One of the most common sources of errors in measurements is the presence of vertical noise, which can decrease the accuracy of signal measurement and lead to such problems as inaccurate measurements as frequencies change. You can use ENOB (effective-number-of-bits) testing to more accurately evaluate the performance of digitizing systems, including oscilloscopes. The ENOB figure summarizes the noise and frequency response of a system. Resolution typically degrades significantly as frequency increases, so ENOB versus frequency is a useful specification. Unfortunately, when an ENOB specification is provided, it is often at just one or two points rather than across all frequencies.
In test and measurement, noise can make it difficult to make measurements on a signal in the millivolt range, such as in a radar transmission or a heart-rate monitor. Noise can make it challenging to find the true voltage of a signal, and it can increase jitter, making timing measurements less accurate. It also can cause waveforms to appear “fat” in contrast to analog oscilloscopes.

**THE ENOB CONCEPT**

Digitizing performance is linked to resolution, but simply selecting a digitizer with the required number of bits, or quantizing level, at the desired amplitude resolution can be misleading because dynamic digitizing performance, depending on the technology, can decrease markedly as signal speeds increase. An 8-bit digitizer can decrease to 6, 4, or even fewer effective bits of performance well before reaching its specified bandwidth.

When designing or selecting an ADC, a digitizing instrument, or a test system, it is important to understand the various factors affecting digitizing performance and to have some means of evaluating overall performance. ENOB testing provides a means of establishing a figure of merit for dynamic digitizing performance. You can use it as an evaluation tool at various design stages and as a way to provide an overall system-performance specification. Essentially, ENOB is a means of specifying the ability of a digitizing device or instrument to represent signals of various frequencies (Figure 1).

The figure illustrates that effective digitizing accuracy falls off as the frequency of the digitized signal increases. In this case, an 8-bit digitizer provides 8 effective bits of accuracy only at dc and low frequencies. As the signal you are digitizing increases in frequency or speed, performance drops to lower and lower values of effective bits.

This decline in digitizer performance manifests itself as an increasing level of noise on the digitized signal. Noise in this case refers to any random or pseudo-random error between the input signal and the digitized output. You can express this noise on a digitized signal in terms of SNR (signal-to-noise ratio): $SNR = \frac{rms_{\text{SIGNAL}}}{rms_{\text{ERROR}}}$, where $rms_{\text{SIGNAL}}$ is the root-mean-square value of the digitized signal and $rms_{\text{ERROR}}$ is the root-mean-square value of the noise error. The following equation yields the relationship to effective bits: $EB = \log_2(SNR) - \frac{1}{2}\log_2(1.5) - \log_2(A/FS)$, where $EB$ is the peak-to-peak input amplitude of the effective bits, $A$ is the peak-to-peak full-scale range of the digitizer's input. Other commonly used equations include $EB = N - \log_2(rms_{\text{ERROR}}/IDEAL\_QUANTIZATION\_ERROR)$, where $N$ is the nominal, or static, resolution of the digitizer, and, $EB = -\log_2(rms_{\text{ERROR}}) \times \sqrt{12/FS}$.

These equations employ a noise, or error, level that the digitizing process generates. In the second equation above for $EB$, the ideal quantization error term is the $rms$ error in the ideal, N-bit digitizing of the input signal. The IEEE Standard for Digitizing

![Figure 1](image1.png) When comparing digitizer performance, it is important to test the full frequency range.

![Figure 2](image2.png) Quantizing errors are inherent parts of digitization.
Waveform Recorders (IEEE Standard 1057) defines the first two equations (Reference 1). An alternative for the third equation assumes that the ideal quantization error is uniformly distributed over one LSB (least-significant bit) peak to peak. This assumption allows you to replace the ideal quantization error term with \( \frac{\text{FS}}{2^N \sqrt{12}} \), where FS is the digitizer’s full-scale input range.

These equations employ full-scale signals. Actual testing may use test signals at less than full-scale—50 or 90% of full-scale, for example. Improved ENOB results can improve this result, so comparisons of ENOB specifications or testing must account for both test-signal amplitude and frequency.

Noise or error relating to digitizing can come from a number of sources. Even in an ideal digitizer, quantizing causes a minimum noise or error level amounting to \( \pm \frac{1}{2} \) LSB. This error is an inherent part of digitizing (Figure 2). It is the resolution limit, or uncertainty, associated with ideal digitizing. A real-life digitizer adds further errors to this basic ideal error floor. These additional real-life errors can include dc offset; ac offset, or “pattern” errors, sometimes called fixed pattern distortion, associated with interleaved sampling methods; dc and ac gain error; analog non-linearity; and digital nonmonotonicity. You must also consider phase errors; random noise; frequency-timebase inaccuracy; aperture uncertainty, or sample-time jitter; digital errors, such as data loss due to metastability, missing codes, and the like; and other error sources, such as trigger jitter.

### ENOB MEASUREMENT

Beyond these error sources, still other possible sources of digitizing error exist. For example, in high-speed real-time digitizing without sample-and-hold or track-and-hold tracking, the LSBs must change at high rates to follow a quickly changing signal. This requirement increases bandwidth requirements for data lines and buffer inputs for these lesser bits. If you do not meet bandwidth requirements, quickly changing lesser bits can be dropped, lowering the ENOB.

It is often easier to measure overall performance instead of trying to distinguish and measure each error source in a digitizing system. A good place to start is by determining the digitizing system’s SNR and the resulting effective bits according to the preceding equations. This approach provides an easily understood and universal figure of merit for comparisons.

The basic test process involves applying a known, high-quality signal to the digitizer and then analyzing the digitized waveform. The test uses a sine wave as the test signal because high-quality sine waves are relatively easy to generate and characterize. The general test requirements are that the sine wave generator’s performance must significantly exceed that of the digitizer under test. Otherwise, the test will be unable to distinguish digitizing...
and use in comparisons. ENOB depends on the input signal’s percentage of full-scale digitizer amplitude. Testing a digitizer at less than full-scale amplitude generally yields a somewhat better ENOB figure than does testing it at full-scale. Whatever test approach you use—full-scale or partial scale—the input test signal’s amplitude specification should accompany the results.

**SCOPE NOISE**

When comparing digital oscilloscopes with analog oscilloscopes, a common misperception is that digital oscilloscopes have a higher level of vertical noise. With digital oscilloscopes, the trace may appear fatter than that of its analog-oscilloscope equivalent. A digital oscilloscope does not have higher noise levels than the equivalent analog oscilloscope, however; it just appears that way.

Analog oscilloscopes with CRT displays do not display the extreme ranges of noise because they occur quickly and infrequently (Figure 4), meaning that the phosphor lights quickly and infrequently, and those extremes are dim or not on the screen at all. Analog instruments do not just display voltage versus time but have a third dimension: intensity. Intensity relates to the frequency of occurrence of the signal. A DSO (digital-signal oscilloscope) shows every hit with the same intensity, no matter the frequency of pixel hits (Figure 5). DPOs (digital-phosphor oscilloscopes)
offer a way to restore that third dimension by grading the signal employing the frequency of the hits (Figure 6).

**REAL-WORLD SIGNAL NOISE**

ENOB performance indicates noise that has an effect on both amplitude and timing measurements. To illustrate the effects of noise on amplitude, a test applied a 6.5-GHz sine wave to a Tektronix (www.tektronix.com) DPO/DSA70000B oscilloscope with a 13-GHz bandwidth and a 400-mV full-scale voltage. It also has infinite display persistence so that you can see variations across all acquisitions. With no averaging, the test run included approximately 10,000 acquisitions. The result is approximately 15.9 mV of trace thickness at the peak, representing 3% of full-scale on this oscilloscope (Figure 7). This result corresponds to approximately 5.9 ENOBs at 6.5 GHz (Figure 8). Comparative testing shows other oscilloscopes with more than 35-mV trace thickness at the peak and approximately 4.5 ENOBs using identical test setups.

**ENOB EFFECTS**

ENOB effects can also be seen on
you should carefully evaluate ENOB performance, especially for applications involving high bit rates and fast edges.

**REFERENCE**


**AUTHOR’S BIOGRAPHY**

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The test applies this signal to the Tektronix DPO70000B oscilloscope, with the instrument set up to measure TIE (time-interval-error) jitter, affecting both jitter and amplitude noise. The measured jitter for this test was 3.08 psec p-p. In comparison testing, some oscilloscopes show more than 11 psec p-p on the same signal.

Similarly, noise also affects the eye's amplitude. In this case, a measurement of the eye height at the 50% point of the eye shows approximately 582-mV amplitude. This result compares with less than 525 mV measured on other instruments.

All digitizing systems have noise that only gets worse as speeds increase. Therefore, it is useful to have a way to evaluate the real-life noise performance of digitizing systems, including test instrumentation. ENOB is a general figure of merit for signal integrity in any analog or digital system, representing the cumulative errors across a frequency range. Generally, the ENOB figure decreases as frequency increases.

You can easily see errors relating to lower ENOB performance in real-world signals as increased noise when performing amplitude measurements and increased jitter when making jitter measurements. As the ENOB figure decreases, the measurement precision of the instrument decreases, directly equating to the margin available for the tests you are performing on the instrument. With these factors in mind,