APPLICATION NOTE

Why Is Oscilloscope Vertical Accuracy Important?

Evaluating oscilloscope signal accuracy

KEYSIGHT

What Does “Vertical Accuracy” Mean?

The horizontal axis of an oscilloscope is the time base (seconds per division or s / div), and the vertical axis shows us the voltage (volts per division, V / div). Vertical accuracy refers to the accuracy of the voltage we see on screen, both visually and in measurements. How close is the voltage you are reading on the oscilloscope screen to the actual voltage of your signal? It depends on the vertical accuracy.

Highest ADC bits + Lowest noise floor = Highest vertical accuracy

Two key specifications define vertical accuracy:

- The number of analog-to-digital converter (ADC) bits.
- The front-end noise floor of the oscilloscope.

The higher the number of ADC bits, the more vertical resolution you have. The more vertical resolution you have, the more accurate a signal you see. Furthermore, the lower your front-end noise floor is, the less your oscilloscope impacts the signal you are measuring. All oscilloscopes have some intrinsic noise, just like every electronic device has some noise. Any noise present in the oscilloscope is going to ride on top of your signal and skew your measurements. You want an oscilloscope with the least amount of noise possible so that it does not affect your measurements. This consideration is important with any type of signal but even more critical when measuring very small voltages.

Using an oscilloscope with a low ADC and high noise floor can cause inaccurate measurements and lead to redesigns, resourcing components, and, ultimately, wasting valuable time. To minimize the time you spend validating and redesigning, you should evaluate an oscilloscope’s vertical accuracy to ensure reliable measurements. Figure 1 shows that high vertical accuracy makes a difference visually and in the voltage measurements.

InfiniiVision 3000G X-Series with low accuracy

New HD3 Series with high vertical accuracy

Figure 1. When comparing measurements taken on the Keysight InfiniiVision 3000G X-Series oscilloscope and the HD3 Series using the same probing setup, we find that the HD3 Series provides more accurate measurements. The HD3 features significantly higher vertical resolution with a 14-bit ADC and a low noise floor of 50 µV$_{RMS}$. In contrast, the 3000G has 8 bits and a 250 µV$_{RMS}$ of noise. The difference significantly affects measurement accuracy.

ADC Bits and Minimum Resolution

The ADC is crucial for vertical signal accuracy. The higher the number of ADC bits, the more resolution the oscilloscope has. An oscilloscope with a 14-bit ADC should provide 64 times the resolution of a scope with an 8-bit ADC.

Resolution refers to the smallest quantization level determined by the ADC in the oscilloscope. An oscilloscope's ADC with a resolution of 8 bits can encode an analog input into one in 256 levels since $2^8 = 256$. We will refer to these as quantization levels (Q levels).

The ADC operates on the oscilloscope's full-scale vertical value. For both current and voltage measurements, the Q-level steps are associated with the full-scale vertical scope setting. If the user adjusts the vertical setting to 100 mV per division, full screen equals 800 mV (8 divisions * 100 mV / div), and Q-level resolution is equal to 800 mV divided by 256 levels, or 3.125 mV.

Let's look at the example shown in Figure 2. Two scopes are scaled to 800 mV full screen. A scope with an 8-bit ADC has a resolution of 800 mV / (2^8 = 256 Q levels), or 3.125 mV. A scope with a 14-bit ADC, like the Keysight InfiniiVision HD3 Series, has a resolution of 800 mV / (2^{14} = 4,096 Q levels), or 48.8 µV. Each scope can only resolve signals down to the smallest Q level.

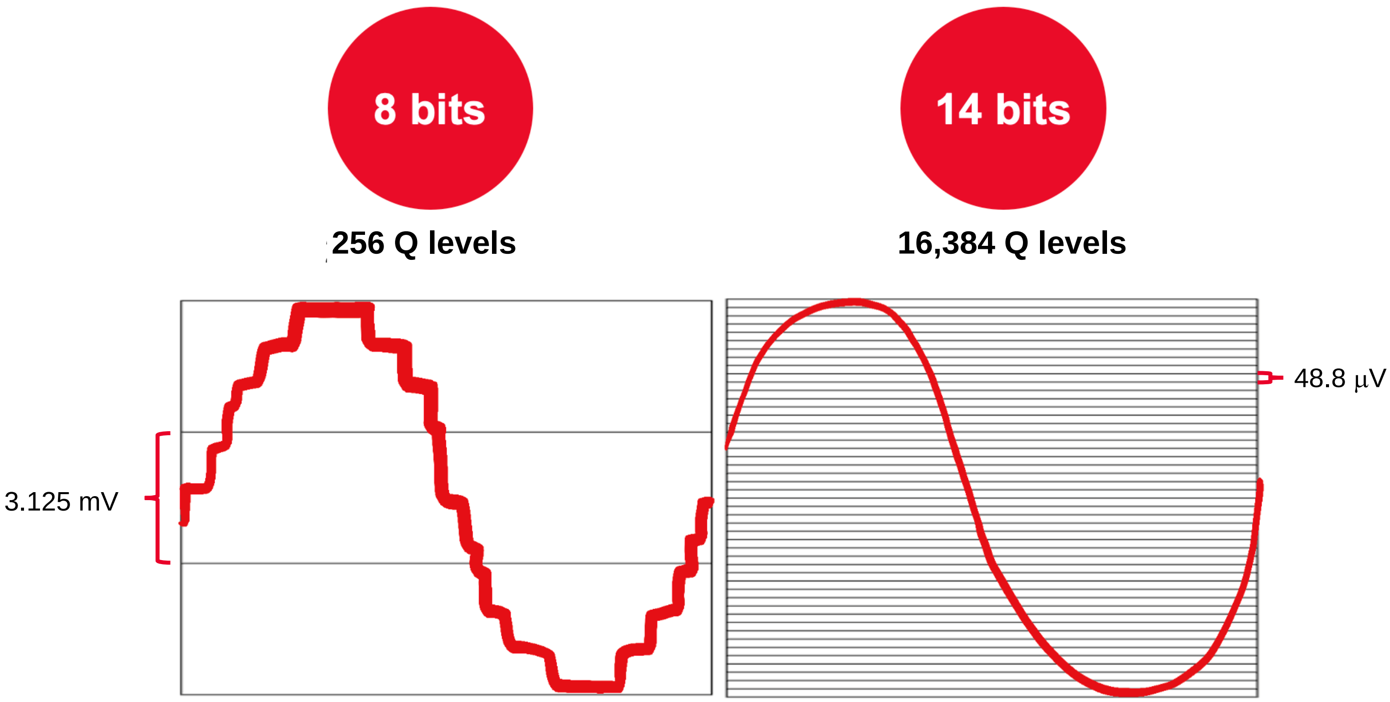


Figure 2. While most oscilloscopes use 8- to 12-bit ADCs, the HD3 Series has a 14-bit ADC. This is four times the resolution of a 12-bit ADC and 64 times the resolution of an 8-bit ADC. Higher ADC + low noise = higher resolution.

Many oscilloscopes also offer high-resolution mode. Oversampling techniques combined with digital signal processer (DSP) filters can increase vertical resolution. Vendors often refer to this increase in terms of bits of resolution. In the case of the InfiniiVision HD3 Series, high resolution enhances the bit depth from the intrinsic 14-bit ADC resolution to a 16-bit resolution. This technique requires an ADC architected with an excess sample rate relative to the hardware bandwidth needed for a particular measurement.

A high number of ADC bits will theoretically increase resolution. However, that is not always the case. Vertical resolution depends on not only the ADC, as we learned above, but also the front-end noise of the oscilloscope. The effective number of bits (ENOB) specification takes the noise of the system into account and tells you how many of those bits are actually effective in making measurements. Not only does the HD3 Series have a 14 bit ADC and low noise (50 mV), but it also has high ENOB. Learn more about ENOB in the following section and the *Understanding ADC Bits and ENOB* white paper.

ENOB

Effective number of bits is a measure of dynamic performance. While some oscilloscope vendors may give the ENOB value of the oscilloscope’s ADC by itself, this figure has no value. What is important is the ENOB of the entire system. The ADC might have a great ENOB, but poor oscilloscope front-end noise would dramatically lower the ENOB of the entire measurement system. While oscilloscope vendors rarely publish overall ENOB values, they typically do characterize them and will provide these values for a specific model number upon request.

Oscilloscope ENOB is a series of curves, not a specific number. ENOB measurement occurs when a fixed amplitude sine wave is swept in frequency. Each curve is created at a specific vertical setting while frequency is varied. The oscilloscope captures and evaluates the resulting voltage measurements.

In the time domain, calculating ENOB involves subtracting the theoretical best-fit sine wave from the measured wave. The error between these curves can come from the front end of the oscilloscope, resulting from attributes such as phase nonlinearities and amplitude variations over frequency sweeps. Error can also come from interleaving distortion from ADCs.

In the frequency domain, calculating ENOB involves subtracting the power associated with the primary tone from the total broadband power. Both techniques yield the same result.

ENOB values will be lower than the oscilloscope’s ADC bits. For example, the 8-bit InfiniiVision 3000G / 4000G X-Series scopes have a system ENOB of about 6.9. A 14-bit HD3 Series oscilloscope with an extremely low-noise front end has a system ENOB of over 10.4 bits.

In general, a higher ENOB is better. However, engineers should be cautious about relying exclusively on ENOB to assess signal integrity. ENOB does not account for offset errors or phase distortion that the scope may inject.

Learn more about the importance of ENOB and how it differs from ADC bits in the white paper *Understanding ADC Bits and ENOB*.

Scaling's Impact on Resolution

Scaling plays a significant role in maximizing the resolution of your oscilloscope. Scaling the waveform to take the whole display of the oscilloscope enables the scope's ADC converter. If a signal is scaled to take up only half of the vertical display, you've just decreased the number of ADC bits used from 14 to 12. Scale the waveform to one-quarter of the vertical display, and you've reduced the number of ADC bits used from 14 to 10. Scale the waveform to consume close to the full vertical display, and you are using all 14 bits of the oscilloscope's ADC. To get the best resolution, use the most sensitive vertical scaling setting while keeping the waveform on the display.

The combination of the ADC, the scope's front-end architecture, and the probe determine how sensitive the vertical scaling can be. At a certain point, the oscilloscope hardware cannot reach a lower vertical scale setting, even if the knobs allow it. Vendors call this the point where the scope moves into software magnification. Turning the scope's vertical scale to a smaller number only magnifies the displayed signal without adding resolution. Most traditional scopes use software magnification below 2 mV / div. Some vendors limit bandwidth at small vertical settings (below 2 mV / div) because of significant front-end noise, which makes it hard to see small signals at full bandwidth.

Let's compare two scopes. A small signal has a magnitude such that a vertical scaling of 16 mV full screen allows the signal to fill nearly the entire vertical display height.

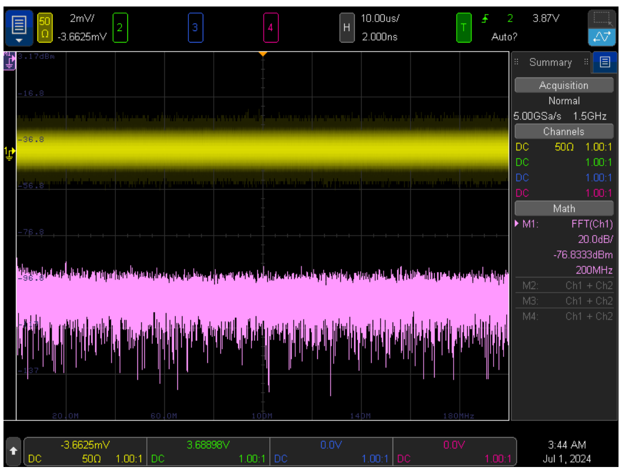
- A traditional scope such as the InfiniiVision 3000G / 4000G X-Series has an 8-bit ADC and goes into software magnification at 7 mV div. Minimum full-screen resolution equals 56 mV (7 mV / div * 8 div) / 256 Q levels. This results in minimum resolution of 218 μV.
- The InfiniiVision HD3 Series oscilloscope has the industry's only 14-bit ADC and stays in hardware all the way down to 2 mV / div with no required bandwidth reduction. Minimum full-screen resolution equals 16 mV (2 mV / div * 8 div) / 16,384 Q levels. This results in minimum resolution of 0.15 nV — 64 times the resolution of the traditional 8-bit scope shown in Figure 2.

Oscilloscope Noise

Having a scope with low noise (high dynamic range) is critical for observing small currents and voltages or small changes in larger signals.

Note: You won't be able to see signal detail smaller than the noise level of the scope. When a signal is "in the noise," it is smaller than the noise floor (Figure 3).

InfiniiVision 3000G X-Series with high noise



New HD3 Series with the lowest noise

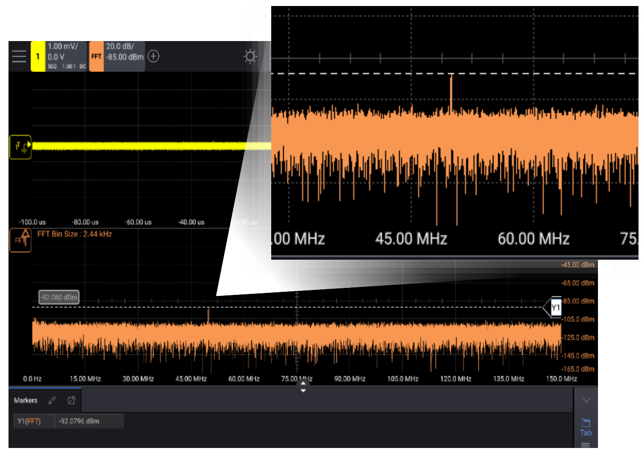


Figure 3. This example measures a 53 µV signal. On the left, the 3000G X-Series oscilloscope, at 2mV / div, has a noise floor of 372 μV_{RMS}, making it impossible to see a 53 µV tone on the fast Fourier transform (FFT) because of high front-end noise. On the right, the HD3 Series, with a noise floor of less than 50 μV_{RMS} at these settings, clearly shows an extremely small 53 µV tone on the FFT because of its low front-end noise. Low oscilloscope noise enables you to capture even the smallest signal details.

If noise levels are higher than ADC quantization levels, users will not be able to take advantage of the additional ADC bits.

Noise can come from various sources, including the front end of the scope, the ADC in the scope and the probe, or the cable connected to the device. The ADC has a quantization error. For oscilloscopes, quantization noise typically contributes less to overall noise; the front end of the oscilloscope plays a more significant role.

Most oscilloscope vendors characterize noise for specific bandwidths and include these values on the product datasheet. If the information is not available, you can ask for it or find out yourself. It is easy to measure in a few minutes. Disconnect all inputs from the front of the scope and set it to a 50 Ω input path. You can also run the test for the 1 MΩ path. Turn on sufficient acquisition memory, such as 1 Mpt, with a fixed high sample rate for full-scope bandwidth. Run the scope with infinite persistence and see how thick the resulting waveform is. The thicker the waveform, the more noise the scope is producing internally. You can turn on an “AC RMS (full screen std. deviation)” to see what the noise level is at each V / div setting.

The InfiniiVision HD3 Series oscilloscope has an all-new custom front end with incredibly low noise floor (< 50 μV_{RMS} at 2 mV / div, 50 Ω).

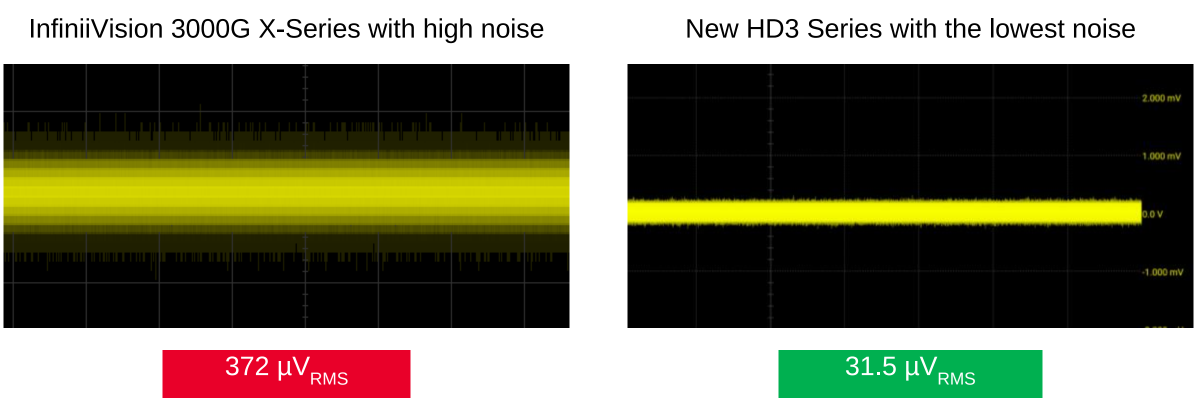


Figure 4. We took this AC RMS noise measurement at 1mV / div and the 50 Ω path on each oscilloscope. The oscilloscope’s base noise level will ride on top of every signal you measure, so consider that when comparing competitor oscilloscopes. The front-end channels of the HD3 Series have the lowest noise in the industry, minimizing the impact on your signals and measurements.

Each scope channel will have unique noise qualities at each vertical setting. You can assess the noise by observing the wave shape thickness, or you can take a more analytical approach by measuring a V_{rms} AC to quantify it. These measurements indicate the amount of noise on each scope channel at various vertical settings, enabling you to measure signals that are lower than the scope’s noise level. All acquired vertical values are subject to deviation up to the noise value of the scope. Noise impacts horizontal and vertical measurements.

The lower your oscilloscope’s noise, the better the measurement results will be.

Frequency Responses

Each oscilloscope model has a unique frequency response, which measures the scope’s ability to accurately acquire signals up to the rated bandwidth. To accurately acquire waveforms, oscilloscopes must meet three key requirements:

- The oscilloscope must have a flat frequency response.
- The oscilloscope must have a flat phase response.
- Captured signals must be within the bandwidth of the oscilloscope.

Deviation from one or more of these requirements will cause an oscilloscope to inaccurately acquire and draw a waveform. The more variance from these requirements, the greater the error in acquiring and drawing the waveform.

Fast edges contain multiple harmonics, and scope users expect the oscilloscope to accurately measure each harmonic component using the correct magnitude. Ideally, oscilloscopes would have a uniform flat magnitude response up to the bandwidth of the scope, with the signal delayed by precisely the same amount of time at all frequencies (phase). Flat frequency responses indicate that the oscilloscope is treating all frequencies equally. Without a flat phase response, the scope will show distorted waveforms.

> The HD3 Series oscilloscopes use correction filters to produce an extremely flat magnitude and phase response.

A frequency response that is not flat will cause distortions in the displayed signal. You can ask your oscilloscope vendor to provide a frequency response for an oscilloscope you are considering. These plots are typically not in data sheets but are available.

The overall frequency response results from the combination of the oscilloscope’s frequency response and that of any probes or cables connecting the device under test and the instrument. If you put a 1.5 GHz BNC cable on the front of a 4 GHz scope, the cable, not the oscilloscope, limits the overall bandwidth of the system. The same principle applies to probes and accessories that attach to the probes. Probes and cables also have their own frequency response. If you need to make a precise measurement, make sure your probes, accessories, and cables aren’t the limiting factor.

Correction Filters

Some oscilloscopes use analog front-end filters to determine frequency response. Others apply correction filters in real time. Hardware DSP blocks, tuned for specific oscilloscope families to create a flat magnitude and phase response, typically implement these correction filters. Combining correction filters with analog filters results in flatter magnitude and phase responses compared to using raw analog filters alone. High-quality oscilloscopes, like the HD3, include both analog and correction filters to achieve a uniform and flat frequency response.

Frequency response shapes get their names from their roll-off characteristics. Brick-wall filters are desirable because they produce less noise by quickly attenuating out-of-band noise. For fast edges, they quickly attenuate out-of-band higher harmonics, resulting in slight under- and overshoot. Gaussian roll-off responses show less ringing, but the trade-off is additional noise.

Summary

When evaluating a new oscilloscope, it is crucial to ensure you get the best view of your signals under test across a wide frequency range. Make sure you choose an oscilloscope that excels in all areas of signal accuracy: high resolution, low noise, flat frequency response, and high ENOB. If you are concerned about accuracy, look no further than the HD3.

Vertical accuracy metric	Scope technology block	Where can you find the answer?
Resolution	ADC	Product datasheet
Noise	Front-end channels	Product datasheet
ENOB	ADC / front-end	Some vendors include this, others don’t. If you don’t find this information in the datasheet, be sure to ask for it.
Hardware vertical scaling	ADC / front-end	Data sheets don’t always specify when software magnification starts. Some vendors limit bandwidth at small sensitivities.
Frequency response flatness	Analog filters and correction filters	Vendors do not typically include this 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 datasheet

Glossary

Analog-to-digital converter (ADC)

In an oscilloscope, the ADC converts voltage to a digital amplitude value. Total quantization or output levels of the ADC will equal 2^n, where n equals the number of ADC bits.

Bits of resolution

Bits of resolution defines total potential output levels the oscilloscope can create using ADC bits, high-resolution mode, or averaging.

Effective number of bits (ENOB)

The dynamic range of an ADC or oscilloscope is often summarized in terms of its ENOB. ENOB accounts for noise and a number of other sources of vertical distortion. The ENOB of the scope’s ADC will be greater than the scope’s overall ENOB.

Filter

A filter is a circuit or algorithm with specific frequency response characteristics. Users can implement filters from discrete analog circuits or hardware, where they are known as DSP hardware filters. Filters performed in software offer greater flexibility but typically operate at a slower speed.

Frequency response

The frequency response describes the magnitude or phase characteristics of an oscilloscope over a specific bandwidth range. Ideal frequency response plots are flat with a brick-wall roll-off.

Front end

The front end describes the oscilloscope circuitry between the BNC input on the oscilloscope and the scope’s ADC. The front end includes analog filters, switching between 1 MΩ and 50 Ω paths, and attenuation required to scale the signal properly for the ADC.

Jitter

Jitter describes the deviation from an ideal horizontal position. Oscilloscopes are useful for measuring the jitter of target systems. Scopes also inherently include internal jitter sources that contribute to jitter measurements.

Noise

Noise represents the vertical deviation from a true signal value. Users will be unable to see signal detail smaller than the noise level of the scope. If noise levels exceed ADC quantization levels, users cannot take advantage of the additional ADC bits. The oscilloscope’s front end tends to be the most significant contributor to its overall noise.

Resolution

The resolution of an oscilloscope’s ADC is the smallest quantization level it can detect. Oscilloscopes can achieve smaller resolution by averaging points in time across multiple acquisitions or using high-res mode, where oversampling combined with a DSP filter enables higher resolution.

Time base

The time base is the circuitry in the oscilloscope responsible for horizontal accuracy and keeping sample clock jitter low.

Related Literature

Publication title	Publication number
InfiniiVision HD3 Series Oscilloscope — Datasheet	3124-1567.EN
Understanding ADC Bits and Effective Number of Bits (ENOB) — White Paper	5992-3675EN
Making Ripple and Noise Measurements on DC Voltage Lines and Power Rails — Application Note	5992-0946EN
Oscilloscope Measurement Tools to Help Debug Automotive Serial Buses Quickly — Application Note	5991-0512EN

See What You’ve Been Missing: 4x the Resolution and Half the Noise

The InfiniiVision HD3 Series oscilloscope enables you to capture small signals accurately with its low noise frontend and 14-bit ADC. This offers you four times more vertical resolution relative to other 12-bit general-purpose oscilloscopes. Combine this with an uncompromised waveform update rate, powerful new features such as Keysight Fault Hunter, deep memory, and hardware accelerated testing, the HD3 Series enables you to debug your designs.

Learn more about the portable precision of the HD3 at keysight.com/find/HD3.

Figure 5. The all-new HD3 Series, built of custom components optimized for oscilloscope measurements