How to get more than 8 bits from your 8-bit scope

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Measurements are key to all scientific and engineering disciplines. For the electronics industry, oscilloscopes provide a number of critical measurements required by engineers to conduct real-world testing and gain needed insight. The majority of today's oscilloscopes are designed with 8-bit ADCs (analog-to-digital converters). At the same time, most oscilloscopes include settings that enable higher resolution measurements. These controls are largely unknown to most scope users, yet have enormous potential for users who want to maximize their ability to view signals with greater accuracy, especially for small signals measurements, or for high dynamic range measurements. Exploring how to determine when to use these controls as well as associated tradeoffs and benefits empowers scope users to see signals with new clarity.
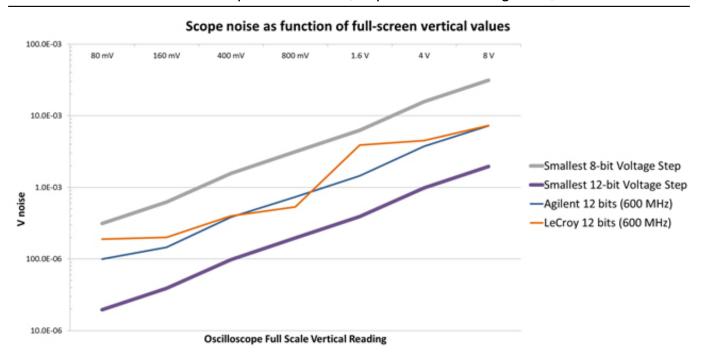
Bits
Oscilloscopes consist of a few key architectural blocks. Analog signals pass through the oscilloscope's front-end where they are conditioned and then routed to an ADC. The ADC then sends the digitized bits to a processing block and on-board memory where signal information is accessed and displayed. Resolution is the smallest quantization level determined by the analog-to-digital (A/D) converter in the oscilloscope.

A scope's ADC with a resolution of 8 bits can encode an analog input to one in 256 different levels, since $2^8 = 256$.   The ADC operates on the scope's full scale vertical value. Thus the Q-level steps are associated with the full-scale vertical scope setting.   If the user adjusts the vertical setting to 100mV per division, full screen equals 800 mV (8 divisions * 100 mV/div) and Q-level resolution is equal to 3.125 mV/level (800mV divided by 256 levels).   If measuring current, for a vertical setting of 10 mA/div, Q-level resolution is set at 312.5 uA/level (80mA divided by 256 levels).

Use of full bits is limited by noise induced by the oscilloscope itself. Noise can come from a variety of sources, including the front end of the scope or the ADC in the scope. The ADC itself has quantization error. Quantization noise is the difference between the original signal and the digitized signal.   The amount of quantization error is less than the least significant ADC digit and exists in all ADCs. However, for oscilloscopes quantization noise plays a lesser role in contribution of overall noise and the front end of the oscilloscope plays a more significant role as shown in figure 1.

Scope noise as function of full-screen vertical values

Oversampling

Models within a single oscilloscope family typically share the same technology blocks, and vendors add different filters to create a series of products each with a unique bandwidth and price point. ADCs are typically designed with maximum sample rate associated with the top memory of the family. This can be an excellent opportunity for consumers of the scopes that aren't the top bandwidth models in a family.

Typically, these lower bandwidth models thus have excess sample rate versus what would be needed to reconstruct signals without aliasing. For example, you will find several 1 GHz scope models on the market today with a maximum sample rate of 20 Gsa/s. Is 20 Gsa/s needed to reconstruct signals with frequency components up to 1 GHz? Certainly not. How much sample rate is needed? Nyquist states that at least 2 GSa/s sample rate is needed. The scope industry as a whole has converged on a ratio of 2.5 times sample rate versus scope bandwidth as an effective method of preventing aliasing. So a 1 GHz bandwidth scope needs 2.5 GSA/s to faithfully reconstruct signals as frequency components above 1 GHz will naturally be attenuated by the scope's front end.
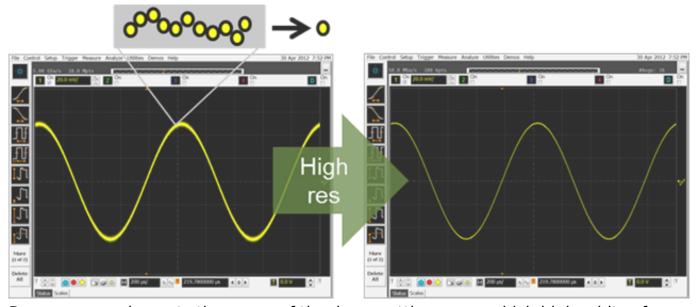
The fact that a 1 GHz scope ships with 20 GSa/s sample rate means the scope vendor overdesigned the scope by leveraging a faster ADC needed by a higher-bandwidth scope in the same family. The excess sample rate would nominally go wasted as it doesn't contribute to better measurement quality despite the thinking that "more is always better." Could the excess sample rate be used for some other purpose?

If a signal is sampled at a rate much higher than the Nyquist frequency, and then is digitally filtered to limit it to the scope bandwidth, the scope magically gets additional resolution. The 8-bit ADC combined with the digital filter can be made to produce more than the 256 Q levels associated with an 8-bit ADC. Using this technique, the scope can obtain an effective resolution that is more precise than

what the ADC would naturally produce.   In fact in the example described above an 8-bit ADC can be made to act like a 12-bit ADC given the excess sample rate relative to bandwidth.

Most scope vendors include a setting that allows the scope to oversample and digitally filter the output of the ADC to achieve more bits of resolution. Some vendors call this high-res mode, while other vendors use different names. All major vendors include this capability in their scopes.   For scopes with sample rate equal or near to the 2.5 times ratio relative to scope front-end bandwidth, turning on high res mode will cut the overall bandwidth while providing more than 8 bits of resolution. For scopes with a sample rate much greater than the 2.5 times ratio relative to bandwidth, turning on high-res mode will enable greater resolution with no tradeoff in overall scope bandwidth.

Deep memory impacts the range of timebase settings over which higher bits of resolution can be retained.   Let's take a look at an example of a scope with bandwidth of 500 MHz, and sample rate of 20GSa/s. The user turns on high-res mode and specifies that the digital processing yield 11-bits of resolution. To go from 8-bits of resolution to 11-bits of resolution the scope ADC doesn't change, but the digital filter based on ADC outputs does. The filter must oversample by 8 times (2^3 = 8) to get 3 additional bits of resolution. Each group of 8 samples will be averaged into a signal vertical value using a boxcar average. The effective sample rate is now 2.5 GSa/s (20 GSa/s divided by 8 samples per boxcar average) still more than sufficient for the scope front-end bandwidth of 500 MHz.

What impact does scope memory depth have on high-res mode? It depends. Check with your scope vendor. As an example, Agilent Infiniium scopes perform the high-res digital filtering after the ADC, but before samples are stored to memory. So while the user might oversample to get 12 bits of resolution, no compromise is made to memory depth. The filtered samples are stored in memory and the scope retains its native memory depth.

All scope acquisition memory is fixed in size. Having deeper memory enables scopes with to retain faster sample rates over bigger windows of captured time. For

example, a 4 GHz scope with 10 GSa/s and 1 Mpts per channel can capture a time window of 100 us at the fastest sample rate. If the timebase is changed to 20 us per division the scope is already using all 1 Mpts per channel memory, and hence must reduce its sample rate by 2 times in order to display the required time window of 200 us. The scope is now sampling at 5 GSa/s. Nyquist tells us that the scope will alias signals greater than 2.5 GHz so we've effectively reduced the scope bandwidth by changing the scope's timebase to see more time on the scope display.   If the scope had 10 Mpts instead of 1 Mpts per channel of acquisition memory, the change to the time base would not have impacted sample rate and effective bandwidth until the scope display window was set to 2 ms or higher.
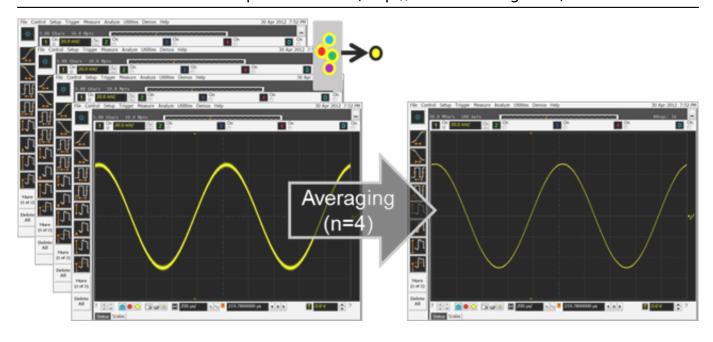
Likewise, high-resolution mode works the same way with memory. Remember the formula, (Acquisition Time Window) = (Memory Depth)/(Sample Rate). When the scope user desires to see longer windows of time on the scope display, the scope will at some point need to reduce sample rate limiting the effective bandwidth of the scope.   This can be a benefit in enabling high-re mode to limit overall scope bandwidth when a low-pass filter is needed.
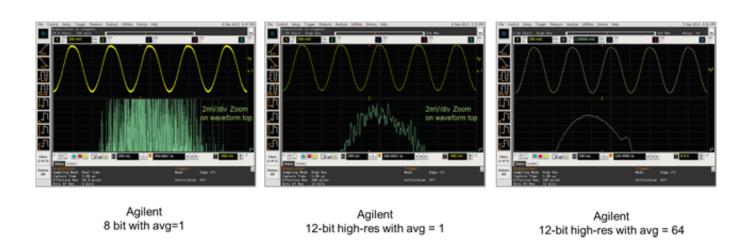
By increasing the number of samples used in each digital filter calculation, the user can lower the effective sample rate and resulting bandwidth of the scope. Why would a user want to do this? This technique can be employed to perform bandwidth limiting that may not be native to the scope.   For example, if you scope has 20 MHz bandwidth limiting on the 1MΩ high-Z path, but not the 50Ω path, you can use this technique to bandwidth limit the scope to bandwidth limit your scope on the 50Ω path. Or use this technique to create addition bandwidth limit filters not found natively on either signal path in your scope. Need to look at small current or voltage current signals and want to reduce noise higher frequency sources? This is an excellent way to accomplish bandwidth reduction.

Averaging

Oscilloscopes include another mode called averaging. Turning averaging causes the oscilloscope to average vertical values along each captured waveform with vertical values from successive waveforms. Oscilloscopes allow the user to specify how many waveforms to average. Averaging is another technique that allows users to reduce noise from the oscilloscope.   Unlike high-res mode using oversampling techniques, average doesn't work for single shot acquisitions. Averaging requires a repetitive signal, and will make infrequent anomalies that may occur. Just like with a spectrum analyzer, another area where averaging is useful is when performing FFT analysis using a scope. Averaging reduces the noise floor and improves SRDR.

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Published on Electronic Component News (http://www.ecnmag.com)

Agilent
8 bit with avg=1

Agilent
12-bit high-res with avg = 1

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12-bit high-res with avg = 64

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