Evaluating High-Resolution Oscilloscopes

Getting More than 8-bits of Resolution From Your 8-bit Oscilloscope

Application Note

In this application note, we will talk about:

- How oscilloscope ADC bits and bits of resolution differ
- The relationship between vertical resolution and noise
- How high-resolution mode works and when to use it
- Average mode and when to use

Over the past decade, oscilloscopes have made significant advances in sample rate, bandwidth, and memory depth. Another key oscilloscope specification is vertical resolution. Seeing additional vertical detail is commonly referred to as high-dynamic range measurements.

Several oscilloscopes today offer more than 8 bits of vertical resolution. In some oscilloscopes, this extra resolution is achieved by applying Digital Signal Processing (DSP) to the output of a standard 8-bit Analog-to-Digital Convertor (ADC). In other cases, the extra resolution is achieved using an ADC with more than 8 bits. Furthermore, some oscilloscopes use a combination of a greater than 8-bit ADCs and DSP to achieve even more bits of vertical resolution.

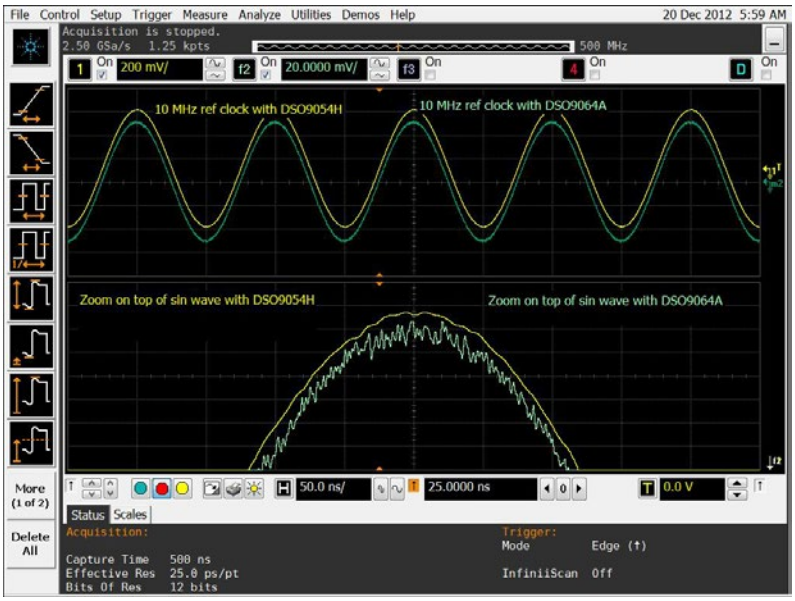

Figure 1.

Figure 1 shows an 8-bit acquisition compared to an acquisition taken on an oscilloscope with 12-bits of resolution. Both oscilloscopes were connected to the identical low-noise 10 MHz reference clock signal. A magnify function was used to zoom in on the top of each captured waveform.

How Does an Oscilloscope's ADC Impact Vertical Resolution?

All manufacturers specify the number of ADC bits in their oscilloscopes, and resolution is the smallest quantization level determined by the analog-to-digital (A/D) converter in the oscilloscope.

The number of unique digital codes or quantization levels (Q levels) is 2^n where n is the number of ADC bits. An 8-bit ADC has 256 Q levels, whereas a 12-bit ADC has 4096 Q levels. Each oscilloscope ADC operates on the oscilloscope's full scale vertical value. Thus the Q-level steps are associated with the full-scale vertical oscilloscope setting. If the user adjusts the vertical setting to 100 mV per division, for example, full screen equals 800 mV (8 divisions * 100 mV/div) and Q-level resolution is equal to 3.125 mV/level (800 mV divided by 256 levels). If measuring current, for a vertical setting of 10 mA/div, Q-level resolution is set at 312.5 µA/level (80 mA divided by 256 levels).

Provided there is a sufficient signal-to-noise ratio (SNR), more ADC bits allow finer details of the signal to be seen. Noise typically plays a greater role in limiting some of the effectiveness of the additional bits of resolution as shown in Figure 2. In this example, both the LeCroy HRO66Zi, which has a 12-bit ADC, and the Agilent DSO9054H, which has 12 bits of resolution, take advantage of about 10 bits of resolution. The lower two bits of resolution are consumed by front-end noise over the entire range of vertical settings.

How Does an Oscilloscope's ADC Impact Vertical Resolution? *(continued)*

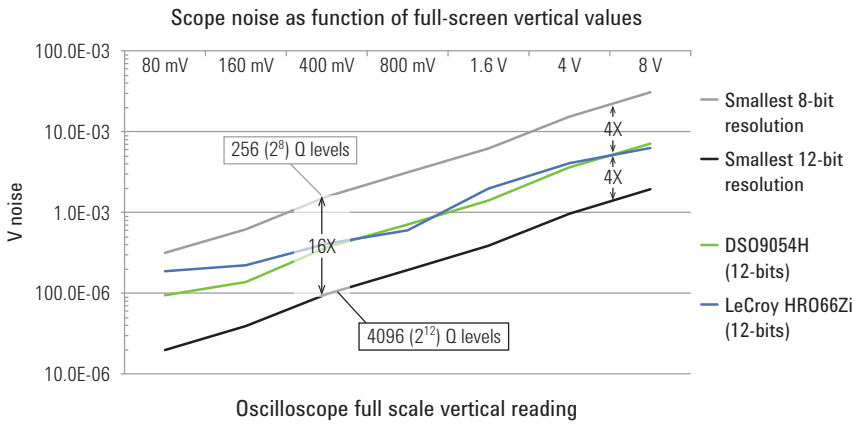

Figure 2.

What Does the "Number-of-Bits" Specification Really Mean?

"Bits of resolution" refers to the number of unique vertical levels that an oscilloscope can map acquisition samples. Oscilloscope families that use this term typically use an 8-bit ADC and DSP to achieve greater than 8 bits of resolution. Setting the oscilloscope to "high-res" mode tells the oscilloscope to oversample and digitally filter the output of the ADC to achieve more bits of resolution.

For Agilent Infiniium oscilloscopes, the DSP method used to increase the number of bits is an N-tap boxcar-averaging filter. Averaging by two adds one bit of resolution. A general expression for the number of bits of resolution, r, is shown in Equation 1.

$$r = n + \log_2(N) \text{ bits of resolution} \quad (1)$$

For example, 12 bits of resolution is achieved with a 16-tap boxcar-averaging filter running on data from an 8-bit ADC.

Some manufacturers prefer to specify the "number of enhanced bits." An enhanced bit is equivalent to an ideal ADC bit in terms of SNR. An implementation that provides m enhanced bits provides the same ideal SNR achieved by an ideal m-bit ADC. By using a boxcar-averaging filter on the output of an n-bit ADC, the number of enhanced bits, m, is given by Equation 2.

$$m = n + \log_4(N) \text{ enhanced bits} \quad (2)$$

For example, a 64-tap boxcar-averaging filter running on data from an 8-bit ADC has 12 enhanced bits of resolution.

How does ENOB Relate to Bits of Resolution and ADC Bits?

Another specification commonly used is "Effective Number of Bits" (ENOB). ENOB is a measure of the SNR for a digitized signal. The definition for SNR in dB is given by Equations 3. Another definition in terms of root-mean-square voltage (V_{RMS}) is given by Equation 4. This definition is useful when computing the SNR for an oscilloscope. Equation 5 shows the relationship between ENOB and SNR.

$$SNR_{dB} = 10 \log_{10}(\text{Signal power} / \text{Noise power}) \quad (3)$$

$$SNR_{dB} = 20 \log_{10}(\text{Signal } V_{RMS} / \text{Noise } V_{RMS}) \quad (4)$$

$$ENOB = (SNR_{dB} - 1.761)/ 6.02 \quad (5)$$

Each additional effective bit improves the SNR by 6.02 dB. An ideal 8-bit ADC has an ENOB of 8 and a SNR of 50 dB. The noise from an ideal ADC is all due to quantization effects. Ideal ADCs with more bits have lower quantization noise and better ENOB. ENOB varies with frequency, and is generally specified for a particular frequency.

ENOB is a good figure of merit when comparing oscilloscope technologies. The ENOB is reduced by all of the noise and error sources in the oscilloscope including ADC quantization noise, ADC differential nonlinearity, ADC integral nonlinearity, thermal noise, shot noise and input amplifier distortion. You should expect an ENOB specification to usually be much lower than the number-of-bits specification due to these noise and error sources. For example, an ENOB between 8 and 9 bits at high frequency, or equivalently, a SNR between 50 dB and 56 dB, is typical for a 12-bit high-resolution digital oscilloscope.

High-Resolution Waveform Examples

Figure 3 shows three waveforms captured on a digital oscilloscope that supports the high-resolution acquisition mode. The input signal is a stair-step ramp signal generated by driving a Digital-to-Analog Convertor (DAC) with a digital counter. The upper grid displays three waveforms with standard magnification. The lower grid displays all three waveforms overlaid with 10X magnification to show more vertical detail. The top waveform was captured at 2.5 GSa/s with the high-resolution acquisition mode turned off.

High-Resolution Waveform Examples *(continued)*

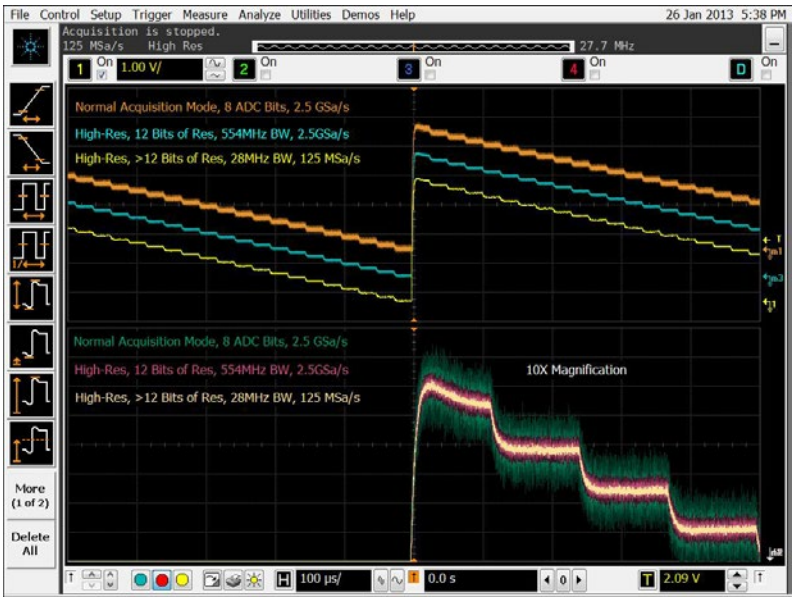

Figure 3. High-resolution signal trace examples

Notice all of the noise on the signal and lack of detail. This is especially apparent in the 10X magnified view. In this case, quantization is not noticeable because vertical dither has been added to the waveform to enhance the display. The middle waveform was captured at 2.5 GSa/s with the high-resolution acquisition mode turned on and set to provide 12 bits of resolution. The bandwidth for this case is 554 MHz. The noise is reduced significantly and more vertical detail can be seen. The bottom waveform was captured with more than 12 bits of resolution. This was achieved by setting the sample rate to 125 MSa/s, which increased the vertical resolution to more than 12 bits and reduced the bandwidth to 28 MHz. For this particular signal, 28 MHz is sufficient bandwidth and provides the best SNR with the most vertical detail.

The signal traces shown in Equation 1 were generated on an oscilloscope that uses an 8-bit ADC and boxcar-averaging to implement the high-resolution acquisition mode. Equation 6 shows the approximate bandwidth for a boxcar-averaging filter.

$$\text{Boxcar bandwidth} \approx 0.4428\ F_s/N \qquad (6)$$

For the middle trace in Figure 3, the bandwidth can be calculated as follows. The sample rate, F_s, into the boxcar averaging filter is 20 GSa/s and the number of bits of resolution is 12 bits. Using Equation 2, the number of taps is $2^{(12-8)}$ or 16 taps. The bandwidth is 0.4428 x 20 G/16 or 554 MHz. Most high-resolution oscilloscopes calculate and display the bandwidth automatically.

High-Resolution Acquisition Architecture

Figure 4 shows an architecture that is commonly used to implement a high-resolution acquisition system. A bandwidth limit filter runs on the analog input signal to eliminate signal content above the Nyquist frequency. The Nyquist frequency is defined as half of the sampling frequency, F_s. Any signal content above the Nyquist frequency folds back into the pass band, causing undesirable aliasing.

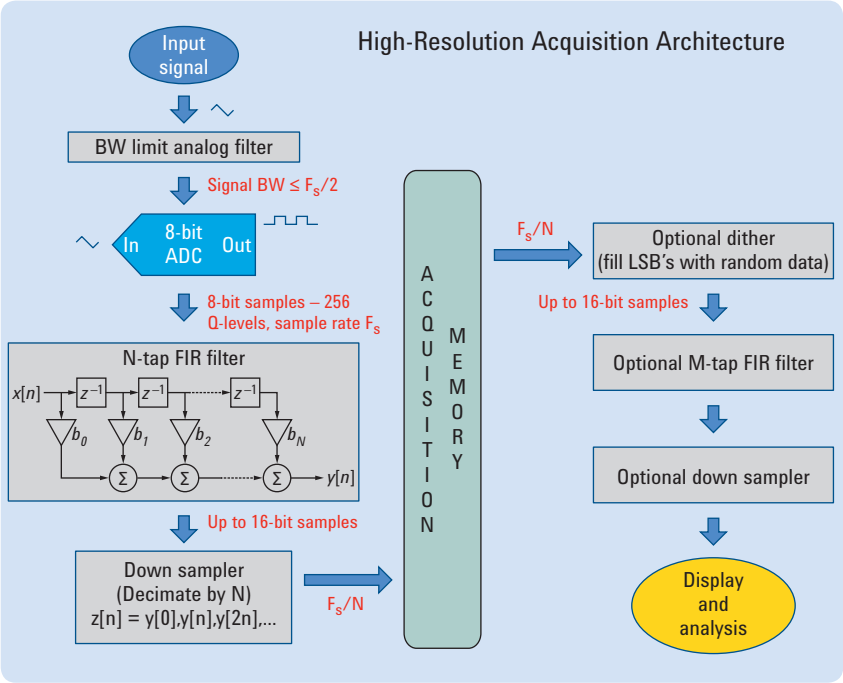

Figure 4. High-resolution acquisition architecture

On Agilent 9000 H-Series oscilloscopes, the term, "hypersampling" is used to describe the sampling process. The minimum sampling frequency required to prevent aliasing is twice the bandwidth of the band limited analog signal. Hypersampling implies a sample rate that is much greater than this. Hypersampling is a useful technique that increases vertical resolution and reduces the noise floor.

Aliasing is an issue for standard full-bandwidth oscilloscopes running at reduced sample rates. The corner frequency for the bandwidth limit filter is set to a value slightly larger than the maximum specified bandwidth and is typically not reconfigurable to support lower sample rates. In high-resolution architecture, aliasing is reduced significantly by running an N-tap low-pass FIR filter prior to down sampling. This filter attenuates signal content that would otherwise fold back into the pass band after down sampling. Aliasing is less of a concern for a dedicated high-resolution oscilloscope because the corner frequency of the bandwidth limit filter is set based on the reduced maximum bandwidth specification. For example, a 4 GHz oscilloscope running the high-resolution mode to achieve 12 bits of resolution at 500 MHz must still set the

High-Resolution Acquisition Architecture *(continued)*

corner frequency above 4 GHz to support the maximum bandwidth available. A dedicated 500 MHz high-resolution oscilloscope, on the other hand, can set the corner frequency slightly above 500 MHz, eliminating aliasing altogether.

Filters with uniform tap weighting are called boxcar-averaging filters. Boxcar-averaging filters are easy to implement and support very high input sample rates and a large number of taps. However, the rectangular time response of the boxcar filter produces a Sin(x)/x response in the frequency domain (see Figure 5).

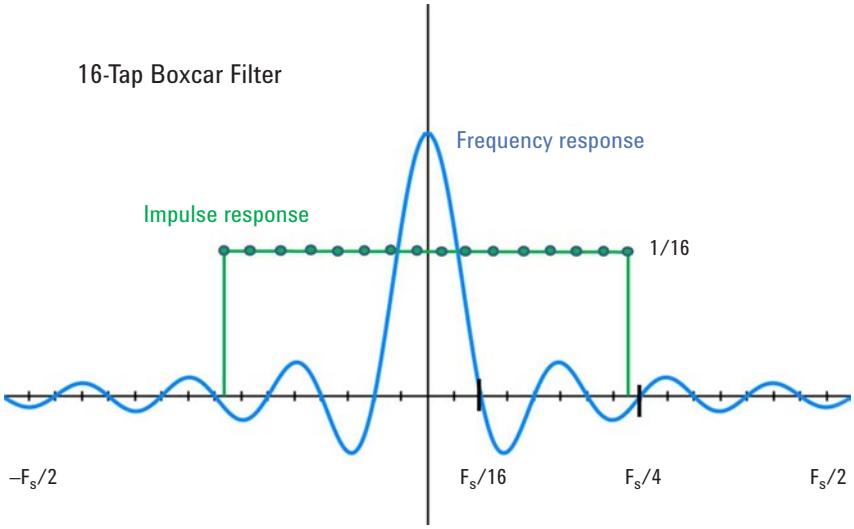

Figure 5. Impulse and frequency response for a 16-tap boxcar-averaging filter

The side lobes in the stop band region allow some signal content beyond the bandwidth to fold back into the pass band, resulting in additional noise, aliasing and distortion. To counter this, some oscilloscopes, like those from Agilent, use non-uniform weighting of the taps to produce a more desirable frequency response.

The down sampler following the FIR filter is required to conserve acquisition memory to support long time ranges. In most implementations, the N-tap filter and down sampler are integrated into one block that only outputs one out every N samples. One artifact of down sampling is that it creates multiple images of the frequency response centered at integer multiples of the decimated frequency, F_s/N. The Nyquist frequency is reduced to $F_s/(2N)$. Any signal content in the stop band region of the FIR filter, beyond $F_s/(2N)$, folds back into the pass-band region, causing additional noise, aliasing and distortion. To counter this, some oscilloscopes also implement an M-tap FIR filter on the output side of acquisition memory. The filtering to achieve high resolution averaging is shared between the M-tap and N-tap filters, allowing the N-tap filter to be shorter and the sample rate for a given bandwidth to be higher.

Using Acquisition Averaging to Improve Vertical Resolution

Oscilloscopes provide acquisition averaging as a way to reduce the noise and improve the vertical resolution. Turning on averaging causes the oscilloscope to average vertical values along each captured waveform with the same vertical sample values from successive waveforms. Oscilloscopes allow the user to specify how many waveforms to average. Unlike the high-resolution architecture, acquisition averaging does not reduce the bandwidth. However, it only works on repetitive signals.

Use acquisition averaging when:

- The maximum oscilloscope bandwidth is required
- The signal is repetitive
- Large memory depth is not required
- Control of the number of averages is desired

Use high-resolution acquisition when:

- The maximum oscilloscope bandwidth is not required, or the oscilloscope has excess sample rate relative to its bandwidth
- The signal must be captured from a single trigger
- Deep memory to capture long time ranges is required

While not all oscilloscope vendors enable this, Agilent Infiniium oscilloscopes allow acquisition averaging and high-resolution acquisition to run simultaneously, allowing the user to make tradeoffs between bandwidth and throughput.

Using Acquisition Averaging to Improve Vertical Resolution *(continued)*

Figure 6. High resolution works great for capturing a low-noise PRBS signal, while averaging does not

Figure 6 shows a PRBS signal captured with a high-resolution oscilloscope set for 10 bits of resolution and 2 GHz of bandwidth. It also shows the PRBS captured with acquisition averaging (four averages) enabled. In this case, acquisition averaging produces a meaningless display because the PRBS signal is not periodic over the captured time range.

Why Purchase a Dedicated High-Resolution Oscilloscope?

If the measurement application requires higher vertical resolution and moderate bandwidth, a dedicated high-resolution oscilloscope like Agilent's 9000 H-Series is probably the best choice. High-resolution oscilloscopes use the latest ADC and DSP technologies to provide superior resolution and low-noise performance. Aliasing is better controlled, as the vendor can implement a hardware-based front end that attenuates higher-frequency signals. No special mode or setup is required to achieve the higher resolution. This makes the oscilloscope easier to use. The number of bits and bandwidth are automatically displayed for documentation purposes.

myAgilent

www.agilent.com/find/myagilent
A personalized view into the information most relevant to you.

www.axiestandard.org
AdvancedTCA® Extensions for Instrumentation and Test (AXIe) is an open standard that extends the AdvancedTCA for general purpose and semiconductor test. Agilent is a founding member of the AXIe consortium.

www.lxistandard.org
LAN eXtensions for Instruments puts the power of Ethernet and the Web inside your test systems. Agilent is a founding member of the LXI consortium.

www.pxisa.org
PCI eXtensions for Instrumentation (PXI) modular instrumentation delivers a rugged, PC-based high-performance measurement and automation system.

Agilent Channel Partners

www.agilent.com/find/channelpartners
Get the best of both worlds: Agilent's measurement expertise and product breadth, combined with channel partner convenience.

Three-Year Warranty

www.agilent.com/find/ThreeYearWarranty
Agilent's combination of product reliability and three-year warranty coverage is another way we help you achieve your business goals: increased confidence in uptime, reduced cost of ownership and greater convenience.

Agilent Advantage Services

www.agilent.com/find/AdvantageServices
Accurate measurements throughout the life of your instruments.

www.agilent.com/quality

For more information on Agilent Technologies' products, applications or services, please contact your local Agilent office. The complete list is available at:
www.agilent.com/find/contactus

Americas	
Canada	(877) 894 4414
Brazil	(11) 4197 3600
Mexico	01800 5064 800
United States	(800) 829 4444

Asia Pacific	
Australia	1 800 629 485
China	800 810 0189
Hong Kong	800 938 693
India	1 800 112 929
Japan	0120 (421) 345
Korea	080 769 0800
Malaysia	1 800 888 848
Singapore	1 800 375 8100
Taiwan	0800 047 866
Other AP Countries	(65) 375 8100

Europe & Middle East	
Belgium	32 (0) 2 404 93 40
Denmark	45 45 80 12 15
Finland	358 (0) 10 855 2100
France	0825 010 700*
	*0.125 €/minute
Germany	49 (0) 7031 464 6333
Ireland	1890 924 204
Israel	972-3-9288-504/544
Italy	39 02 92 60 8484
Netherlands	31 (0) 20 547 2111
Spain	34 (91) 631 3300
Sweden	0200-88 22 55
United Kingdom	44 (0) 118 927 6201

For other unlisted countries:
www.agilent.com/find/contactus
(BP2-19-13)

Product specifications and descriptions in this document subject to change without notice.

© Agilent Technologies, Inc. 2013
Published in USA, May 07, 2013
5991-1617EN

Agilent Technologies