# ENOB: The Best Digitizer Performance Metric

*By Andrew Dawson, Ph.D, Vitrek*

## Introduction

While the nominal vertical resolution of a high-speed waveform digitizer (specified in bits) is often promoted, its true performance is provided by its measured *Dynamic Parameters* and in particular by its *Effective Number of Bits (ENOB)*. This article describes measurement of the Dynamic Parameters and presents measurements for a leading-edge GaGe 12-bit Digitizer.

A widely used digitizer-like device, the Digital Storage Oscilloscope (DSO), is optimized for the visualization of unknown signals. The relatively low 8-bit vertical resolution of most DSOs is sufficient for signal visualization and is offered at the highest sampling rates (~200 GigaSamples/second). Furthermore, high-end DSOs are often optimized for the determination of signal edge positions in the time-domain, such as in eye-diagram measurements. Accordingly, product marketing typically promotes DSO's high input bandwidth and vertical performance parameters are not emphasized.

*Figure 1. GaGe High-Speed Digitizers including PC Oscilloscope Software, powerful SDKs for custom application development and turnkey integrated PC-based measurement systems.*

## Signal Fidelity Considerations

In contrast to DSOs, dedicated digitizers — such as those on modular platforms like PCIe or PXIe — are usually optimized for the rapid acquisition and analysis of small changes in familiar signals. While providing lower maximum sampling rates, digitizers typically offer higher vertical resolutions of 12-, 14-, and 16-bits. Consequently, a proper understanding of the Dynamic Parameters is paramount for digitizer users.

There is an important distinction between the *absolute accuracy* and the *relative accuracy* of a digitizer. The absolute accuracy of a digitizer describes how close its measured voltage values correspond to true absolute voltage reference standards. By contrast, its relative accuracy specifies the fidelity of the shape of the acquired waveform with no reference to absolute voltage standards. Using on-board calibration techniques, a high-speed digitizer may achieve absolute accuracies of order 0.1% of the full-scale input voltage range. In most digitizer applications, however, users are concerned principally with relative accuracy, which is specified by the Dynamic Parameters.

The fidelity of a signal acquired by a digitizer device may be compromised by three distinct factors:

1. Addition of random noise by the digitizer to the acquired signal.
2. Distortion of the acquired signal by the digitizer.
3. Irregularities in uniformity of the time intervals between samples acquired by the digitizer arising from imperfections in the ADC clocking signal.

The distinction between signal noise and signal distortion is illustrated in Figures 2A and 2B. The figures show a pure sine wave, together with a sine wave that has been compromised by the addition of broadband signal noise and by signal distortion. Distortion is shown as attenuation near the input range limits, which is the typical precursor to signal clipping.

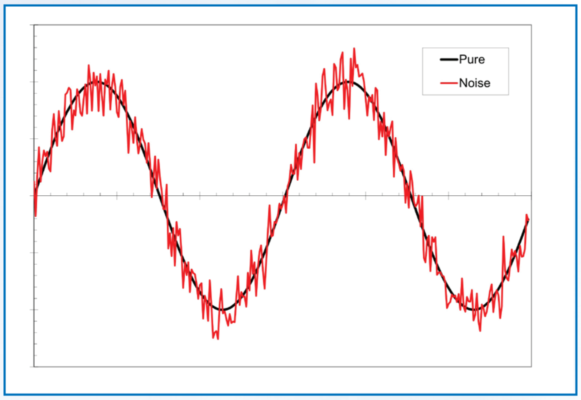


*Figure 2a. Illustration of a pure sine wave (black) and one that has picked up noise (red).*

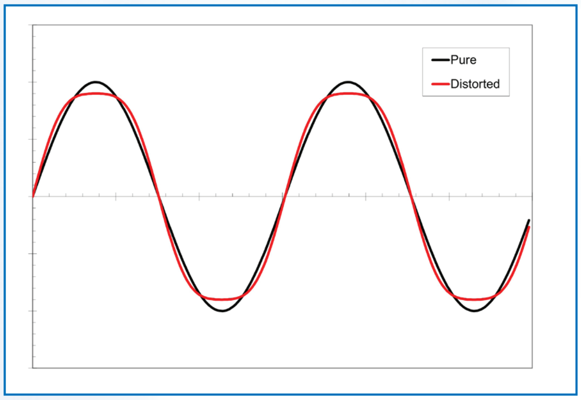


*Figure 2b. Illustration of a pure sine wave (black) and one that has suffered distortion (red).*

As a rule, the design of an amplifier for low noise and for minimal distortion represent opposing design goals. This principal is illustrated in Figure 3, which shows the transfer curve for an idealized amplifier component. Consider that a small amount of random noise is picked up at the output of this amplifier. If the amplifier was configured for high gain, then it operates in the red region of Figure 3. In this case, the signal suffers high signal distortion, due to the visible curvature of the transfer curve at higher voltage where it begins to saturate. Alternately, if the amplifier was configured for low gain in the green region of Figure 3, then the transfer curve is highly linear and distortion is minimal. The reduced output signal amplitude, however, will result in the noise pickup having a proportionately larger effect. This simple example illustrates the interdependencies that links noise and distortion - namely that if one increases the other generally decreases.

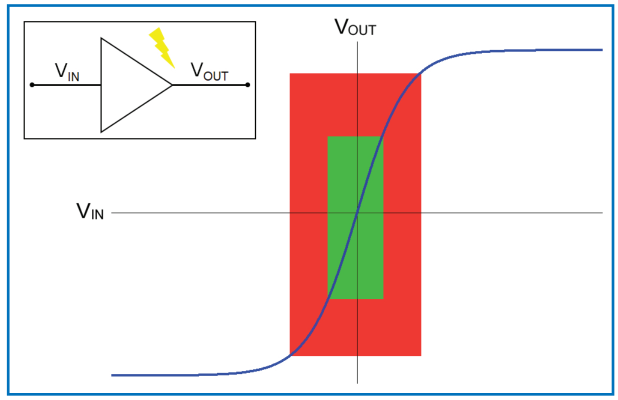

*Figure 3. Transfer function of an idealized amplifier. Small signal (green) and large signal (red) regions are indicated.*

The effects upon signal fidelity of imperfections in the ADC clocking signal are more difficult to describe. In general, we may distinguish two types of imperfections. In the case of *Phase Jitter*, the clock signal edges vary about their correct positions that are spaced exactly uniformly by the fixed clock period. In the case of *Frequency Drift*, however, the actual instantaneous clocking frequency changes over time. Phase Jitter tends to be a greater concern over the shorter term while Frequency Drift error builds up over the longer term. The effect of clocking imperfections will not be directly considered in the measurements below and their effects are assumed to manifest as an associated degradation in measured noise and/or distortion.

## Dynamic Parameter Measurement

There are two different measurement methods for characterizing digitizer performance. One method is performed in the *time domain* and the other in the *frequency domain*. Both methods involve acquisition of a high-purity sine wave signal by the digitizer under test. Creation of this high-purity sine wave usually requires filtering of the signal generator output by a high-quality multi-pole passive band-pass filter to remove noise and distortion intrinsic to the signal.

In the time-domain method, which is specified in IEEE 1057-1994, a sine wave function is fitted to the sine wave signal acquired by a digitizer. The resultant error function is then normalized to obtain the *SINAD*. From the *SINAD*, the *ENOB* is calculated as:

$$ENOB = \frac{SINAD - 20\log_{10}\sqrt{3/2}}{20\log_{10} 2} \approx \frac{SINAD - 1.76\text{ dB}}{6.02}$$

The *ENOB* is the single most important overall indicator of digitizer performance and allows for direct comparison with the number of bits indicated by the digitizer's nominal resolution. The ENOB depends upon signal frequency and also changes with all adjustable digitizer input settings - notably its input range. The main advantage of the time-domain method is that it produces *ENOB* values with no adjustable parameters. The primary disadvantage is that it does not allow for clear separation and characterization of digitizer noise and distortion.

The second method of characterizing digitizer performance requires signal analysis in the frequency domain. The acquired high purity sine wave is subjected to Fourier analysis and a Power Spectrum is obtained (Figure 4), usually after application of a time-domain windowing function to reduce spectral leakage.

Once the Fourier spectrum has been obtained, three different types of frequency bins are identified:

1. *Fundamental Bins* are those within a specified range of the known input sine wave frequency $f_0$.
2. *Harmonic Bins* are those within a specified range of harmonic frequencies ($2f_0$, $3f_0$, $4f_0$...)
3. *Noise Bins* are all remaining frequency bins.

The sum of all power amplitude values within each of the three types of bins respectively provides the Fundamental *Power F*, the *Harmonic Power H*, and the *Noise Power N*. Unlike with the time-domain technique, the identification of these three power values allows calculation of three *Dynamic Parameters:*

**Signal-to-Noise Ratio (SNR):** $SNR \equiv 10\log_{10}\left(\frac{F}{N}\right)$

**Total Harmonic Distortion (THD):** $THD \equiv 10\log_{10}\left(\frac{H}{F}\right)$

**Signal-to-Noise-and-Distortion Ratio (SINAD):** $SINAD \equiv 10\log_{10}\left(\frac{F}{N+H}\right)$

Unlike in the time-domain, the frequency-domain technique requires the adjustment of spectral parameters, such as the windowing function type and the number of frequency bins used to determine *F*, *N* and *H*. However, the method has the clear advantage of separating the noise and distortion introduced by the digitizer, which are respectively quantified by the *SNR* and the *THD*. The spectral display used in the frequency-domain method also provides a useful visual tool for design feedback during digitizer development.

As in the time-domain technique, the *ENOB* is calculated directly from the *SINAD*. The two methods may be shown experimentally to render equivalent *ENOB* values in most circumstances.

Independent of any noise pick-up within the digitizer, the act of digitization intrinsically adds noise to the signal. This is because the digitizer transforms a continuous analog voltage value into a discrete integer value, which results in an associated truncation error. This truncation adds a small uniform power to all frequency bins in the spectrum that can usually be ignored.

Most uncorrelated "random" noise added to the input signal by a digitizer usually results from pick-up of unavoidable local digital signals. This pickup leads to a broad spectrum of noise across the frequency spectrum and contributes to the reduction of the SNR.

The digitizer's *THD* is primarily degraded by signal distortion imposed within the digitizer's front end signal-conditioning circuitry, as illustrated in Figure 3. Unlike distortion, noise pickup is generated within a digitizer independent of an input signal so that the SNR does not depend upon the input signal frequency. In sharp contrast, distortion requires the presence of a signal and usually increases markedly with its frequency due to increased amplifier distortion. As a result, the digitizer's *THD*, *SINAD* and *ENOB*, usually degrade markedly with increasing signal frequency.

The fact that distortion produces harmonic frequency peaks is easily illustrated by considering the simplest possible distortion scheme, which is modeled in the equation:

$$V_{MEASURED} = A \times V + B \times V^2$$

where V is the voltage input to the digitizer, $V_{MEASURED}$ is the voltage measured by the digitizer and *A* and *B* are constants. The first term is linear and so causes no distortion while the second non-linear term can introduce distortion. Next, we insert a sinusoidal signal with frequency $f_0$ for the input V and use an elementary trigonometry identity:

$$V_{MEASURED} = A \times \sin(2\pi f_0 t) + B \times \sin^2(2\pi f_0 t)$$

$$V_{MEASURED} = A \times \sin(2\pi f_0 t) + \tfrac{1}{2}B \times (1 - \cos(4\pi f_0 t))$$

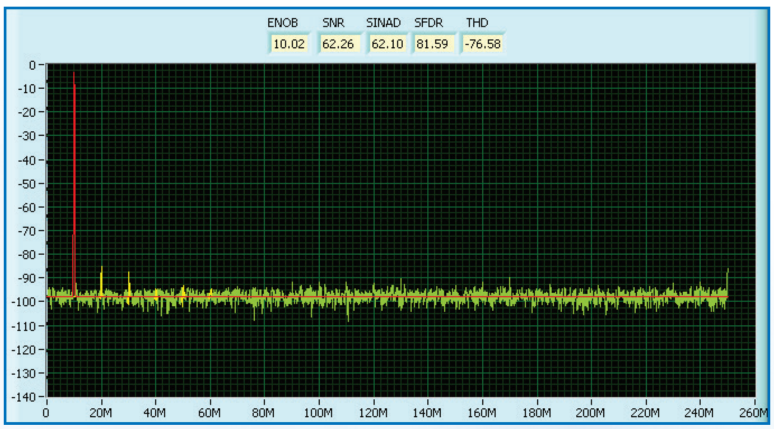


*Figure 4. Fourier Power Spectrum used for calculating Dynamic Parameters for a 12-bit GaGe digitizer with a 10 MHz sine wave input signal and sampling at 500 MS/s. Fundamental, Harmonic and Noise frequency bins are respectively indicated in red, yellow and green.*

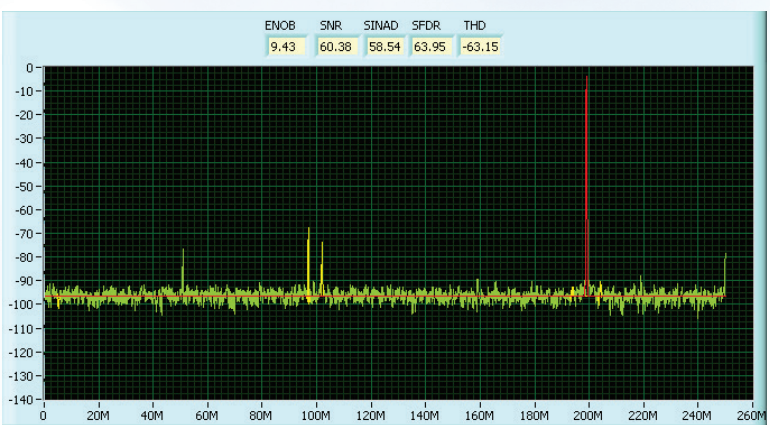


*Figure 5. Fourier Power Spectrum like in Figure 4 but for a 199 MHz sine wave input signal.*


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So, the effect of the second non-linear distortion term is to create a harmonic sine wave component at $2f_0$ - twice the input frequency. Real distortion is represented by a more complex distortion term, which leads to components at all harmonic frequencies $2f_0$, $3f_0$, $4f_0$... Generally, we consider harmonics up to $5f_0$.

Another useful digitizer performance parameter that may be extracted from a Fourier spectra like Figure 4 is the Spurious Free Dynamic Range (SFDR). This aptly named parameter is the vertical measure from the top of the Fundamental frequency peak to the top of the highest non-Harmonic peak in the Fourier spectrum. Valuable in communications, the SFDR determines the effective detectability limit of weak narrowband communications signals.

Discussed above, clocking Phase Jitter leads to broad-band noise and a skirt-like swell around the Fundamental peak and so mostly affects the SNR, not the THD. Long term Frequency Drift on the clock leads to frequency and timing errors. Modern digitizers are equipped with a high-stability sampling oscillator disciplined by high-precision 10 MHz reference oscillators in order to minimize both Phase Jitter and Frequency Drift.

## Dynamic Parameter Results

Having defined the Dynamic Parameters, we now present measurements on a high-performance 12-bit GaGe digitizer. From the definitions, we can conclude that the *ENOB* (and the *SINAD* from which it is trivially derived) is the single most informative digitizer performance parameter since it combines both digitizer noise and distortion into a single metric.

Like the noise and distortion, a digitizer's *ENOB* and input bandwidth are inversely related - if one improves then the other degrades. A simple illustration is the filtering of a signal by a low-pass filter. This action reduces high frequency noise and attenuates distortion harmonics - thus improving the *ENOB* while reducing the input bandwidth to the filter's roll-off frequency.

Both Figure 4 and Figure 5 show the Fourier signal spectrum from a GaGe 12-bit digitizer sampling at 500 MS/s with accompanying Dynamic Parameter Measurements. The two figures were produced with input signals frequencies of 10 MHz and 199 MHz, respectively.

The 10 MHz *ENOB* from Figure 4 is just over 10, which is not especially good for a 12-bit digitizer. The near equality of the *SNR* and *SINAD* (or equivalently, the much higher absolute value of the THD) show that the performance is principally limited by noise and that distortion is insignificant.

The impressive performance of the 12-bit digitizer is highlighted only in Figure 5, for which the signal frequency is 199 MHz. First, because of the high signal frequency, harmonics are aliased to lower frequencies. Specifically, they are reflected by the Nyquist frequency of 250 MHz (half the 500 MS/s sampling frequency). For example, the second harmonic at 2 x 199 MHz = 398 MHz is aliased to 500 MHz - 398 MHz= 102 MHz.

In contrast to Figure 4, Figure 5 shows that noise and distortion are significant contributors to *ENOB* since the *SNR* and *THD* have absolute values of the same order. The 9.43 ENOB is excellent for a signal frequency of almost 200 MHz. Taken together, Figures 4 & 5 illustrate how GaGe has sacrificed some *ENOB* performance at 10 MHz in order to achieve excellent performance at near 200 MHz. This achievement resulted from making design choices to minimize distortion at the expense of noise, which corresponds to choosing the green region over the red region in the simplified picture of Figure 3.

Dynamic Parameter measurements at several signal frequencies allow the digitizer user to understand the performance when using signals from their real-world application. Furthermore, such multiple measurements inhibit digitizer manufacturers from specifying parameters at strategic signal frequencies to maximize performance, for example by hiding spurious peaks under the fundamental.

Superior Dynamic Parameters are paramount in applications where the signal has a high dynamic range and so contains both high and low amplitude components. For example, a high SNR enables a low threshold for the detection of low-level time-domain pulse amplitudes, which routinely occur in the signals acquired in particle physics applications and in ultrasonics and other time-of-flight applications. Alternately, in frequency-domain application like communications and spectroscopy, a high SFDR and THD are required to minimize spurious spectral peaks. Consequently, manufacturers should provide the complete set of Dynamic Parameters (ENOB, SNR, THD, SINAD and SFDR) in the digitizer technical specifications.

## Conclusion

We have presented the correct frequency-domain method of characterizing the signal fidelity of a digitizer device. Our discussion focused on the Dynamic Parameters *SNR*, *THD*, and the *SINAD*. The SINAD may be trivially transformed into the *ENOB*, which is the best overall single metric of digitizer performance. We reported upon a 12-bit GaGe digitizer that has achieved excellent performance at near 200 MHz with slightly compromised performance at 10 MHz. In choosing a digitizer, a user must carefully consider both the operating signal frequency range and the performance needs. A good rule is to target a digitizer input bandwidth that is high enough to meet the signal frequency requirements but no higher.

*For information on selecting the correct digitizer for your application contact ProdInfo@GaGe-Applied.com or call (514) 633-7447.*


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