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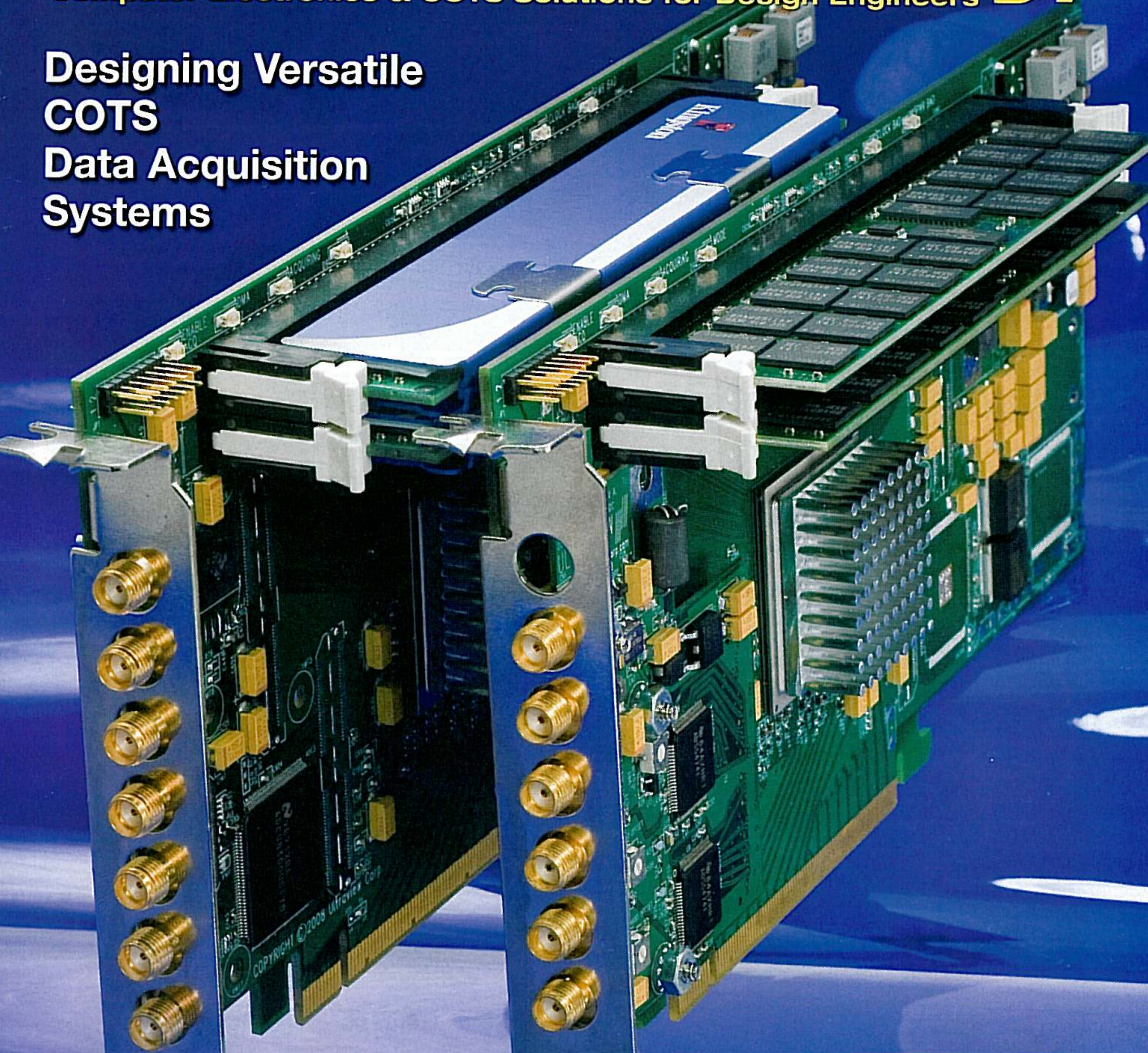

Measuring Digitizer Performance Using Dynamic Parameters

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Using Dynamic Parameters to Measure Digitizer Performance

Much confusion exists about characterizing the performance of a high-speed digitizer device. Nominal vertical resolution is routinely presented as an indicator of a digitizer's performance, but the relevance of this parameter is dubious since a digitizer's true performance is characterized by the Dynamic Parameters*.

The Digital Storage Oscilloscope (DSO), a widely used digitizer-like device, is optimized for the visualization of unknown signals[1]. The relatively low 8-bit nominal vertical resolution of the DSO (and *ENOB* of 6~7) is sufficient for signal visualization and may be offered at the highest sampling rates (~80 GigaSamples/second). As a result, DSO product specifications typically emphasize their high input bandwidth and rarely list their vertical performance parameters. By contrast, digitizers are usually optimized for the rapid acquisition and analysis of small changes in broadly-known signals. While providing lower maximum sampling rates, digitizers typically offer higher vertical resolutions of 12-, 14-, and 16-bits.

It is important to distinguish between the *absolute accuracy* and *relative accuracy* of a digitizer device. The absolute accuracy of a digitizer describes how close its measured voltage values are to the true MKS voltage reference values. By contrast, its relative accuracy specifies the fidelity of the shape of the acquired waveform with no reference to absolute voltage values. Using on-board calibration techniques, high-speed digitizers may achieve absolute accuracies of order 0.1% of the full-scale input voltage range. In the majority of digitizer applications, users are concerned not with the absolute accuracy but rather with the relative accuracy, which in turn is specified by the Dynamic Parameters.

Generally speaking, the fidelity of the signal acquired by a digitizer device may be compromised by three distinct factors:

1. Addition of random noise by the digitizer;
2. Distortion of the signal by the digitizer itself;
3. Irregularities in the time intervals at which samples are converted.

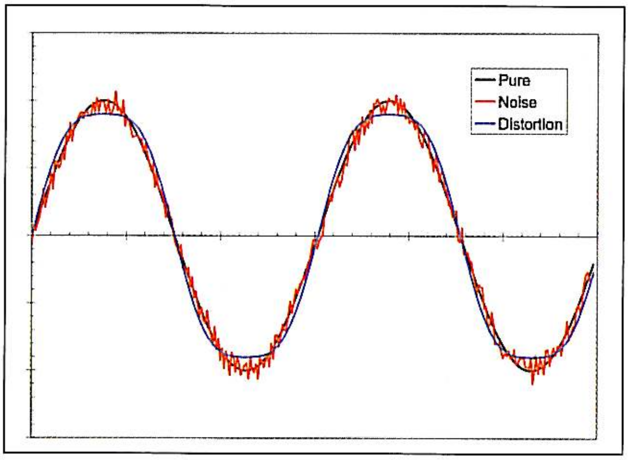

Figure 1. Typical examples of Moise and Distortion on a pure sine wave signal.

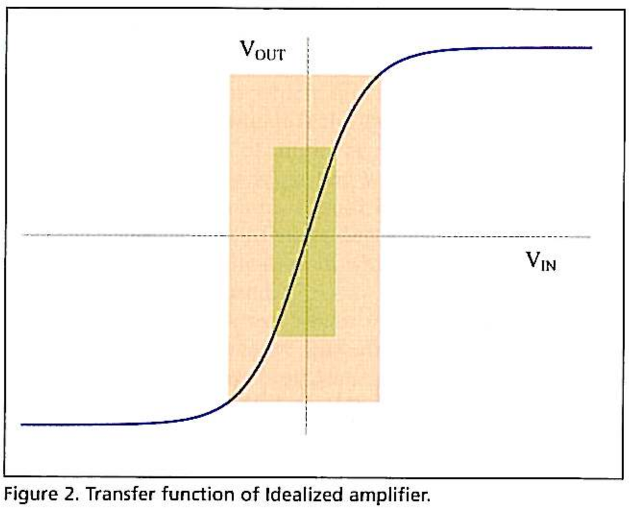

Figure 2. Transfer function of Idealized amplifier.

The distinction between signal noise and signal distortion is illustrated in Figure 1. The figure shows 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.

Strictly speaking, signal artefacts cannot be classified as either noise or distortion based on a single waveform acquisition. This distinction requires a comparison of multiple acquisitions in order to determine whether an artefact is correlated or uncorrelated with the signal, which then classifies it respectively as distortion or noise. For example, while it is certainly not random, pick-up of spurious 60 Hz line frequency is considered to be noise unless the underlying signal is correlated with the line frequency, in which case it is considered to be distortion.**

As a rule, the engineering of amplifier stages that add low noise and that impose minimal distortion are incompatible design goals. Consider a generalized amplifier circuit with transfer curve that is shown in Figure 2. Imagine also that a small amount of random noise is picked up at the output of this amplifier.

Designing a circuit using the amplifier in Figure 2, if an engineer elects to work with the signal amplitudes that are within the red region, the signal will suffer high signal distortion, as evident from the visible local non-linearity. Alternatively, the engineer can decide to reduce distortion by working with the signal amplitudes that are within the green region of Figure 2. While the signal distortion will then be significantly reduced, the reduced output signal amplitude will result in noise pickup having a proportionately higher effect.

Imperfections in a digitizer's analog-to-digital converter (ADC) timing present an additional source of signal corruption. The instants at which the ADC samples the signal are determined by

* Dynamic Parameters are a set of digitizer characteristics that specify the vertical performance of its conversion and includes Ratio of Signal-to-Noise-and-Distortion (*SINAD*), Spurious Free Dynamic Range (SFDR), Effective Number Of Bits (*ENOB*), Total Harmonic Distortion (*THD*), and some others.

the clocking signal, which is usually a continuous wave with a single oscillation frequency. The clocking signal is typically not recorded by the digitizer, and its properties are assumed to be perfect in subsequent data analysis. In reality, the period of the clocking signal is not strictly fixed over time. Two distinctive types of clocking signal imperfections can be identified:

Phase Jitter:
$y(t)=\sin[2\pi(ft+\varepsilon(t))] \quad \varepsilon(t) << 1$

Frequency Drift:
$y(t)=\sin[2\pi(f+\varepsilon(t))t] \quad \varepsilon(t) << 1$

With *Phase Jitter,* the clock signal edges vary about positions that are spaced exactly uniformly in time. With *Frequency Drift,* however, the instantaneous clocking frequency changes over time. Moreover, since the signal frequency may be only determined relative to the clocking signal, the frequency drift is indistinguishable from the input frequency modulation. There are two different measurement methods for characterizing digitizer performance — one that is performed in the time domain and one that is performed in the frequency domain. Both methods involve acquisition of a high-purity sine wave signal by the digitizer under test***.

In the time-domain method specified in IEEE 1057-1994, a sine wave function is fitted to the waveform acquired by the digitizer. The error function is then normalized to obtain the *SINAD.* From the *SINAD,* the Effective Number Of Bits (*ENOB*) is calculated as:

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

The *ENOB* is the single most important overall indicator of digitizer performance. The *ENOB* allows comparison of the given digitizer to an ideal one with the specified resolution. The *ENOB* depends on signal frequency and, in principle, 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 clear separation and characterization of digitizer noise and distortion. The sine wave fitting method is iterative and it is not guaranteed to converge, especially in the case of significant frequency drift. It is possible to add harmonics to the sine wave fit in an attempt to separately characterize noise and distortion, but this approach further complicates the already non-linear sine function fit and makes convergence less probable

The second method of characterizing digitizer performance requires analysis in the frequency domain. The acquired high purity sine wave is subjected to Fourier analysis and a Power Spectrum is obtained (Figure 3). Usually, the waveform data are pre-multiplied by a time-domain Windowing function, which reduces spectral leakage.

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

1. Fundamental bins: those within a specified range of the known input sine wave frequency, illustrated as green in Figure 3.
2. Harmonic Bins: those within a specified range of harmonics of the known sine wave frequency, illustrated as blue in Figure 3.
3. Noise Bins: all frequency bins, illustrated as black in Figure 3.

The sum of all power amplitude values within each of the three types of bins respectively provides 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, which are listed below:

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*):

$$SINAD \equiv 10\log_{10}\left(\frac{F}{N+H}\right)$$

While the frequency-domain technique requires selection of the values of

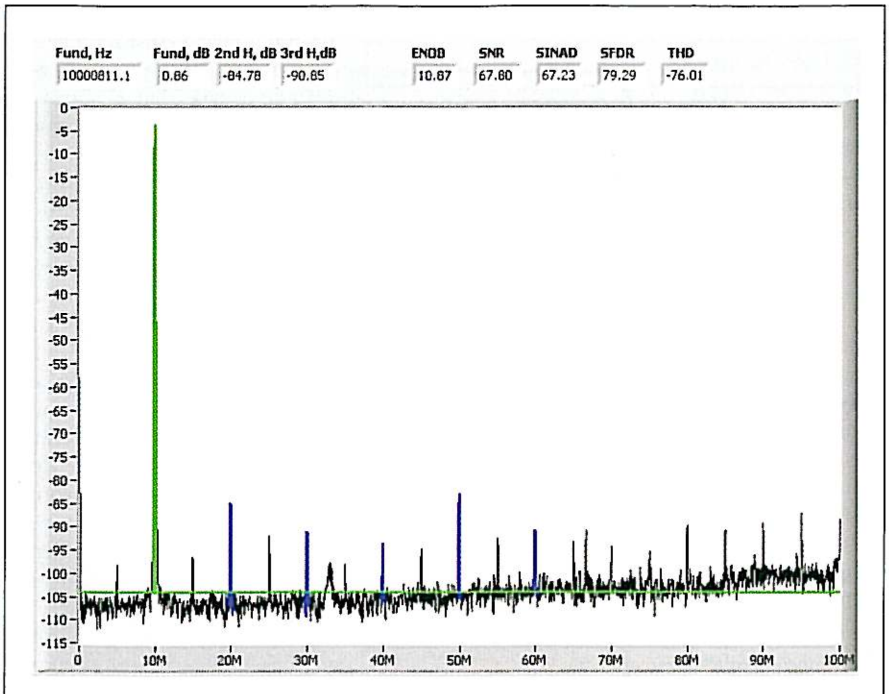

Figure 3. Fourier Power Spectrum used for calculating Dynamic Parameters for a 12-bit digitizer at a 10MGz sine wave frequency.

** In a signal processing technique called Signal Averaging (also Boxcar Averaging), successively acquired waveforms are summed together, after correct alignment with respect to their trigger positions. Since, by our definition, signal noise is uncorrelated with trigger position, averaging operations progressively reduce the noise amplitude, while the correlated distortion is summed constructively and does not diminish with signal averaging. This different behaviour under signal averaging underscores the importance of low distortion in a digitizer as compared to low noise, since noise may be eliminated through signal averaging, while distortion may not.

*** 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. The quality of the original signal, and the bandwidth and linearity of the filter, affect the measurements.

adjustable parameters, such as the Windowing function type and the number of bins comprising the "specified range" mentioned above, it has the clear advantage of separating the noise and distortion introduced by the digitizer, which are respectively quantified by the *SNR* and the *THD*.

As in the time-domain technique, the *ENOB* is calculated directly from the *SINAD*. The two methods may be experimentally shown to render equivalent *ENOB* values in most circumstances[2]. The notable exception is clocking frequency drift, which complicates sine-fitting, and thus renders incorrectly high *ENOB* values for the time-domain technique.

The act of digitization intrinsically adds signal noise since a continuous voltage value is transformed into an integer value, which results in an associated rounding error. For a sine wave input signal, this rounding action adds a small uniform power to all frequency bins that increases slightly with signal frequency, but can usually be ignored. The majority of uncorrelated "random" noise is usually caused by the pick-up of unavoidable local digital signals. This pickup also leads to a broad spectrum of noise across the frequency spectrum and mainly results in reducing the *SNR*.

The digitizer's residual *THD* primarily arises from the signal distortion through the digitizer's front-end signal-conditioning circuitry. Although the *SNR* usually does not vary significantly with the sine wave signal frequency, the harmonic distortion of high-speed amplifier circuits — and hence the digitizer's *THD*, *SINAD* and *ENOB* — usually degrades markedly with the increase of signal frequency.

Clocking phase drift leads to broadband noise and mostly affects the *SNR*, not the *THD*. It manifests itself as a slight rise in the noise floor with the increase in frequency. Frequency clocking drift, however, leads to a distinct skirt-like swell around the fundamental peak. Many modern digitizers are equipped with a high-stability disciplining 10 MHz reference oscillator to which all sampling clock signals are locked in an effort to minimize clocking drift.

The input of any digitizer generally acts like a low-pass filter on the input signal and the frequency at which the signal suffers 3 dB attenuation is defined as its input bandwidth. While the Dynamic Parameters of a digitizer do not directly depend on its sampling rate, they do change significantly with digitizer input bandwidth. *ENOB* performance and digitizer bandwidth are, in fact, complementary quantities and one rises at the expense of the other. Bandwidth-limiting low-pass filtering will smooth the signal out and reduce the random noise to improve the *SNR*. Filtering will also attenuate higher frequency harmonic peaks, improving the *THD*. Consequently, any digitizer *ENOB* specification must be accompanied by the digitizer's input bandwidth at the time the measurement was performed.

There are other useful digitizer performance metrics that may be derived from the Fourier spectra of an acquired sine-wave signal. Valuable in communications, the Spurious Free Dynamic Range (SFDR) is the vertical measure from the full scale 0 dB point to the top of the highest power value outside of the Fundamental frequency peak. The True Noise Floor is the sum of all non-Fundamental power bins and it is useful for performance comparisons with spectrum analyzers. Finally, the Intermodulation Distortion (IMD) pertains to the appearance of spurious new signal frequencies from a multi-tone input signal. This characteristic is vital when dealing with broadband signals.

We have presented the correct frequency-domain method of characterisation of a digitizer device- specifically focusing on the *SNR*, *THD*, and the *SINAD*, from which one may calculate the *ENOB*, which is the best overall signal metric of digitizer performance. The decision regarding which performance parameters should be considered important to the user depends upon the specific application in which the digitizer is being used.

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