0.63 and 0.5 to achieve the net gain used to produce the JPEG image. The JPEG values for middle gray end up between 131 through 145 with an average of about 139. The average may seem high compared to other models. The variations are due to a less precise mechanical shutter.

Results measured for the Df:

	ISO	1/ss	log(raw)	JPEG
Lo 1	50	1	*11.74*	145
Lo .7	62	1.25	*11.38*	144
Lo .3	79	1.67	*11.05*	144
Base	100	2	10.61	139
	200	4	10.74	146
	400	8	10.63	140
	800	15	10.68	143
	1600	30	10.65	141
	3200	60	10.62	139
	6400	125	10.70	142
	12800	250	10.58	136
Hi 1	25600	500	10.55	136
Hi 2	51200	1000	10.52	131
Hi 3	102400	2000	10.52	132
Hi 4	204800	4000	10.68	145
		Average	10.62	140.2



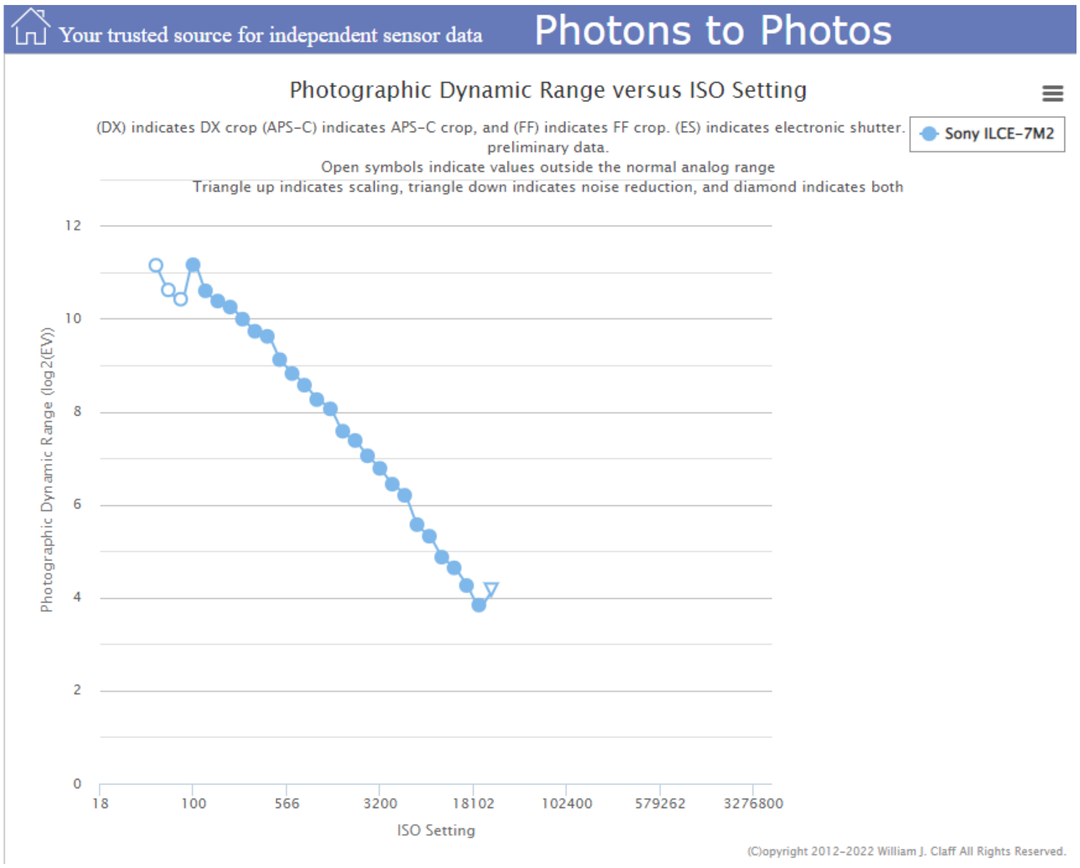


Notice that the shutter speed changes are more regular than for the X100T. But the actual shutter speeds may not precisely match the setting. That explains the slight changes in the log(raw) plot above base ISO.

Sony A7 II (2014)

The model being tested has had its Bayer array removed. The result is an increase in effective ISO over the value set in the camera. Even with a yellow filter on the lens the effective ISO is 200 when the setting in the camera is 100, base ISO.

The A7 II is similar to the two Nikons in that the shutter speed doubles with each doubling of the ISO. But below the base ISO 100 the raw values get doubled. It appears to record ISO 80, 64 and 50 using the analog gain from ISO 160, 125 and 100. Here is a view of what happens to the DR as the ISO is changed:

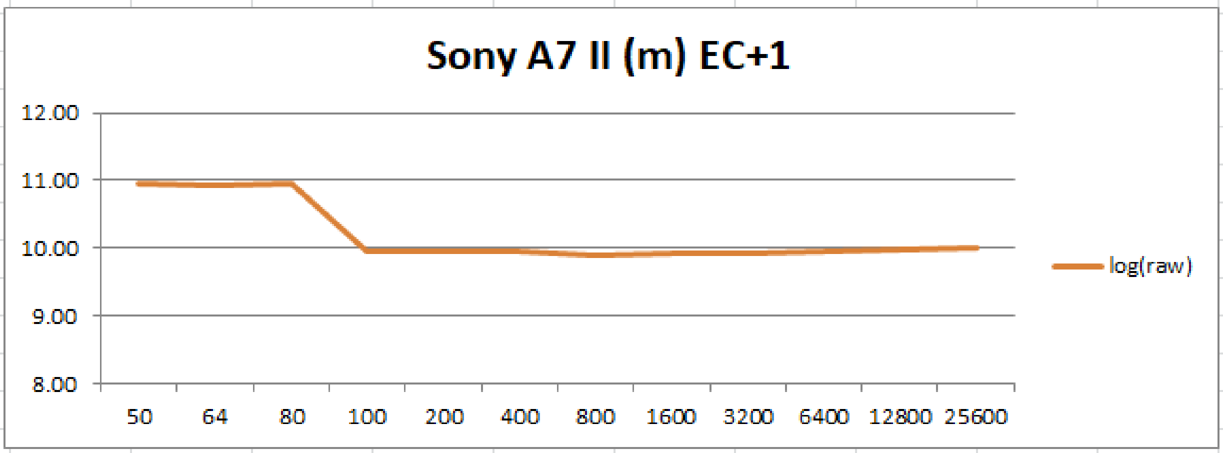


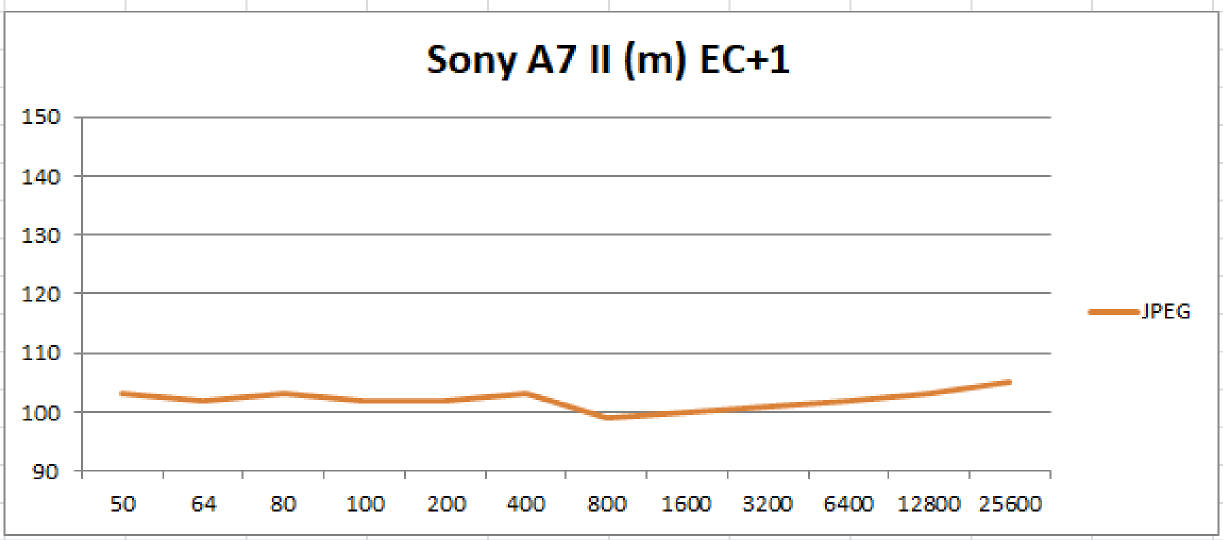
ISO 50, 64 and 80 are below the normal analog range. ISO 25600 gets a boost in dynamic range from scaling.

The A7 II needs to be set to EC+1 for the raw data and JPEG to be comparable to the other cameras.

Here are the measurements from the A7 II at EC+1:

	ISO	1/ss	log(raw)	JPEG
	50	6	*10.95*	103
	64	8	*10.94*	102
	80	10	*10.95*	103
Base	100	13	9.94	102
	200	25	9.94	102
	400	50	9.95	103
	800	100	9.91	99
	1600	200	9.92	100
	3200	400	9.93	101
	6400	800	9.95	102
	12800	1600	9.97	103
	25600	3200	10.01	105
		Average	9.95	102.1

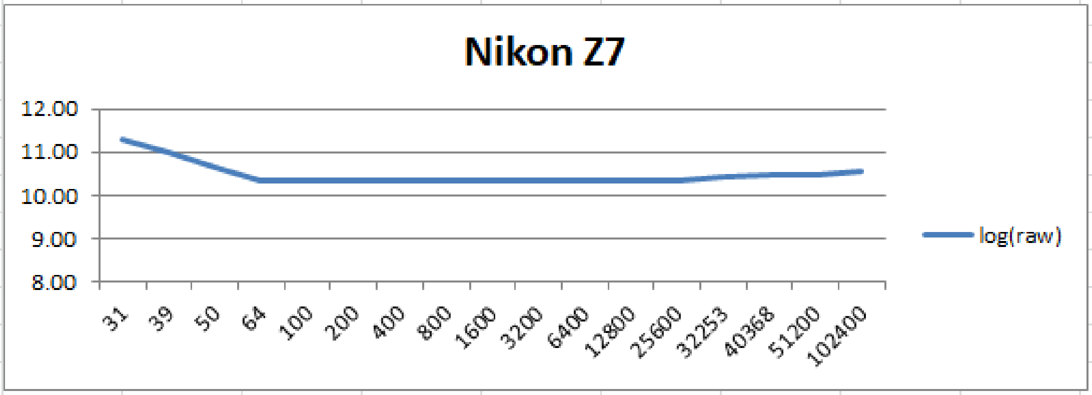


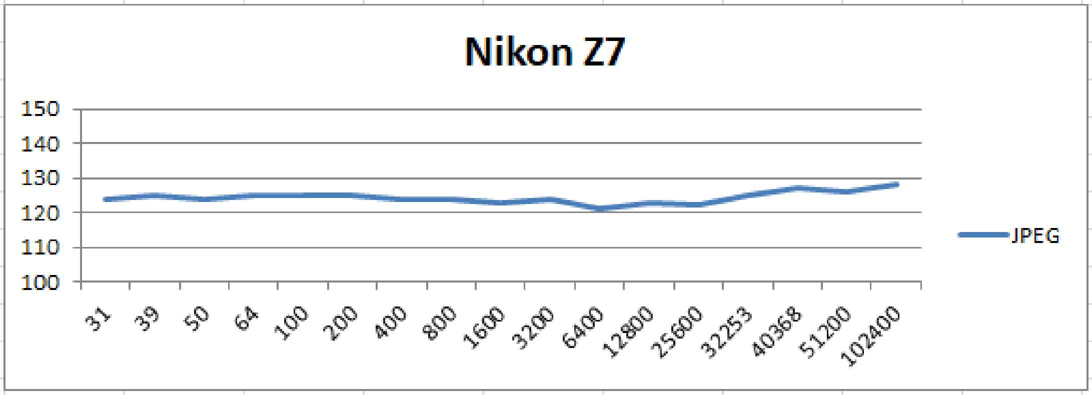


The Nikon Z7 (2018)

The Z7 has both a mechanical and silent (electronic) shutter. The extended high ISO settings are only available for the mechanical shutter. The base ISO is 64.

	ISO	1/ss	log(raw)	JPEG
Lo 1	31	2	*11.31*	124
Lo .7	39	2.5	*11.01*	125
Lo .3	50	3.333	*10.66*	124
Base	64	4	10.35	125
	100	6	10.33	125
	200	13	10.33	125
	400	25	10.33	124
	800	50	10.33	124
	1600	100	10.34	123
	3200	200	10.33	124
	6400	400	10.33	121
	12800	800	10.34	123
	25600	1600	10.34	122
Hi .3	32253	2000	10.43	125
Hi .7	40368	2500	10.45	127
Hi 1	51200	3200	10.48	126
Hi 2	102400	6400	10.56	128
		Average	10.38	124.4

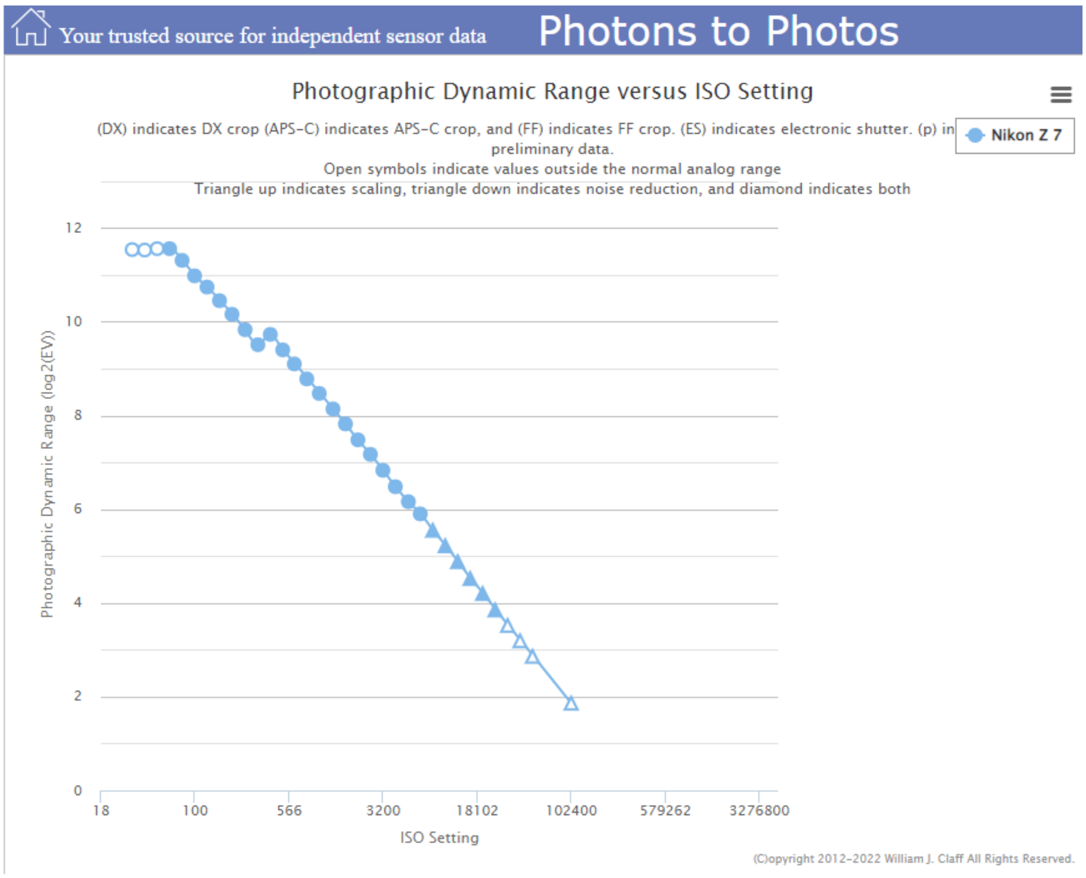




The Z7 uses the same approach as the Df but the electronic shutter is more than its mechanical shutter. Middle gray for the JPEG is lower than for the Df.

Over the normal range the shutter is seems as precise as the A7 II.

Here is how the camera's DR is affected by changes in the ISO:



The open symbols represent the ISO settings beyond the normal range –Low 1, 0.7, 0.3 and above High 0.3, 0.7, 1, 2. Between ISO and 320 and 400 there is a shift in analog noise processing. The solid triangles indicate scaling (digital gain within the A/D conversion). They don't alter the decline in DR so their effect is mainly to keep the raw values in line.

Conclusion

For ISO to work properly there needs to be a high correlation between the ISO setting and the exposure selected by the camera. With the Nikons and the Sony that correlation is very high (1.0000) throughout their entire range, including the extended ranges. It's almost as high for the X100T (0.9968) for its limited ISO range of 200 through 6400.

The selected shutter speed may not actually be executed precisely but all cameras came very close.

For film cameras the relationship between ISO and shutter speed is exactly the same as for digital. Shutter speeds are less precise, especially for leaf shutters. The film negative is the counterpart of the raw file. For transparency film (slides) the film is the equivalent of the JPEG. The way that film ISO is determined is flexible. The photographer often deviates from the ISO on the box.