Educational Note

UNDERSTANDING OSCILLOSCOPE ENOB VALUES

Selecting You Next Oscilloscope:

Products:
R&S®MXO 4 Oscilloscope
R&S®MXO 5 Oscilloscope
R&S®MXO 5C Oscilloscope / Digitizer

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ENOB OVERVIEW

If you are selecting your next oscilloscope and want more insight on how to understand ENOB values measured and published by oscilloscope manufacturers, this document is for you. The effective number of bits (ENOB) is a way of quantifying the quality of analog to digital conversion. A higher ENOB means that voltage levels recorded in analog to digital conversion are more accurate. Understanding oscilloscope vendor-supplied ENOB values can be complex. This document focuses on interpretation of measured ENOB results made on oscilloscopes rather than the math behind ENOB calculations. Key oscilloscope ENOB take-aways include:

1. ENOB values depend on both the scope settings and the input signal
2. A very spectrally pure input signal is needed to measure / compare ENOB values. Don't expect to get the manufacturer-reported ENOB values if a random signal generator is used.
3. ENOB values should be reported as sets of curves, but manufacturers typically report them as spot values. These values are less useful if the ENOB measurement parameters don’t match your application parameters
4. ENOB is only one part of overall scope performance. Just because a scope has a higher ENOB for a specific input frequency and oscilloscope setting, doesn’t necessarily mean it provides a more faithful representation of waveforms that contain a variety of different frequencies.

1 ENOB Overview

ENOB stands for Effective Number of Bits and is a quantitatively measured value that represents the "goodness" of analog to digital conversion. The higher the value, the better the ADC (analog to digital converter). All analog to digital conversion includes sources of noise and harmonic distortion. ENOB can be used to assign a numerical value describing the quality of the analog to digital conversion is for a pure single-tone sine wave.

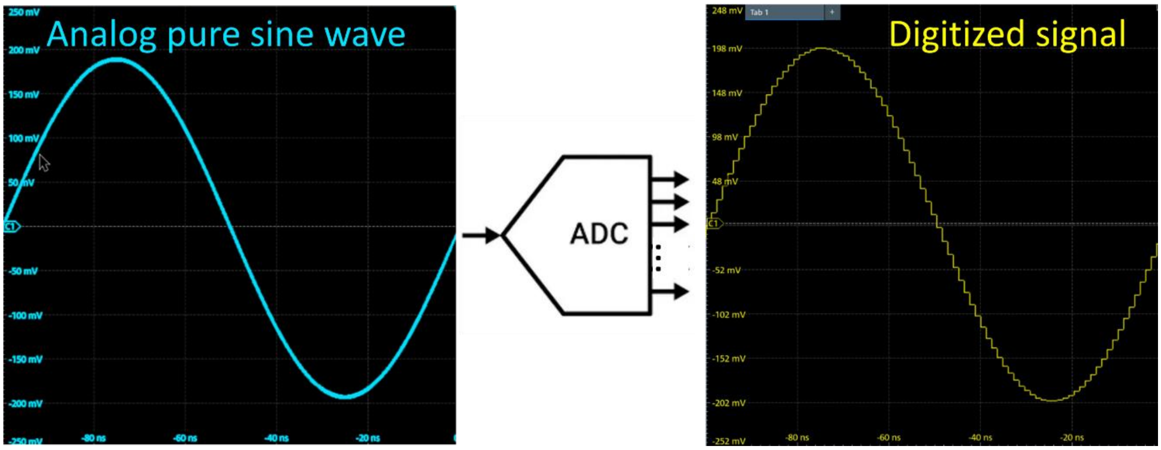
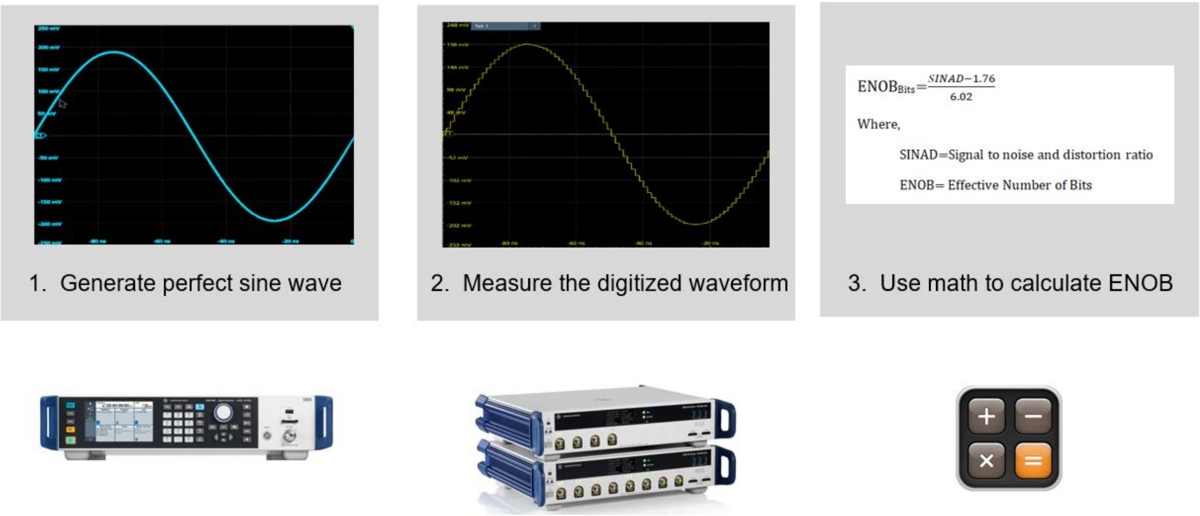


Figure 1. ENOB measures the quality of analog to digital conversion of a single-frequency input signals. The higher the number of effective bits, the better the digitization for that specific input frequency.

For oscilloscopes and digitizers, ENOB encompasses the entire signal path from the input connector on the instrument through post processing after the ADC. This is because the entire signal path impacts signal quality metrics that are measured together with ENOB. When measuring oscilloscope ENOB, this value can be computed by providing a scope with a pure single-tone wave input, capturing the sine wave on the instrument, and evaluating how well the captured signal compares to the signal before it went into the scope.

2 Oscilloscope ENOB characterization challenges

Oscilloscope ENOB characterization is a simple concept. Generate a pure single-tone sine wave, measure it on a scope, and use math to compute ENOB. It sounds simple. Right?



$$ENOB_{Bits}=\frac{SINAD-1.76}{6.02}$$

Where,

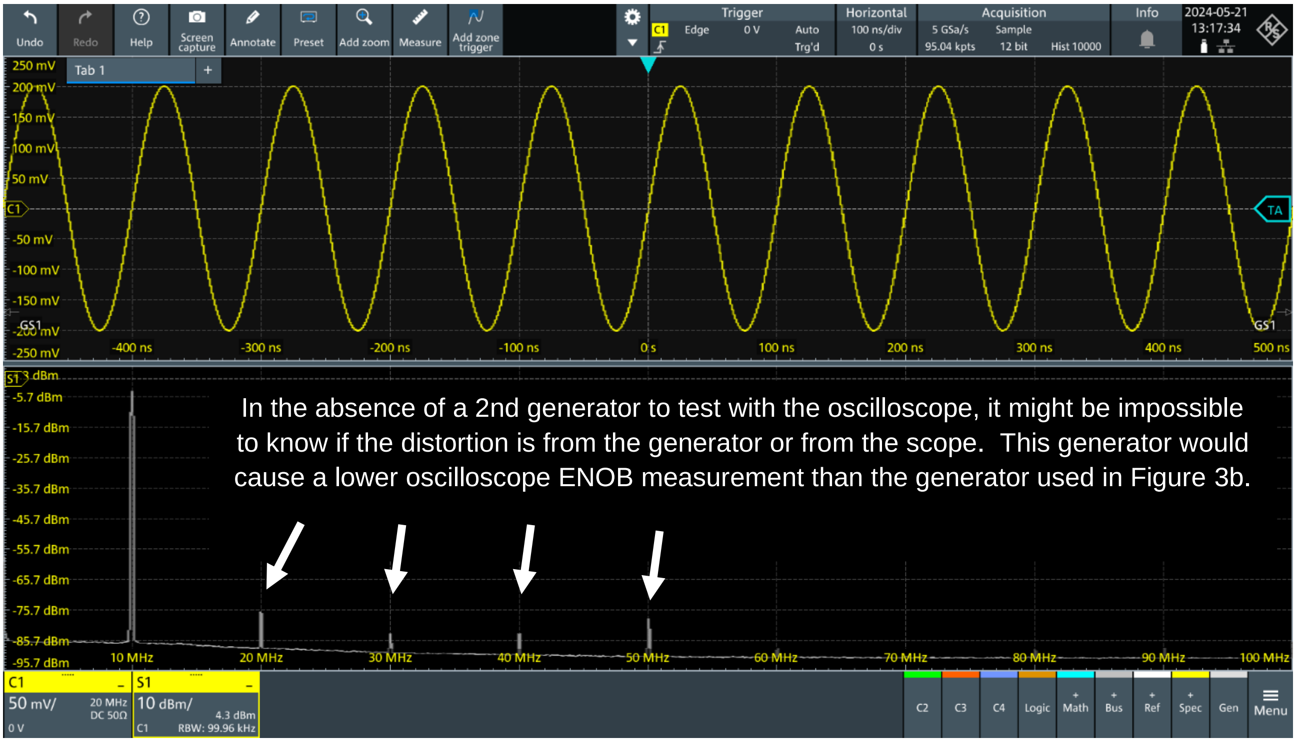
SINAD=Signal to noise and distortion ratio

ENOB= Effective Number of Bits

1. Generate perfect sine wave
2. Measure the digitized waveform
3. Use math to calculate ENOB

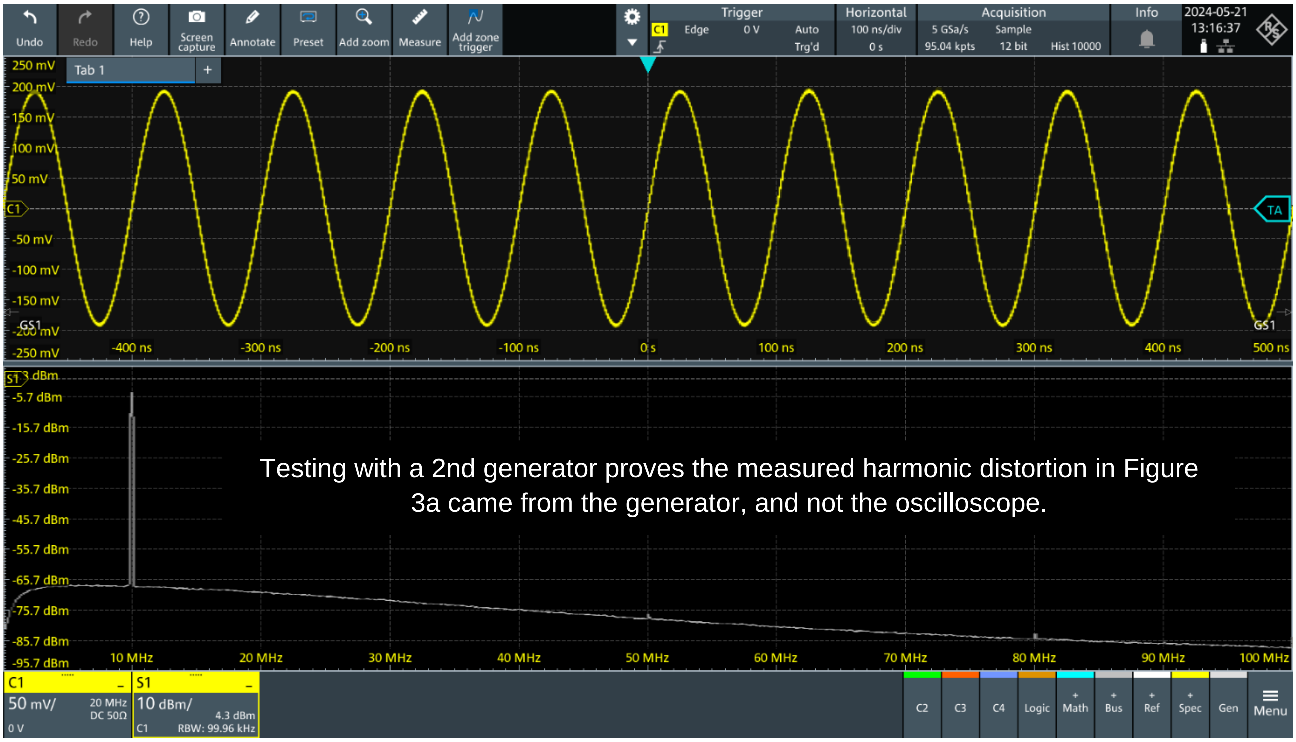
Figure 2. While oscilloscope ENOB characterization sounds simple, a number of challenges make the task complex.

1. Accurate and meaningful measurements require source ENOB >> oscilloscope ENOB. Generating a pure sine wave with no distortions is very difficult, even for the highest-quality generators. Measuring oscilloscope ENOB > 8 bits is very difficult as the oscilloscope waveform is often a result of the generator signal quality, not the ENOB of the oscilloscope. The choice of generator impacts ENOB. Let's look at the following measurement examples. In figure 3 the screen at the left shows the oscilloscope measuring a "pure" sine wave from a generator. One might think the harmonics are from the oscilloscope. Figure 3ba shows the exact same oscilloscope connected to a slightly better generator. The harmonics have largely disappeared and the only thing that changed was the generator. If we had done an oscilloscope ENOB measurement using the generator on the left, we would have measured the signal purity of the generator and not the ENOB of the oscilloscope.



In the absence of a 2nd generator to test with the oscilloscope, it might be impossible to know if the distortion is from the generator or from the scope. This generator would cause a lower oscilloscope ENOB measurement than the generator used in Figure 3b.

Figure 3a. Oscilloscope ENOB measurements of greater than 8 bits can be tricky as the instrument ENOB measurement may be directly related the goodness of the generator creating the "pure" sine wave rather than the ENOB of the oscilloscope. The scope's spectrum shows harmonic distortion. It's impossible to know if this is from the generator or from the oscilloscope



Testing with a 2nd generator proves the measured harmonic distortion in Figure 3a came from the generator, and not the oscilloscope.

Figure 3b. Shown is the identical oscilloscope spectral view as in figure 3a using a generator with greater spectral purity at 10 MHz than the generator used in Figure 3a.

In addition to choosing a generator with sufficient signal spectral purity, one method for improving source generator tone quality is to use a low-pass filter, or very narrow notch filter directly on the output of the generator. This attenuates out-of-band harmonics and ensures higher purity of the generated sine wave. While this is practical for a single tone such as 10 MHz, finding notch filters and measuring at every tone using this tactic up to the instrument's bandwidth is not practical. It's also really hard to make a notch filter that doesn't have significant ripple, and so a low band pass filter is typically used. To further ensure a pure input from a generator, oscilloscope and digitizer manufacturers often state a measured ENOB value made with a 10 MHz sine wave input since there are methods for generating this frequency with greater spectral purity versus higher input frequencies.

2. Measured oscilloscope ENOB is a function of the incoming sine wave frequency. ENOB is really a curve, not a single data point, and the curve covers a range of frequencies as the generator is swept up to the instrument's bandwidth. With all other instrument settings static, the oscilloscope will have a different ENOB value if the incoming sine wave is 10 MHz versus a 1 GHz sine wave. Generally, measured ENOB values are higher for lower frequencies, but this isn't always the case. Oscilloscopes generally have some 3rd order harmonic distortion. If the incoming sine wave is near the full bandwidth of the oscilloscope, the 3rd order harmonic will be out-of-band, and hence attenuated. Therefore, measured oscilloscope ENOB values often increase at the frequency where the 3rd harmonic goes out of band and no longer negatively contributes to the measured ENOB value.
3. Measured oscilloscope ENOB values are dependent on a number of oscilloscope settings. ENOB measurements will yield different results as these settings are changed. Key oscilloscope setting that impact ENOB are:
   - Signal path: 50 Ω or 1 MΩ
   - Vertical sensitivity: 1 mV/div, 2 mV/div, 5 mV/div, 10 mV/div, 20 mV/div, 50 mV/div, etc.
   - Instrument bandwidth: more bandwidth means more broadband noise and more potential of broadband harmonic distortion that contribute to SINAD.
   - % of the instruments dynamic range (FS=full scale): the ratio of the input signal amplitude vs the maximum amplitude on the oscilloscope display
   - Additional instrument digital and/or analog filters/processing: these can be turned on/off to limit bandwidth, reduce noise, or perform other processing on acquired samples to yield high signal quality. One example is HD (high-definition) mode for R&S oscilloscopes.

4. Perhaps the most straightforward path is the math computation. However, as described above, ENOB is an n-dimension measurement for oscilloscopes. It's a series of plots, with each plot containing a swept frequency with a set of fixed scope settings. A large stack of plots isn't an effective form of communication for users who want a simple ENOB value as a reference or a metric of signal quality comparison from one scope to another scope. Therefore, ENOB communication is often simplified by reporting one specific datapoint where measured ENOB is at a maximum value. When multiple manufactures use the same datapoint and setup, the value can be used to provide comparison. Unfortunately, often is this not the case making comparison more difficult.

3 R&S MXO Oscilloscope ENOB Values

Like other oscilloscope manufacturers, R&S characterizes instrument ENOB values. In both the oscilloscope and digitizer industry, manufacturers often pick specific a specific common measurement point in order to more effectively communicate ENOB. For oscilloscopes, this is usually:

- 50 Ω path
- 50 mV/div vertical scale (500 mV Full Scale)
- Input signal near 10 MHz where a high-quality low-pass or notch filter can be used to increase the purity of the sine wave.
- Use of instrument filters that can be turned on and still allow the incoming generator tone to be measured (digital and/or analog filters)

This results in an ENOB value that can be used for comparison of how well a scope's digitization works with a specific input tone. These published ENOB values are typically not characteristic of instrument's signal quality for user applications, unless the user is operating with the specific oscilloscope settings.

MXO4, MXO5, and MXO5C Series oscilloscopes achieve impressive ENOB values of 10 bits. This exceptional ENOB performance comes from a combination of the scope's excellent signal integrity such as low noise and advanced filter and processing technology.

MXO 4 Series oscilloscope

MXO 5C Series oscilloscope / digitizer

MXO 5 Series oscilloscope

Oscilloscope bandwidth	R&S MXO 4	R&S MXO 5, 5C
10 MHz	10.1	10.0
20 MHz	9.6	9.6
100 MHz	8.7	8.7
200 MHz	8.4	8.3
300 MHz	8.2	8.0
500 MHz	7.9	7.7
1 GHz	7.3	7.0

Measured using 10 MHz sine from SMA generator. Oscilloscope settings: 50 Ω path, 50 mV/division, 80% full screen, filters.

Figure 4. Measured ENOB values for MXO 4, MXO 5, and MXO 5C oscilloscopes.

4 Comparing ENOB Values Across Scopes

Oscilloscope manufacturers sometimes do not report measured ENOB values because it's easy to draw misleading comparisons when different test parameters and settings are used by different manufacturers. Remember that a single ENOB value provides a quantified metric of signal quality for a single generated frequency with one set of oscilloscope settings. ENOB comparisons between different oscilloscope models can only provide value if the same test settings and procedures are used.

It is important to also keep in mind that ENOB is only one signal integrity metric. ENOB is only one part of overall scope performance. Just because a scope has a higher ENOB for a specific input frequency and oscilloscope setting, doesn’t necessarily mean it provides a more faithful representation of waveforms that contain a variety of different frequencies. While ENOB includes errors from a single-tone distortion and noise, it omits other signal quality attributes that also impact an oscilloscope's ability to correctly represent a signal. Signal quality attributes not included in ENOB include frequency response flatness, DC offset accuracy, phase linearity, and timebase accuracy.

This document focuses on providing a foundation for understanding how to interpret ENOB results measured on oscilloscopes and digitizers. For an in-depth technical understanding of the math behind ENOB calculations, there are a number of industry papers available.

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