How Good is your Oscilloscope?

Can you trust what you see on your Oscilloscope Screen and the measurements you make? Oscilloscope signal integrity impacts signal shape and measurement values. Evaluate the signal integrity of your Oscilloscope and make measurements you can trust.

By Erik Babbé

Signal integrity is the primary measure of signal quality. Its importance increases with higher signal speed, Oscilloscope bandwidth, the need to view small signals, or the need to see small changes on larger signals. Signal integrity impacts all Oscilloscope measurements. Oscilloscopes themselves are subject to the signal integrity challenges of distortion, noise, and loss.

Oscilloscopes with superior signal integrity attributes provide a better representation of your signals under test, while those with poor signal integrity attributes show a poorer representation. This difference impacts engineers' ability to gain insight, understand, debug, and characterize designs. Selecting an Oscilloscope that has good signal integrity attributes is important as Oscilloscopes with poor signal integrity can increase risk in development cycle times, production quality, and components chosen. To evaluate Oscilloscope signal integrity, we will look at ADC bits, vertical scaling, noise, frequency and phase response, ENOB and intrinsic jitter.

ADC bits

Resolution is the smallest quantization (Q) level determined by the analog-to-digital converter (ADC) in the Oscilloscope. The higher the number of ADC bits, the more resolution the Oscilloscope has. For example, an 8 bits ADC can encode an analog input to one in 256 different levels (since $2^8 = 256$) while a 10 bits ADC ideally provides 4 times the resolution of that with $2^{10} = 1024$ Q levels.

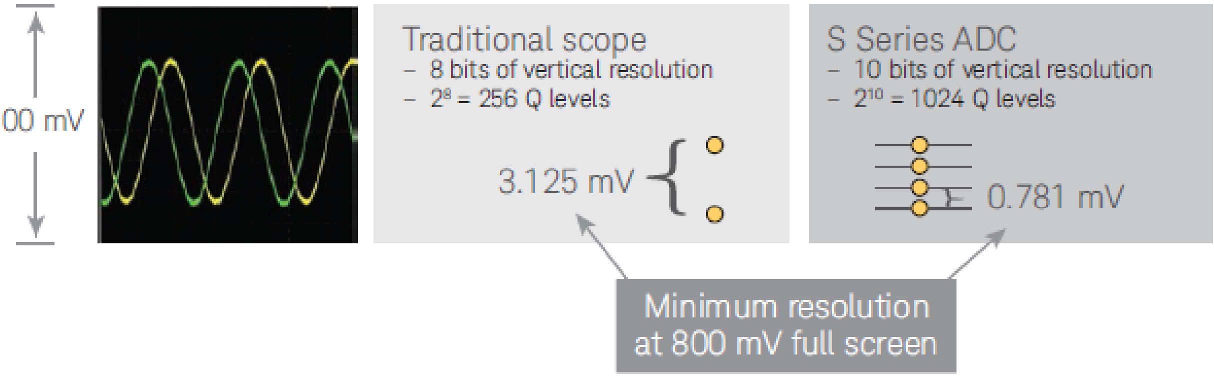


Figure 1. Resolution is an important signal integrity attribute. Having an Oscilloscope with more ADC bits, and proper vertical scaling are two ways to increase resolution.

Vertical scaling

Since the ADC operates on the full scale vertical value, proper vertical scaling also helps increase Oscilloscope resolution. Figure 1 shows a full screen of 800 mV (8 divisions * 100 mV/div).

An Oscilloscope with an 8-bit ADC has a resolution of 3.125 mV (800 mV/256 Q levels), while a 10-bit ADC has 0.781 mV. Each Oscilloscope can only resolve signals down to the smallest Q level.

To get the best resolution, use the most sensitive vertical scaling setting while keeping the full waveform on the display. Scale the waveform to consume almost the full vertical display and you are making full use of your Oscilloscope's ADC. If a signal is scaled to take up only half or less of the vertical display, you will lose 1 or more ADC bits.

The combination of the ADC, the Oscilloscope's front-end architecture, and the probe used determine the limit of vertical scaling the Oscilloscope hardware supports. At a certain point, each family of Oscilloscopes cannot go to a lower vertical scale. Vendors will often refer to this as the point where the Oscilloscope moves into software magnification. Turning the Oscilloscope's vertical scale to a smaller number simply magnifies the displayed signal but doesn't result in any additional resolution.

Figure 2 gives an example of two Oscilloscopes evaluating a small signal that has magnitude such that a vertical scaling of 16 mV full screen allows the signal to consume almost all the vertical display height. The traditional 8-bit Oscilloscope goes into software magnification at 7 mV div resulting in a minimum resolution of 218 µV (7 mV/div * 8 div/256 Q levels). A 10-bit Oscilloscope such as the Keysight Infiniium S-Series stays in hardware all the way down to 2 mV/div giving a minimum resolution of 16.6 uV (2 mV/div * 8 div)/1024 Q levels), 13 times the resolution as the 8-bit Oscilloscope.

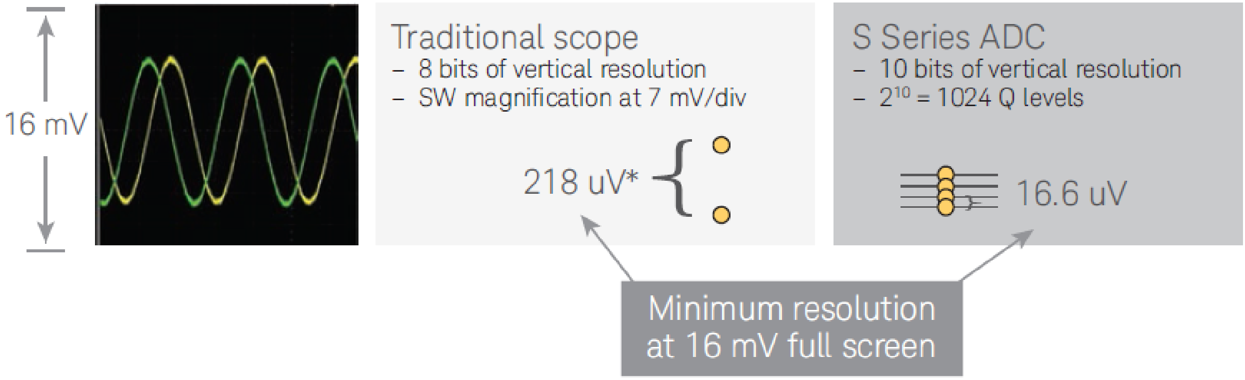


Figure 2. The minimal vertical setting an Oscilloscope supports in hardware will be important to see small signal detail.

Noise

Noise impacts both horizontal as well as vertical measurements. The lower the noise, the better signal integrity you can expect. If noise levels are higher than ADC quantization levels, you won't be able to take advantage of the additional ADC bits. Having an Oscilloscope with low noise (high dynamic range) is critical if you want to see small currents and voltages, or small changes on larger signals.

Noise can come from a variety of sources, including the Oscilloscope's front end, its ADC and the probe or cable used to connect the device. The ADC itself has quantization noise, but this typically plays a lesser role in overall noise contribution than the front end.

Most Oscilloscope vendors will characterize noise and include these values on their product datasheet. If not, you can ask for the data, or find out yourself. The measurement is easy and takes only a few minutes. Each Oscilloscope channel will have unique noise qualities at each vertical setting. Disconnect all inputs from the front of the Oscilloscope and set it to 50 Ω input path (you can also run the test for the 1 MΩ path). Turn on a decent amount of acquisition memory such as 1 Mpt, with sample rate fixed at high sample rate to ensure you are getting the full Oscilloscope bandwidth. You can view the noise visually by looking at wave shape thickness, or quantify by measuring Vrms AC. These methods will enable you to know how much noise each Oscilloscope channel has at each vertical setting.

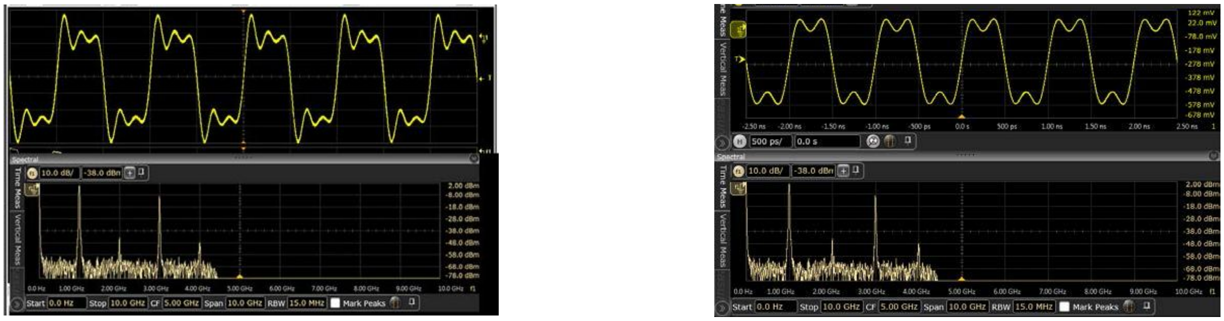
Frequency response

Uniform and flat Oscilloscope Frequency Response is highly desired for signal integrity. Each Oscilloscope model will have a unique frequency response that is a quantitative measure of the Oscilloscope's ability to accurately acquire signals up to the rated bandwidth. Three Oscilloscope must-have requirements to accurately acquire waveforms are:

1. A flat frequency response.
2. A flat phase response.
3. Captured signals must be within the bandwidth of the Oscilloscope.

A flat frequency response indicates that the Oscilloscope is treating all frequencies equally, and a flat phase response means the signal is delayed by precisely the same amount of time at all frequencies. Deviation from one or more of these requirements will cause an Oscilloscope to inaccurately acquire and draw a waveform.

Some scopes have correction filters that are typically implemented in hardware DSP blocks and tuned for a family of oscilloscopes. Figure 3 shows how correction filters can improve signal integrity of the measurement by creating a flat magnitude and phase response. The Oscilloscope on the right shows a waveform that accurately matches the spectral content of the signal while the one of the left does not.



Start 0.0 Hz Stop 10.0 GHz CF 5.00 GHz Span 10.0 GHz RBW 15.0 MHz

Figure 3. Two Oscilloscopes having identical bandwidth rating, sample rate and other settings, were connected to an identical signal. Why the difference? The one on the right uses Hardware DSP correction filters to produce a flat magnitude and phase response, while the one on the left does not.

Your Oscilloscope's overall frequency response will be a combination of the Oscilloscope's frequency response combined with the frequency response of any probes or cables connected between the DUT and the instrument. If you put a BNC cable that has bandwidth of 1.5 GHz on the front of a 4 GHz Oscilloscope, the overall bandwidth of the system is limited by the BNC cable and not the Oscilloscope. Make sure your probes, accessories, and cables aren't the limiting factor for a precision measurement.

Effective Number of Bits (ENOB)

ENOB is a measure of the Oscilloscope’s dynamic performance expressed in a series of bits-vs-frequency curves. Each curve is created at a specific vertical setting while frequency is varied. The resulting voltage measurements are captured and evaluated. In general, a higher ENOB (expressed in bits) is better.

While some vendors may give the ENOB value of the Oscilloscope’s ADC by itself, this figure has no value. ENOB of the entire system is what is important. The ADC could have a great ENOB but poor Oscilloscope front-end noise would dramatically lower the ENOB of the entire system. Engineers who look exclusively at ENOB to gauge signal integrity should be cautioned. ENOB does not consider offset errors or phase distortion that the Oscilloscope may inject.

An Oscilloscope doesn’t just have one ENOB number but has different ENOB values for each vertical setting and frequency.

Intrinsic Jitter

Jitter describes deviation from the ideal horizontal position and is measured in ps rms or ps peak-to-peak. Jitter sources include thermal and random mechanical noise from crystal vibration. Traces, cables, and connectors can further add jitter to a system through intersymbol interference.

Oscilloscopes themselves have jitter. The term “jitter measurement floor” refers to the jitter value that the Oscilloscope reports when it measures a perfect jitter free signal. The jitter measurement floor value is comprised not only of the sample clock jitter, but also of vertical error sources, such as vertical noise and aliased signal harmonics. These vertical error sources affect horizontal time measurements because they change the signal of threshold crossings.

Excessive jitter is bad as it can cause timing violations resulting in incorrect system behavior or poor bit error rates (BER) in communication systems resulting in incorrect transmissions. Measurement of jitter is necessary to ensure high-speed system reliability. Understanding how well your Oscilloscope will make those measurements is critical to interpreting your jitter measurement results.

Figure 4. Keysight’s Infiniium S-Series oscilloscopes include a new time base technology block. It’s clock accuracy is an impressive 75 parts per billion. Intrinsic jitter for short record lengths is less than 130 fs.

Summary

While each attribute is important, the most overall accuracy will be seen in the Oscilloscope that has a better overall composite of the 7 attributes as listed in Table 1. Looking at only a single signal integrity attribute in the absence of others can lead to false conclusions of how good your Oscilloscope is, which can then lead to unnecessary risk in getting your products to market or meeting product performance.

Table 1. The seven important signal integrity attributes for an Oscilloscope.

Signal integrity metric	Oscilloscope technology block	Where can you find the answer?
Resolution	ADC bits	Product sheet
Noise	Front-end	Most vendors include in product datasheet.
Vertical scaling supported in HW	ADC/front-end	Datasheets do not always specify when SW magnification starts. Some vendors BW limit at small sensitivities.
Frequency response flatness	Analog filters and correction filter	Not typically included in product datasheets. You will need to ask the vendor to see a magnitude and phase response for the model you are evaluating.
Time scale accuracy	Time base	Product sheet
Amount of intrinsic jitter	Time base	Some vendors include, others don’t. If not in the datasheet, ask the vendor.
ENOB	Combination of both vertical and horizontal Oscilloscope system	Some vendors include, others don’t. If not in the datasheet, ask the vendor.

For more detailed information, please download the Application Note.