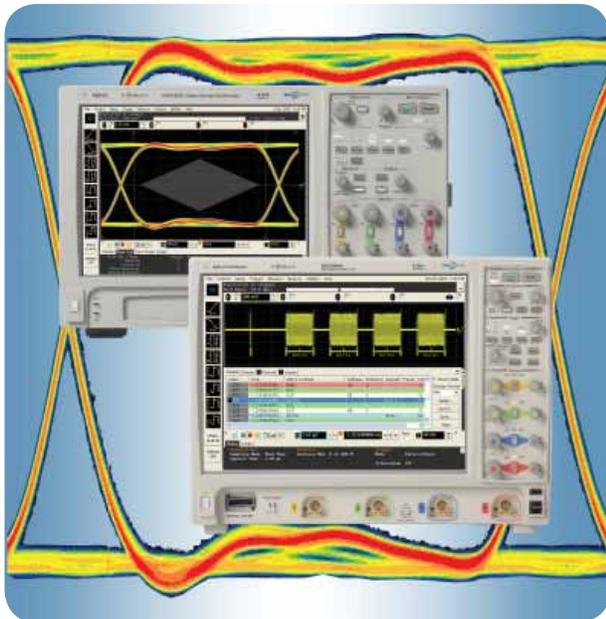


Understanding the Right Metrics to use when Evaluating Oscilloscope Quality

Application Note

Introduction

The oscilloscope is today an indispensable tool in any engineer's toolbox. With its ability to view signal voltages, the oscilloscope can be used to diagnose malfunctions in electronic equipment and check the electronics in a range of applications in the scientific, medical, engineering, and telecommunications industries. The trick, of course, is selecting the right oscilloscope and that means having to evaluate its performance (see the sidebar, "Understanding Oscilloscope Accuracy"). Banner specifications like bandwidth, sample rate and memory depth can provide a basis for comparing different vendor's oscilloscope. Yet, even if an oscilloscope has superior banner specifications it may fail to provide the accurate results today's engineers demand. Selecting the right oscilloscope therefore, is not quite as easy a task as it might sound.



Understanding Oscilloscope Accuracy

Why is accurate performance so critical in an oscilloscope? To answer that question, consider that during operation, the oscilloscope's front end conditions a sampled signal so that the A-to-D converter (ADC) can properly digitize the signal. This front end is comprised of an attenuator, pre-amplifier and path routing.

When designing an oscilloscope for accuracy, designers need to consider the entire signal path, involving both the front-end and ADC blocks. They may spend years designing front-end chips that have a flat frequency response, low noise and high bandwidth. Moreover, since oscilloscopes demand cutting-edge ADC technology, especially those operating in the high GHz range, oscilloscope vendors will typically design their own ADC chips. Such development can take years of design work and cost millions of dollars. This investment is well worth the effort though, when design teams are able to maximize an oscilloscope's accuracy, meaning that both the front-end and ADC technology blocks induce the least possible change in measured signals.

To accurately evaluate an oscilloscope's quality, engineers must consider both banner and non-banner specifications like update rate, jitter measurement floor, noise floor, and measurement repeatability. Effective Number of Bits (ENOB) is another specification that can be useful in this evaluation and is often advertised by vendors as the best way to measure an oscilloscope's "goodness." Can engineers rely solely on ENOB to evaluate an oscilloscope, or is it merely one of a number of figures of merit they should consider? Let's take a closer look



Evaluating Oscilloscope Measurement Quality

One of the key criteria that can be used to evaluate an oscilloscope's measurement quality is noise floor. To ensure accurate signal measurements, the oscilloscope must have a low noise floor. To better understand this requirement, consider a scenario in which margin testing is being conducted on a digital signal's real-time eye. In this case, oscilloscope noise will erode eye height and impact eye width because it erodes rise times and increases the jitter measurement floor. This leads to ghost noise that may impact a device's pass or fail.

Typically, the higher the oscilloscope's bandwidth the more internal noise it will produce since it accepts cumulative noise from higher frequencies that are normally rejected by the lower frequency roll-off of lower-bandwidth oscilloscopes. Oscilloscope noise adds unwanted jitter and erodes crucial design margins, so accurate measurement demands that the oscilloscope have a low noise floor.

Ideally, the oscilloscope's noise floor should be characterized at different vertical settings and offset. This will let the engineer know just how effective the oscilloscope's designers have been in designing a quiet front-end and ADC converter. The oscilloscope noise can be measured using the following steps:

1. Disconnect all inputs from the oscilloscope channels, such that the measurement screen resembles that shown in Figure 1.

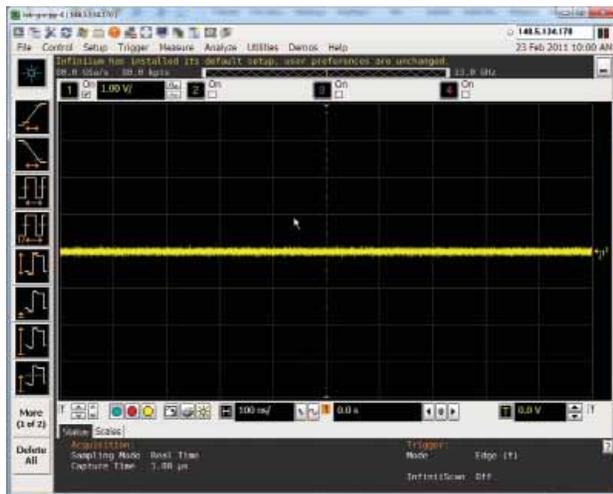


Figure 1. An oscilloscope screen that is not measuring any input

2. Turn on a single channel.
3. Choose the vertical setting that you need to measure. As an example, 100mV/div is a very typical vertical setting.
4. Choose a minimum of 500 kpts of data to be sampled.
5. Change the time scale to 500 nS/div. Note that each vendor does this differently. Ensure that the sample rate is held constant (Figure 2).

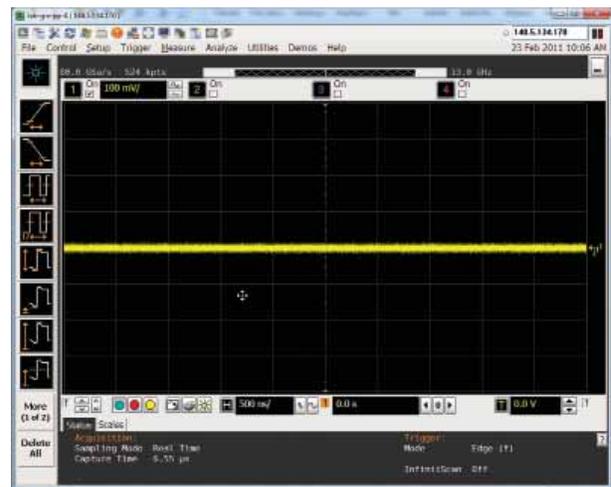


Figure 2. In this example, the sample rate is 80 GSa/s

6. Enable the AC RMS voltage measurement. This measurement is necessary because the vertical histogram is not available on all oscilloscopes. Make sure the measurement enabled is set to "single cycle." For the Tektronix 70000C oscilloscope, the "eye mode" should be enabled as the oscilloscope defaults to "pulse mode." For LeCroy oscilloscopes, the "flat" frequency response should be enabled to ensure equal comparisons.
7. Both Agilent and Tektronix offer a vertical histogram capability, which is an excellent way to compare results with the AC RMS measurement. For these vendor's oscilloscopes, enable the vertical histogram measurement. For Agilent oscilloscopes, this can be done by choosing: Analyze → Histogram → Enable Histogram → Orientation to Vertical (Figure 3). Use the Std Dev measurement in the histogram window. Note that it should be the same as the AC RMS measurement.

Evaluating Oscilloscope Measurement Quality

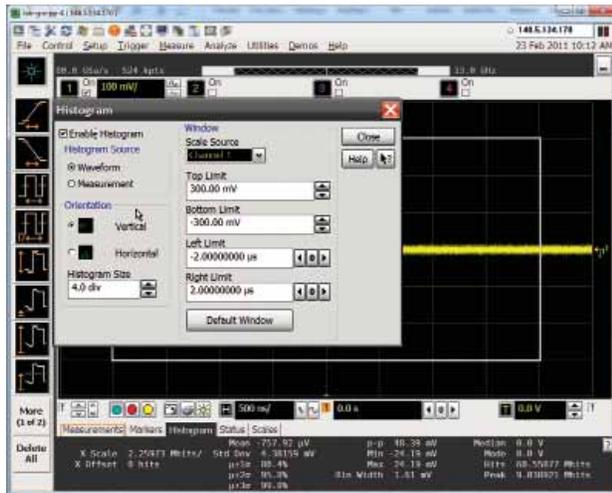


Figure 3. Histogram measurement window for an Agilent oscilloscope

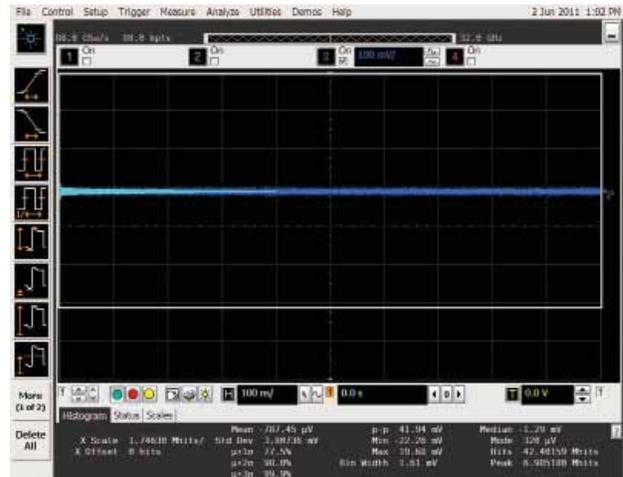


Figure 4. The offset can be changed by adjusting the signal up one division

8. Record the measurement.
9. Repeat steps 3 to 8 at various bandwidth points to achieve a true noise per bandwidth curve.
10. Change the offset by moving the signal up one division on the screen, as shown in Figure 4.
11. Repeat steps 3 to 9.

Understanding ENOB

While the noise floor specification can be very useful in determining an oscilloscope’s measurement quality, it is still just one means of making this assessment. The IEEE defined an alternative method in the late 1900s that relies on the ENOB specification to determine the “goodness” of an oscilloscope’s ADCs. Essentially, ENOB summarizes the bits of resolution of the entire system and represents the cumulative errors across a frequency range. ENOB decreases as frequency increases.

Typically, modern oscilloscopes use one of two ADC architectures: pipelined or flash. Pipelined ADCs use two or more steps of subranging to achieve a higher sample rate. As an example, the 90000 X-Series oscilloscope has a 20 GSa/s ADC that combines 80 subranges of 256 MSa/s to achieve its high sample rate. In contrast, flash ADCs use a bank of comparators to sample the input signal in parallel, each firing for their respective decoded voltage range. The comparator bank feeds a logic circuit that generates a code for each voltage range. Note that each ADC technology has its own inherent limitations. Flash ADCs are more prone to linearity errors, while pipelined ADCs typically have more interleaving error.

To determine limiters to the ADC, vendors will often characterize the overall ENOB of their oscilloscope system. The resulting system ENOB is lower than that of a stand-alone ADC. Because the oscilloscope’s ADC is part of an overall system and cannot be used independently, only the ENOB results from the overall system are useful. Note that ENOB results vary by frequency and that each oscilloscope model has its own unique ENOB plot (Figure 5).

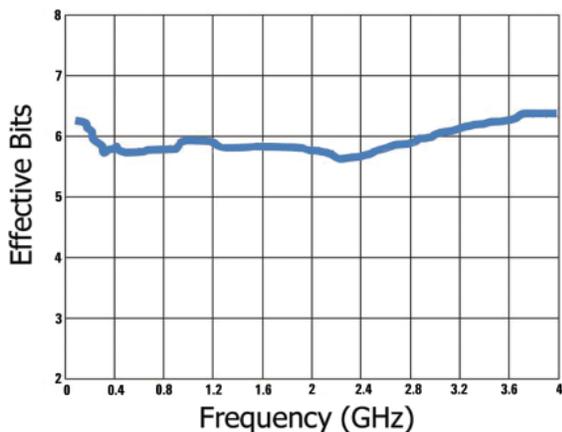


Figure 5. Shown here is sample ENOB plot for Agilent’s Infiniium 9000 Series oscilloscope. The plot represents ENOB for the entire scope system and not just its 8-bit ADC.

Most modern oscilloscopes are typically 8 bits, meaning they are able to display 256 levels. Although, engineers rarely have oscilloscope performance that achieves the full 8 bits of resolution. To maximize the oscilloscope’s effective number of bits, typically the signal must use the entire vertical range. The downside, of course, is that too much signal can be driven into the ADC, causing saturation and undesired effects on the signal. For example, with a signal that is scaled to take 90% of the vertical range, the engineer must reduce the scope’s 8-bit converter to 7.2 bits (0.90×8 bits). Even in a perfect world, oscilloscope users typically deal with less than the full 8 bits. Couple this with the real-world environment in which oscilloscopes are flawed by front-end noise, harmonic distortion and inter-leaving distortion, and the result is even further degradation in ENOB.

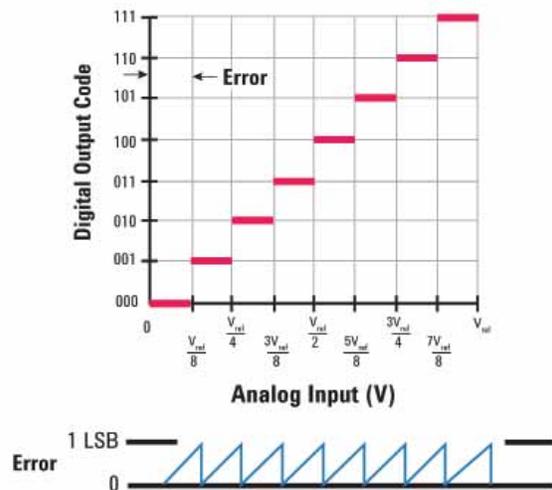


Figure 6. The magnitude of the error ranges from zero to 1 LSB

Figure 6 shows a 3-bit ADC with up to 8 quantization levels. In this example, the signals that increase in voltage also increase in quantization errors by $V_{ref}/(2^3)$. The maximum errors that can be seen are $V_{ref}/8$ or $\pm 1/2$ the least significant bit. The more bits a system has, the less impact any errors will have. This fact can clearly be seen by examining the difference in maximum error between an 8-bit and 14-bit ADC (Table 1).

Bit of Resolution	Quantizing Levels	At 1V Full Scale 1 LSB =
8-Bit	256	3.9 mV
10-Bit	1,024	976 μ V
12-Bit	4,096	244 μ V
14-bit	16,384	61 μ V

Table 1. A system with more bits will have less impact from errors

Measuring ENOB

The oscilloscope's ENOB is measured as a fixed amplitude sine wave that is swept in frequency. Resulting voltage measurements are then captured and evaluated using a post processing tool like the MathWorks MATLAB. It can be measured in either the time domain or frequency domain. When evaluating the signal in the time-domain method, the ENOB is calculated by subtracting the theoretical best fit voltage versus time from what was measured. The difference from this calculation is noise, which can come from the oscilloscope's front-end and be caused by things like phase non-linearities and amplitude variations over frequency sweeps. Noise can also come from interleaving distortion from ADCs. When evaluating the same signal in the frequency domain, the ENOB is calculated by subtracting the power associated with the primary tone from the entire broadband power. The resulting algorithm looks like the following:

1. Apply the RF sine wave to a given channel and frequency well within the bandwidth (Figure 7).

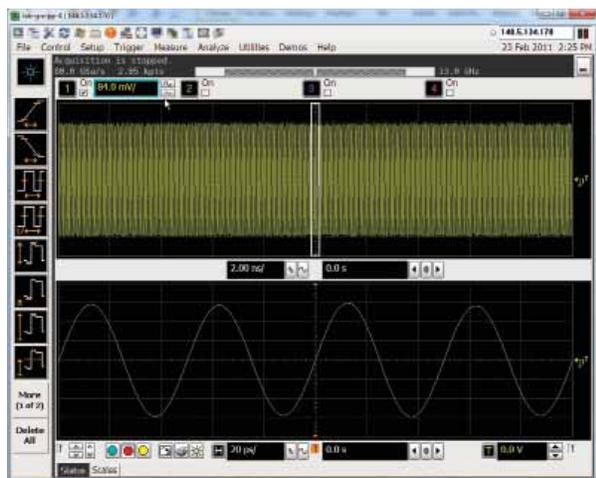


Figure 7. Applying the sine wave to a channel and frequency produces this waveform

2. Note the V_{pp} of the sine wave, as it is very important that the same signal input be used for each step.
3. Set the oscilloscope memory depth to 2000 pts and save the file.
4. Load the file into the MathWorks and calculate the mean-squared error of the data. Note that Agilent provides its oscilloscope users with a script that calculates the mean squared error and ENOB.
5. Repeat steps 1 to 4 at a different sine wave frequency to ensure that the V_{pp} is the same for each step. This is a critical step since variation in V_{pp} results in higher or lower ENOB.

Oscilloscope vendors often remind users how important it is that all instrument settings remain the same when making or analyzing ENOB measurements. If they are not the same, the ENOB results can be impacted by the spectral purity of the source being used. The source and accompanying filters need to ensure that the source's ENOB is larger than that of the oscilloscope. Also, ENOB values are dependent on the amplitude ratio of the source signal to the oscilloscope's full screen amplitude. Consequently, ENOB values will be different if the source is 75% of full screen (what most users run their oscilloscopes at) versus 90% of full screen (recommended by the JEDEC standard). Any comparisons of ENOB or testing must therefore, take into account test signal amplitudes as well as frequency.

Using ENOB as a Measure of Quality

While ENOB does provide a good measure for showing how the ADC is impacted by external effects caused by the scopes internal errors, that doesn't mean it should be used as standalone criteria for selecting the right oscilloscope. Theoretically, if an oscilloscope has a good ENOB then it will have minimal timing errors, frequency spurs (usually caused by interleaving distortion) and low broadband noise. So, if an application relies primarily on sin waves, then it's safe to say that ENOB will provide an effective criterion for oscilloscope selection.

Unfortunately though, while the ENOB can provide the engineer with an indication of the oscilloscope's ADC and front-end "goodness," it fails to take into account several attributes. It does not account for offset, phase irregularities or frequency response distortion, and fails to include the effect of magnitude or phase flatness. For a clearer understanding of this limitation, consider the graph in Figure 8, which shows an input signal and display of this signal on two different oscilloscopes. Both instruments have the same ENOB, yet one displays a dramatically more correct representation of the input signal.

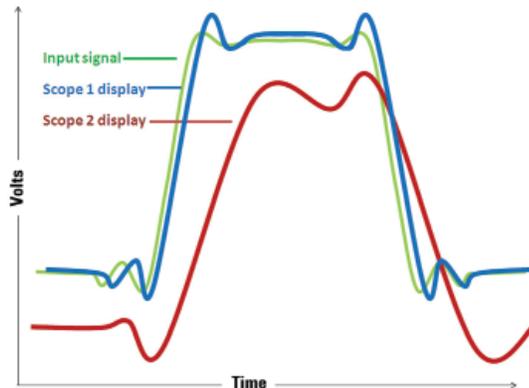


Figure 8. Scope 1 and 2 have the same ENOB, but scope 2 has offset and phase distortion errors that limit its ability to correctly display the input signal.

Another factor that ENOB fails to take into consideration is any offset errors that the oscilloscope may inject. Because of this, two oscilloscopes with equal ENOB may show identical wave shapes offset by differences in absolute voltage. In this case, adjusting the offset and measuring noise, or evaluating DC gain specifications would provide a better evaluation metric.

In an ideal world, oscilloscopes would all treat the frequency response and phase identically. This would definitely make it easier for engineer's evaluating an instrument's performance prior to making a purchasing decision. Phase and frequency plots aren't generally found in vendor datasheets though. Instead what they use are things like flat frequency response and linear phase plots or Gaussian roll-off and linear phase plots. ENOB is unable to account for any frequency response or phase irregularities and every oscilloscope is different.

Consider two oscilloscope models, each rated to 6 GHz. Both instruments produce different wave shapes when looking at a 2.1 GHz sine wave. One might have a slower bandwidth roll-off and minimal phase correction algorithms, while the other has a frequency response that peaks above 6 GHz before rolling off, along with significant algorithms for phase correction. The scope with the higher ENOB doesn't necessarily provide the more accurate representation of the input signal.

Summary

Like noise floor, ENOB provides one basis for oscilloscope evaluation. Yet, its computations fail to take into account a number of parameters that are critical to determining an oscilloscope's quality. Whether ENOB should be used as criteria for selecting the right oscilloscope will depend on what's being measured and whether or not the ENOB will affect the measurement outcome. For signals that are primarily fundamental sine waves, for example, ENOB serves as an excellent quality metric and the engineer will want to see the ENOB plot specific to the oscilloscope model in question. It is important to know what the effective bits performance of the selected oscilloscope looks like across its full rated bandwidth, as ENOB will vary with frequency.

It makes much more sense though, to view ENOB plots collectively with noise floor measurements. That's because high-speed serial data have harmonics at very specific frequencies that may pass through the oscilloscope virtually unaffected by a decrease in effective bits. In this scenario, the oscilloscope's noise floor may be a better indicator of measurement accuracy. Together, the ENOB and noise floor metrics can ensure accurate evaluation of oscilloscope quality and ultimately, help engineers select the right instrument.





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