

## Making Sense of Effective Bits in Oscilloscope Measurements

When considering oscilloscope or digitizer performance, the term “Effective Number of Bits” (ENOB or effective bits) is often used, but it seems seldom fully appreciated or understood, especially in terms of what it means to real-world signals and measurements. In this paper, we will describe effective bits in terms that are useful in better understanding the real world implications.

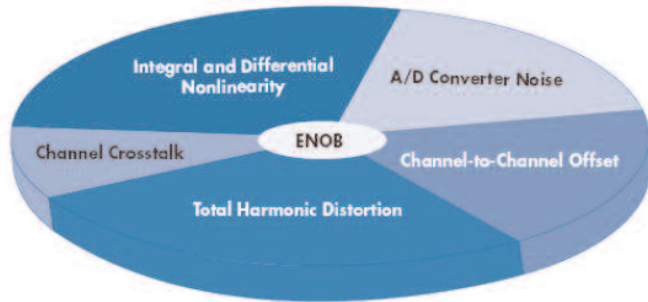


Figure 1. Digitizer Errors Contributing to ENOB (courtesy of datatranslation.com).

Effective bits provides a representation of the signal integrity (or degradation) of the A/D system over a frequency range. To better understand this, let's first consider a few basic points.

1. All digitizing systems have a variety of errors that impact the reported value of voltage at a particular instance in time.
2. All errors, both amplitude and timing related, show up as a change to the expected or "ideal" voltage at a particular time.
3. In an ideal digitizer, the number of effective bits would be the same as the resolution of the A/D (e.g., 8 bits), and this would be consistent from DC to the maximum bandwidth of the instrument. In reality, all instruments are less than ideal. The ENOB is usually lower than the resolution of the A/D, and this usually gets worse as the frequency is increased.
4. To compare any two A/D systems, it is critical that the same conditions are used to characterize the performance. The same stimulus must be used, and the same settings must be used for the instruments being evaluated.

It should be noted that ENOB is defined by the IEEE1057 specification. In addition, the IEEE1057 specification describes how to make ENOB measurements. ENOB is an industry-wide accepted method for determining a general figure of merit for A/D converters, oscilloscopes, and other digitizing systems.

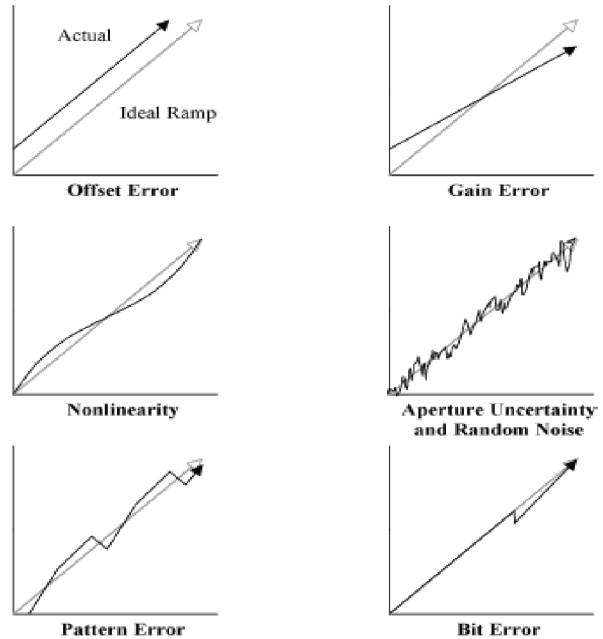


Figure 2. Typical A/D Errors.

## Errors in Digitizing Systems

Numerous papers have been written to describe the typical errors that exist in digitizing systems. An excellent reference paper is "Effective Bits Testing Evaluates Dynamic Performance of Digitizing Instruments" and is available at: [http://www2.tek.com/cmsreplive/tirep/4405/2006.07.18.14.07.40\\_4405\\_EN.pdf](http://www2.tek.com/cmsreplive/tirep/4405/2006.07.18.14.07.40_4405_EN.pdf)

Figure 1 shows examples of some of the common errors which affect ENOB performance in A/D systems.

Effective bits is a composite figure of merit, which includes the effects of digitizing errors shown in Figure 1 and 2. Most importantly, it represents these errors as a function of frequency, so that you can see if a particular instrument has performance issues at specific frequencies. It should be noted that the ENOBs calculation is based on all spectral components, excluding DC, so of the typical errors show in Figure 2, effective bits is not affected by offset error (a DC effect).

# of Bits	# of Digitizing Levels	% LSB change of FS	LSB Volt change with 1V Full Scale
8	256	0.39%	3.91E-03
6.65	100	1.00%	9.96E-03
6	64	1.56%	1.56E-02
5	32	3.13%	3.13E-02
4	16	6.25%	6.25E-02

Table 1. Digitizer Resolution.

## Digitizing Resolution

If a digitizing system has 8 bits of resolution at DC, it has 256 digitizing levels. This means that the input signal must change at least .39% of the full scale in order for the A/D to produce a change in its output. If we had a 1V full-scale range on the 8-bit A/D, the voltage would have to change by more than 3.9mV to have an impact on the output of the A/D. Any changes on the input signal lower than 3.9mV increments would not be detected by the A/D.

Now consider if the resolution is reduced. For example, if the resolution is reduced to 6.65 bits, the input signal must change by approximately 1% to produce a change on the A/D output. Any changes in the input signal that are below that level will be unseen in the output of the A/D. At a 1V full-scale range, a change larger than 10mV would be required to affect the output of the A/D.

Likewise, a resolution of 5 bits provides 32 digitizing levels. In this situation, the input signal must change by at least 3.13% in order to have any impact on the output of the A/D. If we once again consider our 1V full-scale range, it would take a change on the input signal larger than 31.3mV to affect a change on the output of the A/D, as Table 1 illustrates.

## Effective Number of Bits

The effective number of bits is generally presented as a function of frequency, and generally (but not always) degrades as the frequency gets higher. This change in resolution works much like the discussion on digitizing resolution.

Let's consider the situation where we have an 8-bit real-time oscilloscope. This oscilloscope has 8 bits of resolution and a bandwidth of 13 GHz. At DC and low frequency, we

# of Bits	# of Digitizing Levels	% LSB change of FS	LSB Volt change with 1V Full Scale
6.4	84.4	1.18%	1.18E-02
5.6	49	2.06%	2.06E-02

Table 2. Effective Bits Resolution of Tektronix DPO/DSA70000B Oscilloscopes.

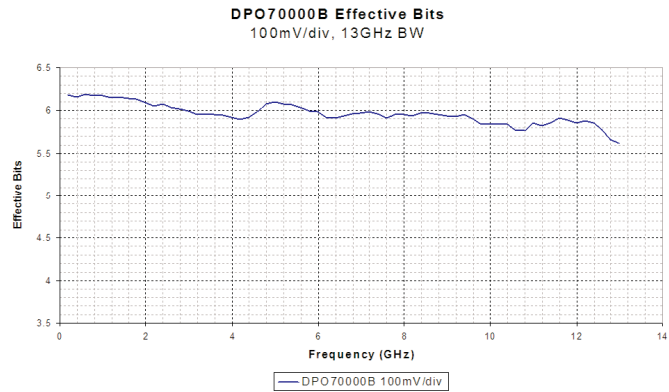


Figure 3. Effective Bits plot for DPO70000B at 100mV/div.

will likely have very close to 8 effective bits of resolution. However, as the frequency of the input signal being measured increases, the impact of instrument noise and other errors will likely degrade the effective bits performance.

Figure 3 shows the plot of effective bits for such an instrument.

Figure 3 shows the performance of a Tektronix DPO/DSA70000B oscilloscope over the range from 200 MHz to 13 GHz. As you can see, at 200 MHz the instrument has 6.4 effective bits of resolution. As the frequency increases, this drops down to 5.6 effective bits at 13 GHz.

The behavior of the A/D is much the same for effective bits as it is for “real bits” as described in the “Digitizing Resolution” section above. Table 2 shows the resolution details for these effective bits levels.

This shows that at 13 GHz, with a 1V full-scale range, the input signal will have a 20mV noise content on the output of the A/D. Said another way, any input signal change smaller than 20mV will likely be masked by the noise, distortion, and other errors in the system.

It might be worth noting here that the A/D will continue to put out 8-bit data, but (at 13 GHz) 2.4 bits of that will actually be noise/distortion/error.

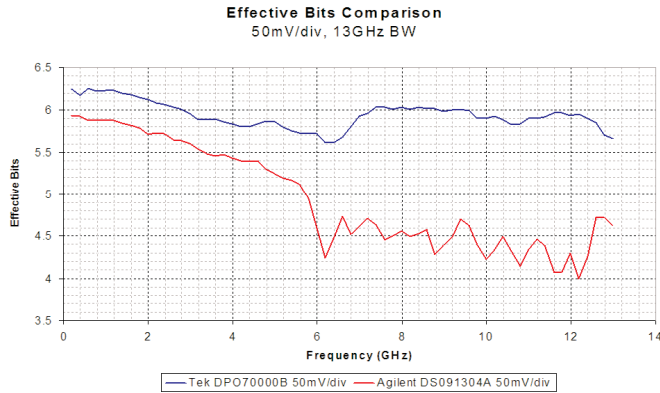


Figure 4. Effective Bits Comparison of Two Real-time Oscilloscopes.

## Not All Digitizing Systems Are Created Equal

After inspecting the effective bits plot of the DPO/DSA70000B oscilloscopes in Figure 3, you might be wondering if this represents good performance or poor performance. First, be assured that it is no easy task to design a system that performs equally well from DC all the way to 13 GHz, 16 GHz, or even 20 GHz. No system is perfect, and it should be expected that some degradation of performance would occur over the frequency range, even for the finest of instruments.

Having said that, some instruments are better than others, and the effective bits performance provides at a glance a very good representation of signal integrity of the digitizing system, for a specific setting, over its entire frequency range. The Figure 4 effective bits chart shows a comparison of the DPO/DSA70000B oscilloscope to a competitive oscilloscope with similar specifications.

# of Bits	# of Digitizing Levels	% LSB change of FS	LSB Volt change with 1V Full Scale
5.9	59.7	1.67%	1.67E-02
4	16	6.25%	6.25E-02

Table 3. Effective Bits Resolution of Agilent DSO90000 Oscilloscope.

Note that the Tektronix oscilloscope has the same range of 6.4 down to approximately 5.6 effective bits of resolution for this setting (400mV full scale) as we saw in the previous graph (1V full scale), while the competitive oscilloscope shows a range of 5.9 down to 4 effective bits of resolution. Table 3 shows the details of the competitive oscilloscope's effective bits level.

As you can see, at 4 effective bits, there will be a noise content due to the instrument of 62.5mV for a range of 1V full-scale.

## The Relationship Between Signal-to-Noise, SINAD, and Effective Bits

As already described, effective bits gives a representation of noise and other errors in a digitizing system. IEEE-1241 and IEEE-1057 standards give formulas for calculating effective bits. These standards link signal-to-noise and distortion (SINAD) performance to effective bits, through the following equation:

$$ENOB = \log_2(SINAD) - \frac{1}{2} \log_2(1.5) - \log_2\left(\frac{A}{(FSR/2)}\right)$$

It is clear from this formula that effective bits performance depends on the signal-to-noise ratio, as well as the distortion effects.

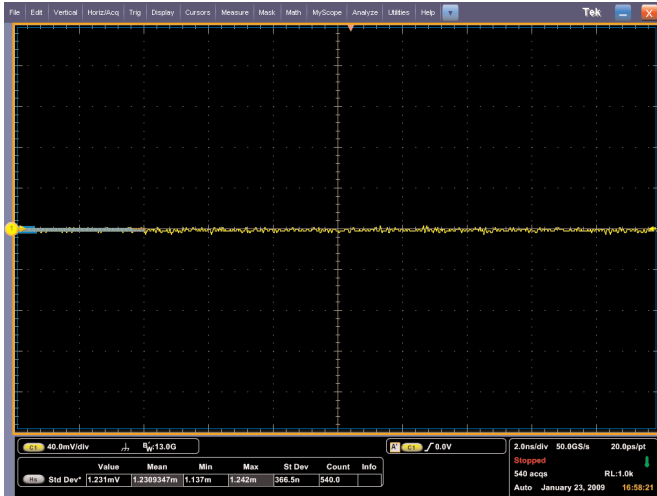


Figure 5. Baseline Noise Measurement.

## Baseline Noise - Not a Good Representation of ENOB Performance

Baseline noise (sometimes called residual noise) is a representation of the instrument noise performance, measured without an external signal applied to the input (input grounded). The measurement is performed using an AC RMS measurement on the channel, or applying a vertical histogram on the scope trace to accomplish the same end result. It is a quick and convenient measurement to make, since it doesn't require a stimulus signal, but cannot tell you anything about the performance at a specific frequency. Because it doesn't make any representation of instrument noise under the dynamic conditions of an AC signal at a given frequency using a substantial range of the A/D, it doesn't really provide a good indication of signal integrity in the instrument.

Having said that, some instrument vendors try to use baseline noise to demonstrate the "quality" of their acquisition system. In these cases, they specify vertical noise as a voltage level at a particular volts/div setting. In comparing instruments, however, it is important to compare "% of Full Scale" to get a fair comparison, since not all instruments have the same full scale range for a particular volts/div setting. It is also important to have the bandwidth set the same when comparing the performance of two different instruments. Higher bandwidth instruments intrinsically have more noise, and setting the bandwidth limit will reduce the noise.

As stated previously, the measurement is performed using a vertical histogram on the oscilloscope trace. The standard deviation of the histogram represents the rms value of the

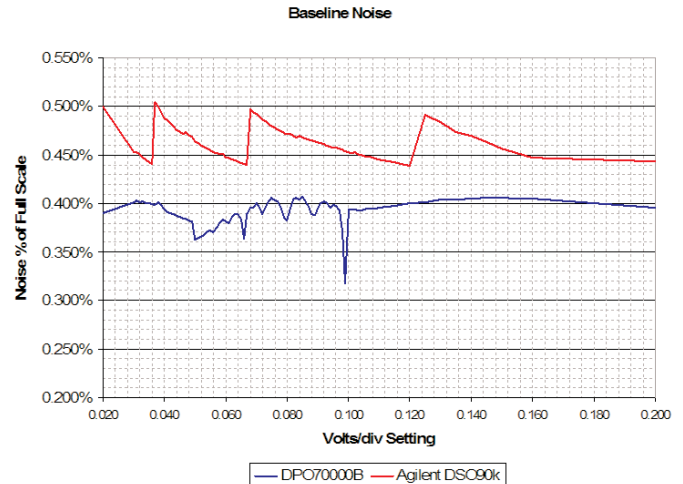


Figure 6. Baseline Noise Comparison Between the Tektronix DPO70000B and the Agilent DSO90000A.

noise. Once this is attained, it is a simple matter of calculating the % of full scale for the particular setting being used. Some systems provide a built-in math function that measures AC RMS directly, without having to set up a histogram manually. It is important not to include the DC offset in this measurement, so histograms or AC RMS measurements must be used. The Figure 5 screen capture shows a baseline noise measurement.

Figure 6 shows a comparison of baseline noise for the Tektronix DPO70000B and the Agilent DSO90000A. The bandwidth was limited to 13GHz on the Tektronix instrument to match the Agilent maximum bandwidth. This plot shows the baseline noise at many settings, so that it is possible to see how the baseline noise as a % of full-screen changes as a function of the volts/div setting. These are the same two instruments that were compared for effective bits performance in Figure 4.

You can see from the comparison that the Tektronix instrument offers the lower baseline noise performance (approximately 10% to 20% lower depending on setting), but compared to the effective bits results we saw in Tables 2 and 3, this is a small % of the full scale. The difference here is generally less than .1% of full scale, whereas the effective bits difference we saw in Tables 2 and 3 was as much as 4.25% of full scale. So, as you can see, baseline noise doesn't really give the full magnitude of the signal integrity picture. Most importantly, it doesn't utilize an actual signal, so it cannot be related to SNR or ENOB performance.

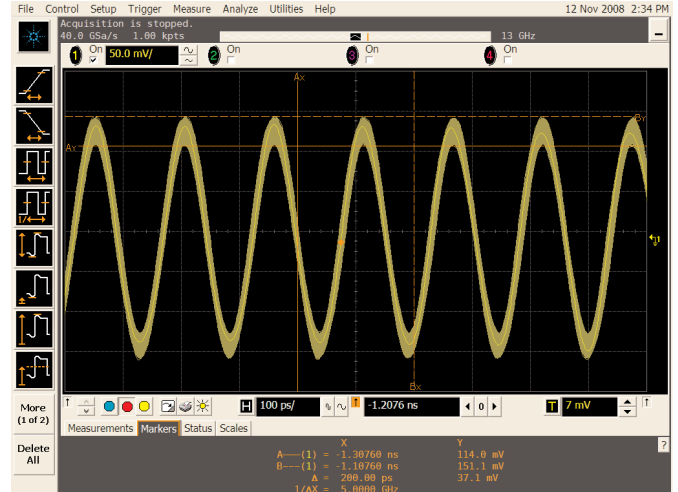


Figure 7. Side-by-Side Comparison of 6.5 GHz Sinewave on Tektronix and Agilent Oscilloscopes.

## How ENOB is Exhibited in Real-world Signals

Effective bits performance will have an effect on both amplitude measurements and timing measurements. The following are discussions on these topics.

### ■ ENOB Effects on Amplitude Measurements

Next, let's consider the acquisition of a sinewave. Again, we will compare the Tektronix DPO/DSA70000B and the Agilent DSO90000A instruments to demonstrate how effective bits performance can be seen in real world measurements.

In Figure 7 we have applied the same 6.5 GHz sinewave to both the Tektronix DPO/DSA70000B and the Agilent DSO90000A oscilloscopes. Both instruments are set for 13 GHz bandwidth, and both instruments are set for 400mV full scale. Both instruments have been set for infinite display persistence, so that variations across all acquisitions can be seen. No averaging is applied to either instrument. Both instruments were run for approximately 10k acquisitions.

On the Tektronix oscilloscope, we see approximately 15.9mV of trace "thickness" at the peak. This represents 3% of full scale on the Tektronix oscilloscope.

On the Agilent oscilloscope, we see approximately 37mV of trace "thickness" at the peak. This represents 9% of full scale on the Agilent oscilloscope.

You can see in Figure 3 that at 6.5 GHz, the Tektronix oscilloscope is at its lowest effective bits (approximately 5.6 bits), while the Agilent oscilloscope is at approximately 4.5 effective bits.

TIE Pk-Pk Jitter Comparison

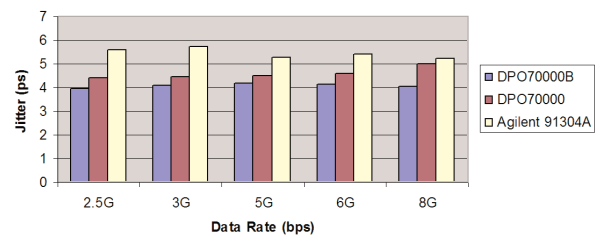


Figure 8. Jitter Measurement Comparisons.

### ■ ENOB Effects on Jitter Measurements

Jitter (aperture uncertainty and other sources of timing error) is one of the error elements represented under effective bits. So, it does not come as much surprise that we can see real-world effects on jitter measurements. In Figure 8, the jitter measurements shown were made using a BERT pattern generator as the signal source, with the data pattern set to a 1010 pattern. The BERT pattern generator is a very clean signal generator. For this test, the pattern generator was set to 5 different data rates, and jitter measurements performed on each of the instruments shown.

The Tektronix DPO/DSA70000B demonstrated the lowest jitter measurement performance for all data rates measured. While the Agilent 90000A oscilloscope exhibited 26% to 41% higher measured jitter, neither of the instruments varied significantly across the data rates measured.

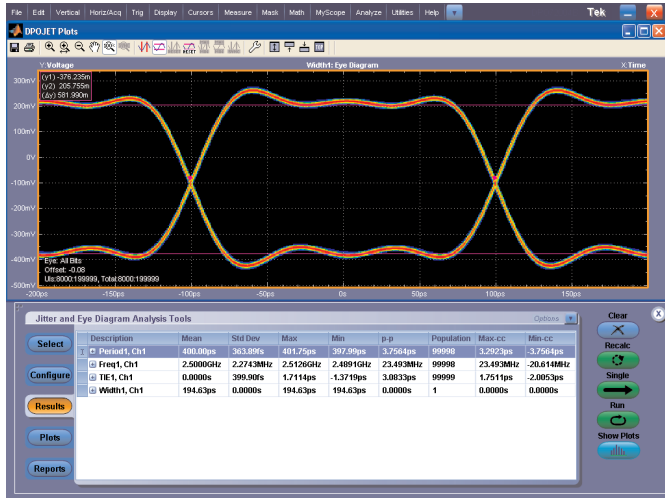


Figure 9. Jitter Noise Floor Test Configuration.

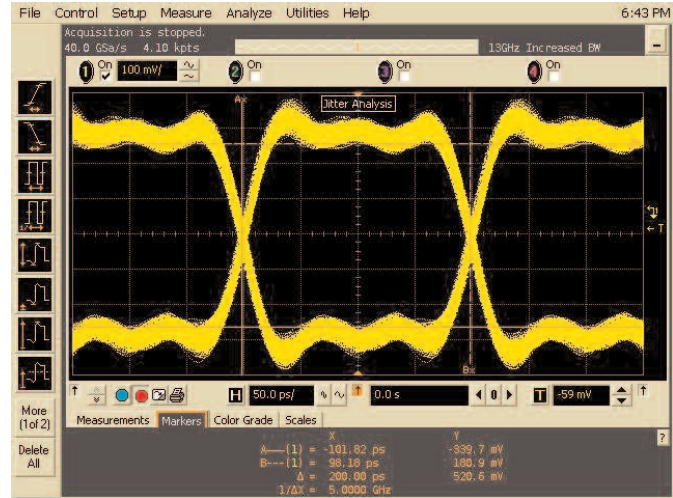
### ■ ENOB Effects on Eye Diagrams

As you might expect, ENOB effects can also be seen on eye diagrams. Both amplitude and jitter on the eye are impacted by ENOB performance

The following are two eye diagrams that were created using the same BERT pattern generator as a signal source, with the data rate set at 5Gbps. This is representative of the signals associated with PCI-E Gen2 and USB 3.0. This signal was applied to the Tektronix DPO70000B, as well as the Agilent DSO81304. Both instruments we set as near as possible to the same settings prior to making measurements. Both instruments were set up to measure TIE Jitter.

From the side-by-side comparison, you can see that both jitter and amplitude noise are impacted. The measured jitter using the Tektronix oscilloscope for this test was 3.08ps pk-pk, whereas the measured jitter using the Agilent oscilloscope shows 11.4ps pk-pk on the same signal. The Agilent oscilloscope measured over 350% more jitter for this signal.

Likewise, the amplitude measurements show substantial differences. In this case, a rough measurement of the eye height at the 50% point of the eye showed approximately 582mV on the Tektronix oscilloscope, as compared to approximately 521mV on the Agilent oscilloscope. In this case, the Agilent oscilloscope measured 10% lower at the 50% point of the eye.



### Conclusion

As we have seen, effective bits is a general figure of merit for signal integrity in any A/D system, including real-time oscilloscopes. Effective bits represents the cumulative errors in a digitizing system across a frequency range, for a fixed instrument setting. Generally, the effective bits decreases as frequency increases.

We have seen that the errors associated with lower effective bits performance can easily be seen in real-world signals as increased noise when performing amplitude measurements, and increased jitter when making jitter measurements.

As the effective bits decreases, the measurement precision of the instrument decreases. This directly equates to the margin available for tests being performed on the instrument. For example, you might find that you are not able to pass a compliance test for a particular standard because the instrument being used simply doesn't have the margin needed for the test limits that are specified. Instruments with higher effective bits will produce more repeatable measurements due to the superior precision of the measurement system.

Gen2 and Gen3 data rates demand more performance from the test instrumentation. It is not enough to have adequate bandwidth on the oscilloscope being used to make measurements. Excellent ENOB performance is also required to assure adequate margin on the measurements being made.

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Updated 30 October 2008

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