Getting the Most Out of Your Scope's Resolution

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Introduction

The oscilloscope is the quintessential benchtop equipment found in practically any electronics lab along with the power supply and multimeter. These devices have evolved quite a bit from their legacy, analog cathode-ray tube based 10 MHz counterparts. With modem analog-to-digital conversion at high sampling rates, digital oscilloscopes offer far more capability in terms of bandwidth, sampling rate, and triggering, often with additional features for analyzing the integrity of high frequency signals. Moreover, the utility and processing power of PC-connected, USB oscilloscopes are growing to meet that of stand-alone benchtop instruments without the associated cost of traditional portable test equipment. Of all of the pertinent specifications of an oscilloscope, resolution ranks quite highly -- especially in signal integrity applications where high clock frequencies make it much harder to detect jitter while the shorter rise/fall times increase the amount of spectral content at high frequencies. This article discusses the importance of oscilloscope resolution and how to get the most out of it for a respective application. Furthermore, with tools such as the ADP3450 portable high resolution mixed signal oscilloscope, the testing of high-speed systems can be accomplished with relative ease.

What is oscilloscope resolution and why is it important?

Oscilloscopes are the go-to for measurement signals in the time domain or in an amplitude versus time format. In order to accurately capture and display these signals, an analog-to-digital converter (ADC) is necessary. Typically, a designer will have to optimize a trade-off between the sample rate and resolution features of the ADCs and DACs within the oscilloscope.

A quick brush up on sampling rate and resolution

Signal amplitude is determined at regular, closely spaced intervals where a series of time/voltage pairs are captured from the continuous-time and continuous-amplitude analog signal to form a discrete-time and discrete-amplitude signal to be displayed. Typically, the higher the sampling rate of the oscilloscope, the better it is able to measure high frequency signals -- a long duration between samples (sample interval) may not capture critical waveform information. The sample rate determines the maximum bandwidth, or range of frequencies, that most oscilloscopes can achieve. This relationship is extrapolated from the translation of the signal in the time domain, to the frequency domain. The analog front-end in an oscilloscope includes gain control circuitry (e.g., variable gain amplitude, attenuator), buffers (e.g., FETs, etc), channel and trigger filters, and ADC drivers. All of which combined, yield a frequency response that looks very much like a low pass filter where the magnitude of the signal decreases with frequency (***Figure 1***). In this case, the bandwidth is the frequency at which an input sinusoidal waveform is attenuated by 70.7% of its amplitude, or the point at which the signal has dropped by 3 dB.

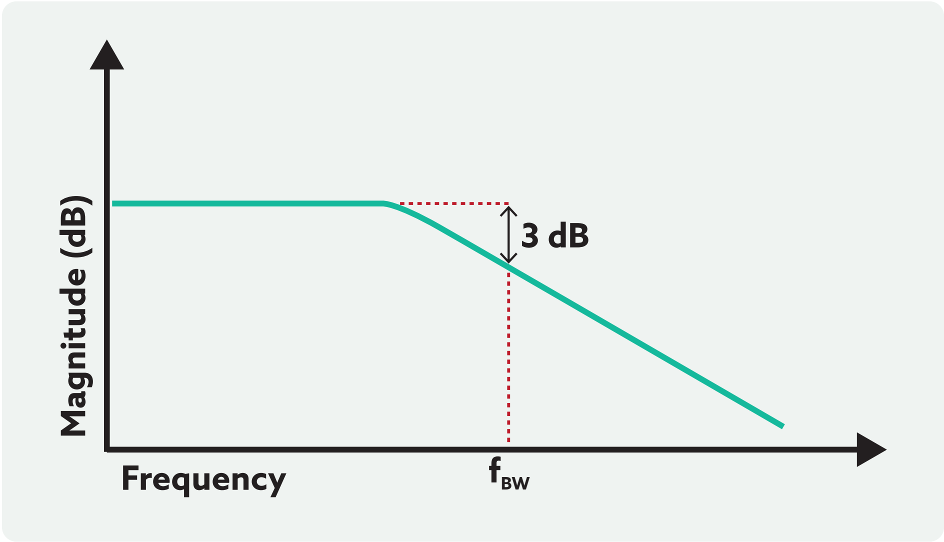

Figure 1: Low pass frequency response found in oscilloscopes and point at which bandwidth is defined.

According to the Nyquist-Shannon sampling theorem, if an ADC operates at a sampling rate that is at least twice the bandwidth (i.e., the highest frequency component) of the desired signal, perfect reconstruction of the signal is possible. However, with real systems this is typically insufficient, so a common rule of thumb is that the sampling rate of the oscilloscope should be at least 2.5 times the bandwidth of the signal. Another estimate is that the bandwidth of the oscilloscope should be three to five times the high frequency component of the signal. For most digital signals, the fundamental frequency is half the data rate and where there is still significant spectral content up to the fifth harmonic not to be attenuated. For example, a 20 Gbps data rate would correspond to a 10 GHz clock signal where a bandwidth of 50 GHz would be required to reveal the fifth-harmonic content. The commonly used relationship between the rise time of a signal and its bandwidth is shown in Equation 1. This provides a quick estimation of the highest frequency components of a signal in the time-domain.

$$BW \approx \frac{0.35}{T_R}$$

Equation 1

The resolution of the oscilloscope relates to the effective number of bits (ENOB) of the ADC, which provides the number of values that can be produced over the allowed range of analog input values. For instance, a 12-bit resolution would be able to discern 4096 different levels (4096 negative and/or positive integers), or encode an analog input to one of 4096 quantization levels. In other words, the resolution relates to the instrument's ability to discriminate between values that are in close proximity in time, for horizontal resolution, and in amplitude for vertical resolution. Typically, when resolution is mentioned on an oscilloscope's specification, it is related to the vertical resolution. While the horizontal resolution is often called "time resolution." The vertical resolution is related to the dynamic range of the oscilloscope, or the ratio of the high input signal that the instrument can handle, to the smallest signal amplitude it can detect -- the smallest and largest signal levels that can be measured simultaneously.

Typically, oscilloscopes leverage an 8-bit ADC where voltage range is divided in 256 vertical steps. This is applied on the display in the volts-per-division (volts/div) setting that adjusts the size of the waveform on the screen. For instance, an 8-bit oscilloscope with around 0.25 V per division (V/div) could fit a signal ranging from -1 V to +1 V (2V total) in 8 divisions, where the resolution (or the ADC's quantization level) is around 8 mV/level, or 2V divided by the 256 levels. If the volts-per-division setting is set at 5 volts, the entire screen can display 32 volts from top to bottom with a resolution of 125mV/level. Higher resolutions allow for the most sensitive vertical scalings while keeping the full waveform on display. While the sampling rate determines the ability of the instrument to accurately capture a high-speed signal, the vertical resolution determines the ability of the oscilloscope to differentiate between amplitude levels that are close to one another. Two entirely different functions that can be critically important depending upon the application.

When should you prioritize high resolution over the sampling rate?

Resolution is critically important when a user is trying to assess minute differences in large amplitude signals for high dynamic range measurements. An oscilloscope with an 8-bit resolution is enough to catch around a 0.4% amplitude signal distortion, or 19.53 mV on a 5V signal. This goes down to 300 μV (0.0061%) on a 14-bit oscilloscope and 76 μV (0.0015%) on a 16-bit instrument (see ***Table 1***).

Resolution	Number of steps (2^n)	Smallest detectable value [$(1/2^n)$*100]	Theoretical dynamic range (6dB per bit)
6 bits	64	1.6%	36 dB
8 bits	256	0.39%	48 dB
12 bits	4,096	0.024%	72 dB
14 bits	16,384	0.0061%	84 dB
16 bits	65,536	0.0015%	96 dB

Table 1

There are a litany of applications that require designers to analyze small signals in the presence of large signal amplitudes. This includes power integrity (PI) testing, radar, imaging systems, and testing other high voltage systems such as assessing an AC ripple in a utility voltage, or in a high voltage (480 V) DC bus for a variable frequency AC motor drive. Validating power supplies on microprocessors, FPGAs, and ASICs, for instance, inherently involves the ability to view ripples, load transients and loop frequency response -- all of which are situations where small signals appear in a noisy environment. Power integrity engineers in these instances must maintain voltages during switching transients to prevent unwanted noise, but this can be a challenging engineering task, especially since power supply voltages are growing smaller and smaller. This often requires displaying small signal differences of a gigahertz frequency signal, in an electrically noisy environment. Most FPGAs, for instance, require a voltage ripple no greater than 2 percent of the rail voltage that often ranges between 1.2 V to 3.3 V, calling for at least 24 mV of resolution. Since no oscilloscope will match its ideal values, a higher resolution than your average 8-bit vertical resolution is required.

Oscilloscopes can be configured to display critical parameters for audio chipsets (amplifiers/ DACs, etc) such as total harmonic distortion (THD), or, the percent of the output signal that is false and contains unwanted distortion. Typically this value must fall below the 0.1% value or there is a perceptible difference in the sound (harmonic content) of the music. Technically, THD is the ratio between the square of the RMS voltage values at all the harmonic frequencies over the RMS voltage of the fundamental frequency or, an equivalent power ratio. This requires a measurement in the frequency domain in order to get the device's output harmonic content. The measurement can be performed with a spectrum analyzer to readily get the power levels at second, third, fourth and fifth harmonics.

This can also be accomplished with a high bandwidth and high resolution oscilloscope after performing a fast fourier transform (FFT) on the signal. Typically, the BW is at least five times greater than the fundamental frequency. Resolution is also critical in these measurements in order to measure the very low distortion levels required in most THD measurements (<0.1%) -- especially at high harmonics -- without adding distortion of its own. In other words, the higher signal-to-noise ratio achieved by high resolution oscilloscopes dramatically cleans up the spectral content in the frequency domain to easily root out the amplitude of the various harmonics that add to THD.

Maximizing the Utility of your Scope's Resolution

The question of how to maximize the resolution of an oscilloscope requires designers to consider multiple competing interests at once, since the dynamic range and accuracy of the instrument is not only affected by resolution, but also by other parameters such as front-end noise, faulty probes, and so on. For cases where small signals need to be detected in the presence of noise, it is critical to ensure that the test equipment is operating optimally and within parameters that mitigate the inherent noise of the oscilloscope. This can be accomplished by:

- Operating at the most sensitive vertical setting possible (or making the waveform take up the whole display) to ensure use of the full resolution of the ADC

- Using a relatively high bandwidth oscilloscope to limit the occupied bandwidth reduce broadband noise

When testing high voltage signals, the measurement might be accomplished by using attenuating probes to attenuate the input signal and effectively multiply the oscilloscopes scaling. For instance, a x1 probe might allow for a measurement range from 4 mV to 400 V. A software-enhanced resolution can also be accomplished through filtering or digital interpolation, where a high sampling rate is used to add samples between the recorded samples. This in effect, smooths the displayed signal to give the impression of more resolution and lower noise; however, it cannot in reality discern between the signal and the noise. This often leads to masking small signals of interest. Figure 2 shows the difference between a 16-bit resolution and a 14-bit resolution oscilloscope in the histogram. There is generally no one-size-fits-all solution to oscilloscopes, and the choice of hardware ultimately depends on the type of testing that is done and the respective speed/bandwidth and voltage ripple tolerances of the signal.

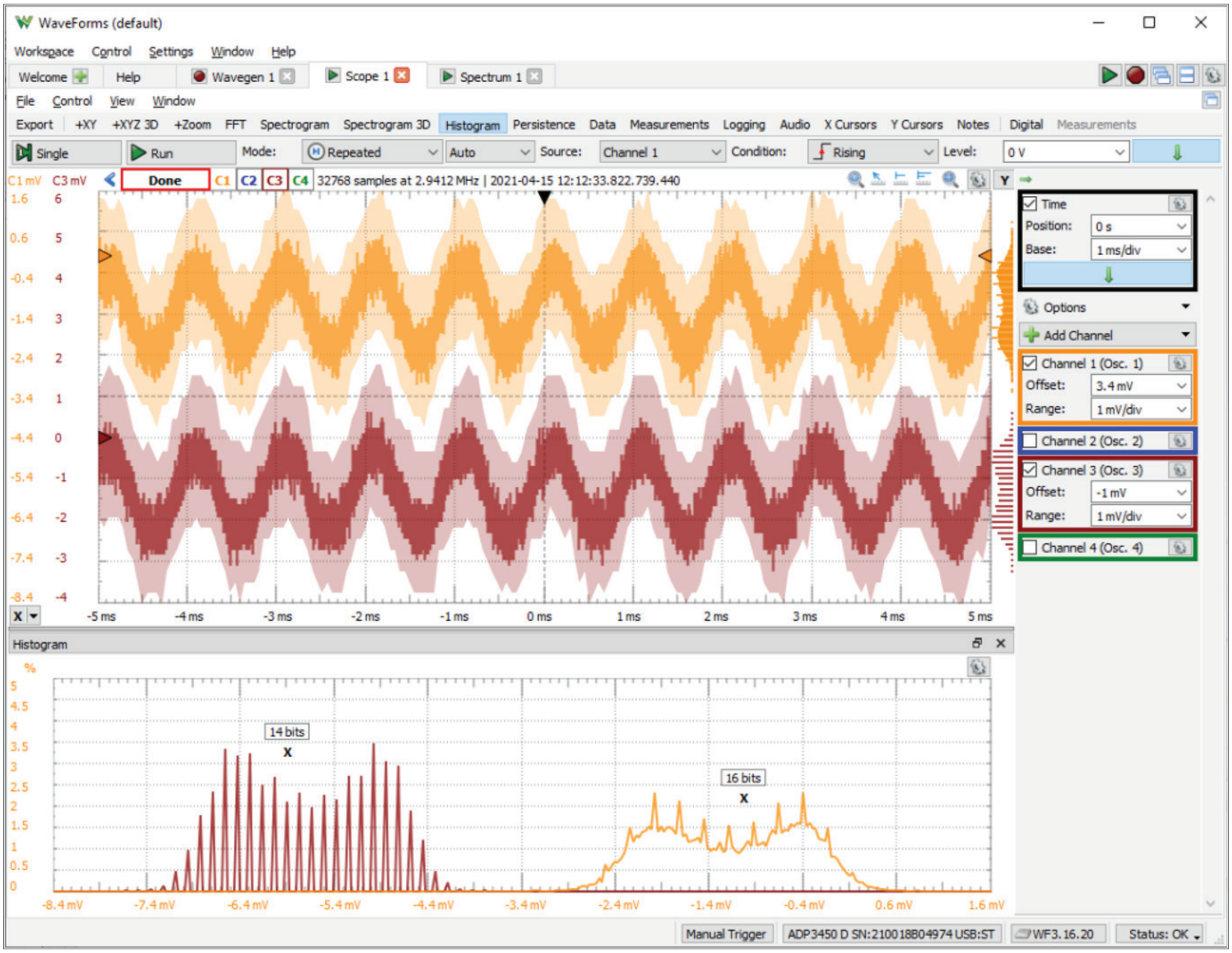

Figure 2: Histogram of 14-bit resolution oscilloscope and 16-bit resolution oscilloscope.

A portable, powerful oscilloscope: Digilent's ADP3450

Digilent's portable ADP3450 oscilloscope offers a 14-bit resolution and 120 megasamples per second (MS/s) out-of-the-box with software enhancements that allow up to 16-bits and 0.5 GS/s. This effectively combines the utility of professional benchtop equipment with the flexibility of a portable instrument. The portability is defined by its stand-alone, Linux Mode, where tests are run and data is stored directly to the device. Entire routines can be scripted to be run on the equipment without the connection with a host PC. While this mixed-signal oscilloscope can readily operate as up to twelve different instruments, the intrinsic resolution of this equipment allows for the ADP3450 to be utilized in a number of the testing scenarios listed above where resolution becomes paramount over sampling rate.

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