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Comparing High Resolution Oscilloscope Design Approaches

High resolution is being extensively marketed across a broad range of high bandwidth oscilloscopes. Oscilloscope manufacturers use a variety of hardware and software design approaches to increase resolution, some of which impose other performance tradeoffs. This white paper provides an overview of the various high resolution design approaches, with examples of their impact on oscilloscope performance.

Ken Johnson

Director of Marketing, Product Architect
Teledyne LeCroy
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Preface

Since the advent of the first digital storage oscilloscopes in the mid-1980s, 8-bit vertical resolution was the norm. We all complained about it, but we didn’t think there was much that could be done. Now, there is an explosion in the market of high definition or high resolution oscilloscopes at 1 GHz or more bandwidth with claims of 10-bit, 12-bit or even (remarkably!) 16-bit resolution. What can be believed? How can you tell if you are getting what is advertised? What is the difference between high definition and high resolution?

Do you remember when only one car company manufactured cars with all-wheel drive (AWD)? Now, it seems every manufacturer makes an AWD car or minivan. Do they all perform the same? The data says “no, they mostly don’t”. Many of these are simply “knockoff” designs that may perform well enough for some people some of the time in undemanding conditions, or “check a box” for a feature that emotionally resonates. But if you are going to drive into the mountains to go skiing, you probably want the best performance you can get, and it wouldn’t hurt if it had four snow tires as well. If the best AWD cost no more than the less-than-good AWD, why wouldn’t you want the best?

This is the situation we are in with high definition and high resolution oscilloscopes. Many systems are marketed with claims of high resolution, but not simultaneous with the claimed bandwidth, sample rate and number of channels. This means they are not truly high resolution oscilloscopes—they are conventional 8-bit oscilloscopes that use software post-processing techniques to achieve higher resolution. They will work for some users some of the time in undemanding conditions.

Once you know what to look for in a high definition or high resolution oscilloscope, you can compare it to your needs and make an honest assessment. If you are going to use it for challenging debug, or want to ensure that your oscilloscope is not hiding something critically important to understanding your circuit’s performance, time invested in understanding real-world high resolution performance is well-spent.

Introduction

12-bit (or higher) resolution oscilloscopes and data acquisition systems have been commonly available at very low bandwidths (low 10s of MHz or kHz) for many years. Historically, 8-bit resolution was used for medium/high bandwidth (200 MHz or higher) oscilloscopes for cost and availability reasons. However, the last several years have seen a profusion of new oscilloscopes with greater than 8-bit resolution. The interchangeable oscilloscope terms “high definition” and “high resolution” have become widely used by a variety of manufacturers to describe performance that is improved in resolution *in at least one operating mode* from a conventional 8-bit oscilloscope. As will be explained, many oscilloscopes advertised as “high definition” or “high resolution” sacrifice some combination of bandwidth, sample rate and number of channels to achieve higher resolution. Advertised claims of high resolution by some manufacturers have also failed to produce realistic noise reduction results in their oscilloscopes. It is important to understand both the manufacturer’s high resolution performance claims and how the real-world performance of some high resolution oscilloscopes impacts testing in embedded computing system, power conversion and EMC/EMI applications.

Oscilloscope Overview

Old-style oscilloscopes—the analog kind—sweep an electron beam across the face of a cathode-ray tube coated with phosphor. A trigger event initiates the sweep. The beam sweeps linearly in time across the face and moves vertically in response to the waveform input voltage. Analog oscilloscopes produce a continuous waveform, albeit one that could only be viewed on a tube display. Today, these oscilloscopes have been replaced with digital storage oscilloscopes (DSOs) that produce digital waveforms. The digital waveform produced by a DSO is discrete in both time and amplitude—it is not an analog signal, though it may represent one very well. Herein, we will just refer to a DSO as an oscilloscope.

Oscilloscope Acquisition System

A simplified oscilloscope acquisition system architecture is shown in Figure 1. The acquisition system contains analog, mixed-signal (analog-digital) and digital components that perform the combined task of converting analog input signals into digital signals. High vertical resolution and the lowest noise is obtained by individually optimizing the performance of each analog or mixed-signal component and then designing a full acquisition system that does not degrade the performance of these same components.

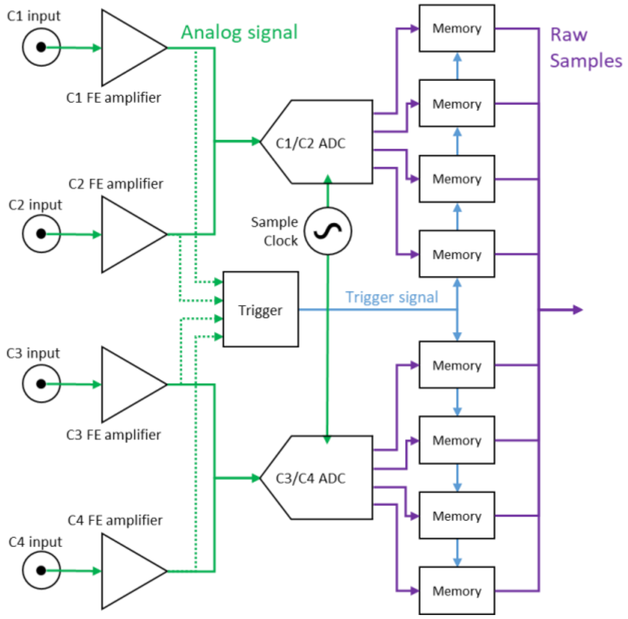


Figure 1 - A simplified oscilloscope acquisition system architecture

Note that Figure 1 does not display other important aspects of the oscilloscope, namely the data pipelining, processing and display rendering of the digital data onto the oscilloscope display. While important aspects of oscilloscope design, they are not germane to a discussion of resolution and noise.

Key Components of the Oscilloscope Acquisition System

Oscilloscopes utilize a variety of components to amplify, digitize and store the signal into digital memory before rendering it on a display. The individual performance of these components needs to support the complete oscilloscope *system performance* and capabilities.

The main banner specifications for an oscilloscope are bandwidth, sample rate, resolution and memory. To achieve high resolution at full bandwidth:

- The front-end amplifier and analog-to-digital converter (ADC) specifically must be specially designed for high resolution applications
- The sample clock must have low jitter
- The ADC must have a sufficient sample rate to bandwidth ratio
- The system-level design cannot detract from the component performance

When a user specifies an oscilloscope, bandwidth is usually the most important criteria. For a given bandwidth, we want the hardware to sample at a high enough sample rate with as many bits of resolution as possible. It is usually assumed that if an oscilloscope is specified with a given bandwidth, sample rate and bits of resolution, that all of these specifications are available at the same time, but this may not be the case with some oscilloscopes.

The memory length governs the total acquisition capture time possible at a given sample rate. It does not directly impact the other banner specifications unless the desired capture time of the oscilloscope acquisition exceeds what is possible for the built-in memory at the maximum sample rate. If this happens, the sample rate will be reduced proportional to the increase in capture time. Thus, it is important to have enough memory for the desired acquisition capture time and to be aware when sample rate is reduced due to lack of sufficient acquisition memory.

The key acquisition system components, figures of merit and design considerations are described in the sections that follow.

Front-end Amplifier

The input channel of the oscilloscope connects to a front-end amplifier that utilizes one or more input stages. Variable gain amplification and input attenuation are provided via gain control, switchable input attenuation or both—the combination provides optimization of the amplifier performance over the widest range of input voltages, best matches the front-end amplifier output to the input of the ADC, and prevents large and potentially damaging signals from being present at the input to the ADC.

The oscilloscope front-end amplifier requires multiple stages to permit very small to very large signals to be amplified. These characteristics generally require the input stage of the amplifier to have the least amount of gain to minimize the non-linear behavior that might result from driving the amplifier with large signals. The noise figure and gain of the first amplifier stage will determine most of the noise characteristics of the oscilloscope system. When the gain of the first stage is high compared to later stages, the first stage gain will dominate the system signal-to-noise ratio (SNR). First-stage amplifier noise, dynamic range and linearity must be expertly balanced so that the oscilloscope can meet the expectation of a high resolution, high-bandwidth system. Wide dynamic range operation coupled with low noise is difficult to achieve in practice.

The front-end amplifier integrated circuit (IC) must be packaged for use in an oscilloscope. Package design is critical for maintaining the expected performance, and poor package designs will increase losses, reduce power integrity and introduce noise. The resistor structures of the input terminations and input stage of the amplifier can negatively impact the thermal noise performance of the IC package. Thus, a good front-end amplifier IC can be compromised by poor package design.

In summary, careful selection of the best IC technology for the front-end amplifier, and a mix of high-speed technology and low-noise amplifier design, creates the right balance between high bandwidth, low noise and excellent linearity. Low noise is the most critical operating characteristic–once noise is introduced into a system, it cannot be eliminated later.

Key Figures of Merit

Key figures of merit for the front-end amplifier include:

- Bandwidth (magnitude response versus frequency)
- Phase and Group Delay
- Rise Time and Overshoot
- Total Harmonic Distortion (THD)
- Signal-to-noise and Distortion Ratio (SINAD)
- Signal-to-noise Ratio (SNR)
- Linearity
- Overdrive Recovery
- Temperature Stability

We will not provide detailed technical descriptions of all of the front-end amplifier key figures of merit. The basic description given furthers our discussion.

Bandwidth

Bandwidth is a measure of the analog frequency content that is passed through the front-end amplifier, with the 3 dB attenuation of the signal (referenced to DC) being the measurement point for bandwidth.

The front-end amplifier is usually the limiting factor in the bandwidth of the oscilloscope system.

Phase and Group Delay

The signal path of the oscilloscope is a complex transmission line. Frequencies are propagated along this transmission line with time delay, and the time delay varies by frequency of the signal. The time delay is commonly represented as a phase response, or phase delay, from the phase of a sinusoidal input and output to the front-end amplifier or other signal processing system. Group delay is calculated by differentiating the phase delay with respect to frequency, and is the time delay of the various frequency components.

Phase delay variation by frequency will cause signals with wideband frequency content (i.e., anything but a pure sinusoid) to contain distortion because different signal frequency components are delayed by different amounts.

When oscilloscopes had relatively low bandwidth (1 GHz or less), phase response characteristics could be ignored—the phase delays were not meaningful in the context of the oscilloscope bandwidth, or the phase delays produced what was seen as a good result (i.e., a pre-shoot free step response). As bandwidths increased, more care was required in amplifier and system design to minimize the impact of phase delay. At higher bandwidths, digital signal processing (DSP) is used to compensation for phase and group delay. For a thorough explanation of the many ways that DSP is commonly used in oscilloscopes, refer to "Digital Signal Processing (DSP) in Oscilloscopes".

Rise Time and Overshoot

The magnitude and phase response of the front-end amplifier largely dictate the rise time and overshoot performance of the front-end amplifier. The amplifier magnitude response versus frequency may have a slow (Bessel) or fast (brick-wall) rolloff, or something in between. The frequency response is typically tailored to the desired step response and noise performance—slower rolloffs produce a step-response with faster rise times and lower overshoot, but increase noise. Faster rolloffs reduce ricompse times and increase overshoot, but reduce noise. The right compromise is largely based on engineer preference or application requirements.

Engineers commonly link bandwidth and rise time using Equation 1:

$$Trise \cdot Bandwidth = 0.35$$

Equation 1 - Rise time and bandwidth relationship

Rise time Trise is in seconds and Bandwidth is in Hz.

The multiple 0.35 is generally true if the magnitude versus frequency response approximates a Bessel rolloff. Amplifiers with steeper rolloffs might produce a multiple of 0.40, while a brick-wall rolloff might be near 0.45. Non-flat phase delay at higher frequencies will increase the multiple further.

THD

THD is a measurement of the harmonic distortion created by the instrument and is defined as the ratio of the sum of the square of all the RMS voltage of the harmonics (V_2, V_3, V_4, V_5, etc.) to the square of the RMS voltage of the fundamental signal (V_1). THD is normally represented in dB as shown in Equation 2:

$$THD = 10 \cdot \log\left(\frac{{V_2}^2 + {V_3}^2 + {V_4}^2 + {V_5}^2 + \cdots}{{V_1}^2}\right)$$

Equation 2 - THD Calculation

SINAD

SINAD is a measurement of the degradation created by the instrument of the signal and is defined as the ratio of the square of the RMS voltage of the signal to the sum of the square of the RMS Voltage of the distortion terms and RMS noise (excluding DC and the signal distortion terms, or V_{noise}). SINAD includes all components of noise and distortion and is the best indication of the dynamic response of the ADC (ADC response in presence of signal). SINAD is normally represented in dB and is shown in Equation 3:

$$SINAD = 10 \cdot \log\left(\frac{{V_1}^2}{{V_2}^2 + {V_3}^2 + {V_4}^2 + {V_5}^2 + \cdots + {V_{noise}}^2}\right)$$

Equation 3 - SINAD Calculation

SNR

SNR is a measurement of the degradation created by the instrument noise of the signal and is defined as the ratio of the square RMS voltage of the signal to the square of the RMS noise, excluding DC. SNR does not include harmonics. SNR is normally represented in dB and is shown in Equation 4:

$$SNR = 10 \cdot \log\left(\frac{{V_1}^2}{{V_{noise}}^2}\right)$$

Equation 4 - SNR Calculation

Linearity

Linearity is the ability of the oscilloscope to capture the input signal without modifying its shape. For example, if the signal is a pure sinewave, the signal presented on the screen should also be a pure sinewave with only the addition of the noise introduced by the amplifier. This is the case if the transfer function of the front-end amplifier ($V_{OUT} = F(V_{IN})$) is linear. If the gain transfer function is non-linear, harmonics (and thus distortion) are added to the signal.

Overdrive Recovery

A front-end amplifier can saturate and require time to recover when the input signal exceeds its operating range. The operating range of the front-end amplifier may be equal to the displayed range on the oscilloscope grid, or it could be larger. Overdrive recovery behavior is typically described by how much time it takes for the amplifier to recover from an overdrive that is some percentage larger than the operating range.

Historically, oscilloscope users relied on the overdrive recovery of the front-end amplifier to maximize resolution of a small part of the signal—displayed on the oscilloscope screen—when the acquired signal was driven outside the operating range of the front-end amplifier (i.e., off the oscilloscope screen). This was an acceptable approach when oscilloscope front-end amplifiers were relatively low in bandwidth and did not have complicated analog designs. However, today's high-bandwidth front-end amplifiers are difficult to design with high permissible overdrive and/or fast recovery.

Acquisition systems with 12 bits (and high bandwidth) provide an alternate approach—adjust front-end amplifier gain to contain the signal within the oscilloscope grid and use vertical zoom to view the signal area of interest. This approach provides the ability to view 16x the vertical resolution and avoids the (often) negative aspects of overdriving the front-end amplifier. Such an approach is also commonly utilized by high resolution digitizers with fixed-gain inputs.

Temperature Stability

An oscilloscope must operate within specifications over a wide range of temperature conditions—typically 10 to 40^{o} C. As high resolution tightens specifications (e.g., 0.5% gain or offset accuracy), thermal stability becomes more critically important. Therefore, stability of the gain and offset over temperature must be designed into the front-end amplifier. If not, the high resolution oscilloscope will have no better than the typical 1.5% to 2% gain accuracy provided by an 8-bit resolution oscilloscope.

ADC

The ADC quantizes the output of the analog front-end amplifier into digital sample point values that are represented as a digital byte or word. Each quantized sample point value is comprised of a discrete time value and a discrete amplitude value and is determined by two related elements in the ADC—the sampler and the track-and-hold. The resolution of the discrete time value is determined by the sample rate of the ADC, and the resolution of the discrete amplitude value is determined by the number of bits in the ADC.

Key Figures of Merit

Well-known figures of merit for an ADC include:

- Bandwidth
- Sample Rate
- Resolution
- Total Harmonic Distortion (THD)
- THD + Noise (THD+N)
- Spurious Free Dynamic Range (SFDR)
- Signal-to-noise-and-distortion Ratio (SINAD)
- Signal-to-noise Ratio (SNR)
- Effective Number of Bits (ENOB)

Bandwidth

Bandwidth is a measure of the analog frequency content that is passed through the ADC, with the 3 dB attenuation of the signal (referenced to DC) being the measurement point for bandwidth.

Usually, the analog bandwidth of the ADC is much higher than that of the front-end amplifier matched to the ADC in the oscilloscope acquisition system.

Sample Rate

Sample Rate is a measure of the number of digital samples captured as a function of time.

Resolution

Resolution is the quantification of the vertical quantization of the waveform. Quantization is the conversion of the analog voltage sample into an integer number. The integer number is formed by comparing the analog voltage to discrete voltage levels. These voltage levels are fixed, and there is a fixed number of these levels across the vertical range of the oscilloscope. Usually, the number of levels is a power of two, and the power of two is referred to as the number of bits in the ADC. Each level produces a code; the number of codes possible in a given vertical range of the oscilloscope is given in Equation 5:

$$Codes = 2^{B}$$

Equation 5 - ADC resolution

B is the number of bits.

Since there is no restriction on the analog waveform, we know that a code at a sample point must be an approximation of the analog waveform sample, because the sample code, under the most ideal conditions, could differ from the analog waveform by ±½ code.

Consider Figure 2 where we see an analog waveform being sampled by three different quantizers— with 8 (blue), 10 (red) and 12 (green) bits respectively. This figure is a magnified view of a noise-free, ideal waveform. Here we can see the error created by sampling this waveform with different resolution. At this extreme zoom setting, the 8-bit converter produces relatively large errors that diminish to a relatively small error with the 12-bit converter. It is important to note that this is an ideal, noise-free waveform, and that it is magnified to show the error.

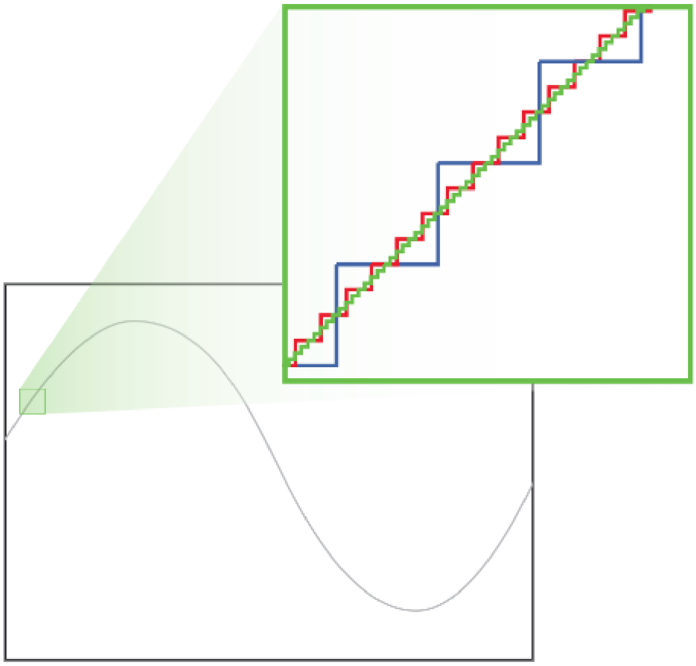


Figure 2 - Quantization of an analog signal with an 8-bit ADC (blue), 10-bit ADC (red), and 12-bit ADC (green)

Figure 3 provides a better view of the quantization differences between the different resolution ADCs.

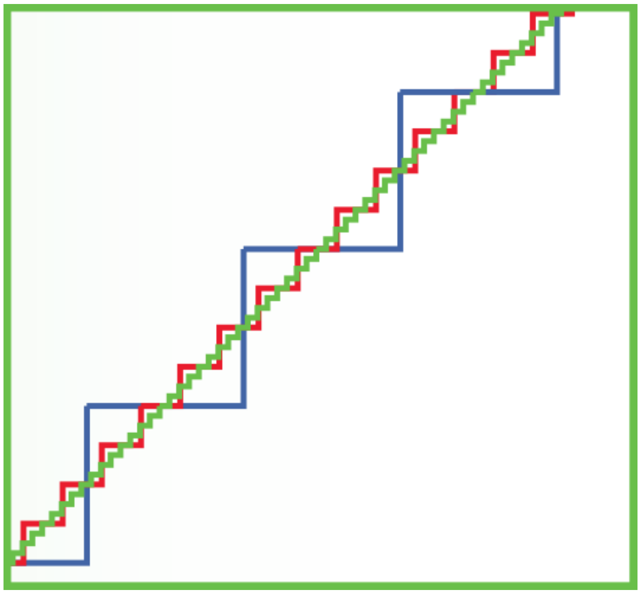


Figure 3 - Close-up of zoom of quantized waveforms

SFDR

ADCs are often interleaved—the ADC chip may contain many lower sample rate ADCs that are combined (time interleaved) to equal the total ADC chip sample rate. These interleaved ADCs will contribute spurious tones (spurs) at multiples of the individual ADC sample frequency. In an oscilloscope, these spurs may be observed using the FFT math function to display a spectrum of a pure sinusoidal frequency measurement, and the spur is usually measured in dBc (with respect to the input signal level and not the full scale, or dBFS). If the spurs are below the noise floor of the oscilloscope (typically -40 dBc for a high-performance 8-bit oscilloscope, or typically -55 dBc for a high-performance 12-bit oscilloscope), they will have no measurable impact on the oscilloscope noise performance. However, if the SFDR performance is worse, the noise and distortion added as a result of the spurs will compromise overall system performance. Note that SFDR values depend on the input frequency—a single SFDR value may or may not tell the user all there is to know about the quality of the ADC. The SFDR value may be the best case performance, typical performance or something else.

High-performance oscilloscopes from reputable oscilloscope manufacturers nearly always have acceptable SFDR for wide-band measurements. Therefore, SFDR performance is almost never a significant contributor for applications focused on wide-band signal acquisitions. Those using oscilloscopes to measure very narrow-band signals may focus on this figure of merit more closely, with good reason.

ENOB

Most oscilloscope users might find it surprising that, while their oscilloscope may employ an ADC with a resolution of “B” bits, the ADC will deliver less than B *effective* bits in practice.

The ADC is a mixed-signal IC. The analog portion contributes noise and distortion, while the digital portion contributes quantization errors. If the digital portion of the ADC was perfect in every way, the best effective number of bits the ADC could have is simply described in Equation 6:

$$ADC\ ENOB = \frac{SINAD - 1.76}{6.02}$$

Equation 6 - ADC ENOB

SINAD is in dB.

This equation is derived from the uniformly distributed noise that comes from quantization. A complete derivation of the simplified formula can be found in “Understanding Vertical Resolution in Oscilloscopes”.

Equation 3 also describes an upper limit on SINAD (in dB) based on the number of bits of resolution in the ADC, as described in Equation 7:

$$SINAD = 6.02 \cdot ADC\ BITS + 1.76$$

Equation 7 - ADC SINAD upper limit, based on ADC resolution

Note that a complete oscilloscope acquisition system will always have a lower ENOB than the ADC alone — other components add their own noise and distortion that will further reduce ENOB. Beware of manufacturer claims of good ENOB performance in a single component of their oscilloscope acquisition system (e.g., ENOB specified for only the ADC), as this is probably indicative of less than stellar performance elsewhere in their system.

ADC Quantization Operation

The sampling process takes snapshots of a waveform at times that are separated by the sample period, defined by the sample clock. This sampling does not in itself create the quantized voltage value of a signal—samplers simply produce impulses whose height or area contain the analog voltage.

A track-and-hold circuit produces the voltage value at the sample time. The track-and-hold element in the ADC holds the signal so that it can be quantized. Usually, this quantization of the signal occurs by determining a digital voltage value held on a capacitor. The track-and-hold output is the fully analog, "steppy" waveform where the step changes begin at the sample period boundaries and the final, settled value contains the analog voltage that becomes the digital N-bit code (quantization level) stored in acquisition memory. The digital code length is equal to or greater than the resolution of the ADC. Thus, sampling followed by quantization allows an oscilloscope to capture and store waveforms as a sequence of discrete time and amplitude (voltage) numerical sets.

Quantization Error

Any ADC has a finite resolution defined by the number of quantization levels, and the rounding up or down of an analog signal to a specified quantization level will introduce some error. Quantization error sets the lower bound of noise performance that can be achieved with an oscilloscope. All things being equal (front-end amplifier noise and distortion, signal path noise and interference, ADC signal fidelity, etc.), an oscilloscope with a higher-resolution ADC will have better noise performance and gain accuracy than an oscilloscope with a lower-resolution ADC. Likewise, utilizing a lower-resolution ADC with consequently larger quantization error, and subsequently applying software post-processing techniques to achieve improved noise performance, cannot achieve the same noise performance as a higher-resolution ADC. As with a front-end amplifier, once noise is introduced, it cannot be later eliminated.

A complete description and derivation of quantization error can be found in "Understanding Vertical Resolution in Oscilloscopes".

ADC Interleaving

A single ADC chip usually contains multiple component ADCs that are time-interleaved to obtain an aggregate sample rate higher than is possible with a single component ADC. The input to the ADC chip may be one or more front-end amplifiers. If more than one front-end amplifier is input to the ADC chip, the total sample rate of the ADC chip would be distributed amongst one or more oscilloscope channels, as determined by the system or user settings.

Nyquist's Criteria

The sample rate needs to be more than twice the highest frequency content present in the waveform so that no aliasing occurs. Given that the bandwidth of the oscilloscope is a rating of the 3 dB attenuation of the amplitude, and high-frequency content is usually present beyond the bandwidth rating (i.e., the frequency response does not follow a brick-wall rolloff), we generally need the sample rate to be at least two-and-a-half to three times the bandwidth to meet the Nyquist criteria. The faster the rolloff, the more the sample-rate-to-bandwidth ratio (SR:BW) can approach the Nyquist minimum (2:1), while still avoiding aliasing.

For measurement precision, we generally desire waveforms with sample rates that are ten times the bandwidth. Higher bandwidth oscilloscopes (e.g., 8 to 100 GHz) require higher absolute sample rates, and sample rate becomes more of a technology or cost limitation compared to bandwidth. Therefore, higher bandwidth oscilloscopes usually have lower SR:BW (2.5:1), whereas lower bandwidth oscilloscopes (e.g. 1 GHz) may have much higher SR:BW (5:1 or 10:1). If Nyquist's criteria is met from a sampling standpoint, a waveform so sampled contains *all* of the information contained in the continuous analog waveform (see P. Pupalaikis, "The relationship between discrete-frequency s-parameters and continuous-frequency responses," in DesignCon, IEC, February 2012.).

Clock Generator

The clock generator provides the master system clock to the ADCs to synchronize the sampling of each ADC. The key figures of merit for the clock generator are the sample clock jitter, clock accuracy and clock drift. High quality, low jitter sample clocks are essential to achieving low noise in high definition oscilloscope designs. The high quality clock signal must be transmitted with minimal crosstalk or interference, and with matched propagation delays to each ADC.

Ideally, the sample clock can be thought as a pure fundamental frequency. Any other additional signal present on the sample clock can be considered as noise and will affect the desired sampling instant. This timing uncertainty in relation to the ideal sample clock period are known as time interval error (TIE) jitter, and is expressed as a root-mean-square (RMS) value of time. Figure 4 shows the ideal sinewave and the noisy sinewave. In the zoomed area below the transitions around 0 are shown for the ideal sinewave and the noisy sinewave

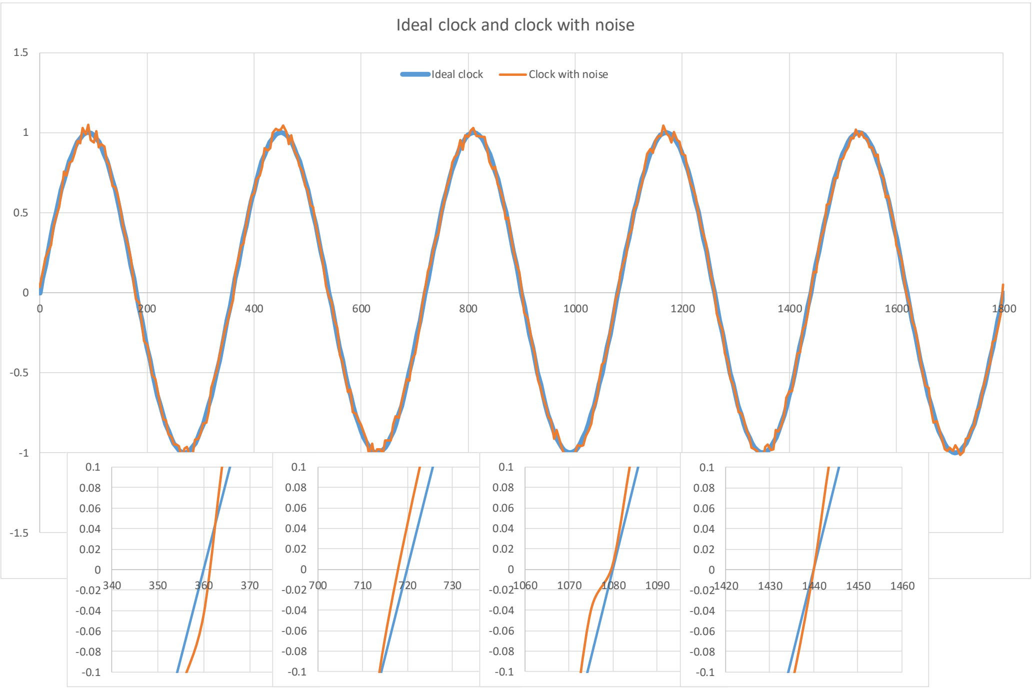
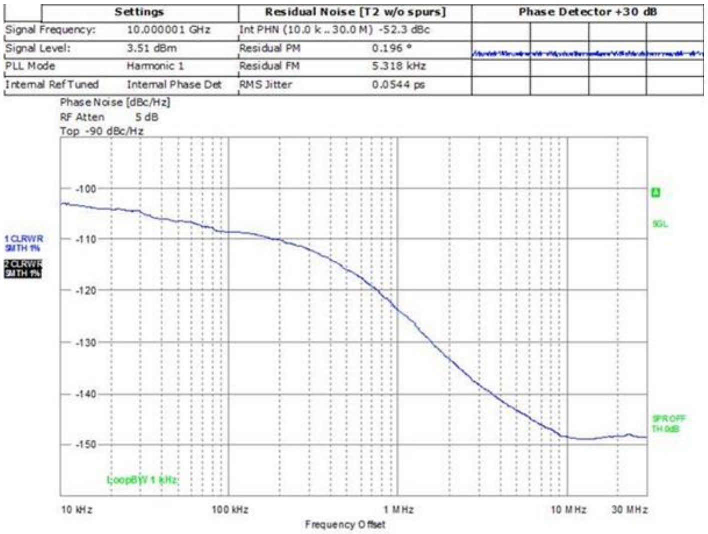


Figure 4 - Ideal and noisy clock signal

Clock jitter can also be described in the frequency domain as a short-term change in the phase of the clock; this is known as phase noise. Phase noise is the spectral composition of the non-ideal sideband components representing the noise. The phase noise density generally increases in magnitude as the frequency difference between the clock and the observed noise frequency decreases as shown in Figure 5. This region of high phase noise density is known as close-in phase noise.

Phase noise is measured as decibels relative to carrier per unit of frequency (dBc/Hz) versus frequency delta from the carrier frequency, which for the example is the sample clock frequency. A plot of phase noise versus frequency is shown in Figure 5.



Settings		Residual Noise [T2 w/o spurs]		Phase Detector +30 dB
Signal Frequency:	10.000001 GHz	Int PHN (10.0 k .. 30.0 M)	-52.3 dBc	
Signal Level:	3.51 dBm	Residual PM	0.196 °	
PLL Mode	Harmonic 1	Residual FM	5.318 kHz	
Internal Ref Tuned	Internal Phase Det	RMS Jitter	0.0544 ps	

Figure 5 - Phase noise in dBc versus frequency for a sample clock oscillator

Sample clock jitter (time error) can be derived by integrating phase noise over a frequency range, with the lowest frequency of the integration boundary correlating to the reciprocal of the oscilloscope acquisition time.

The uncertainty of the sampling point (time error), affects the voltage level measured, especially in the presence of a quickly changing signal at the input of the ADC (Signal with high dV/dt). This time uncertainty transform itself in a vertical error (noise) as shown in Figure 6. If the dV/dt of the input signal of the ADC is not too large, the uncertainty of the sampling point will have small effect on the quantization error. This is also shown in Figure 6.

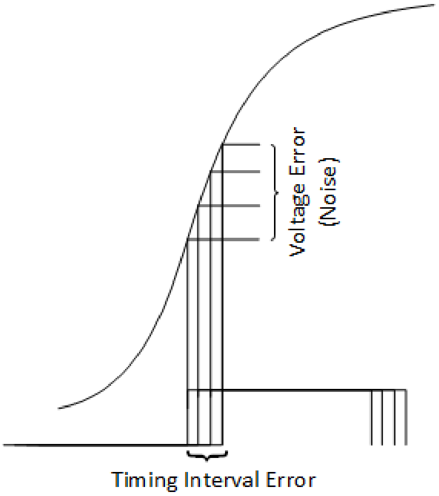


Figure 6 - Phase noise effect on voltage quantization

In a 12-bit resolution system with long memory, high close-in phase noise greatly reduces 12-bit vertical resolution benefits when acquiring very long acquisitions. Phase noise far from the frequency of the sample clock manifests itself as added noise when a high-speed signal is acquired.

Quite high phase noise amplitudes can be tolerated in 8-bit resolution oscilloscopes, or higher resolution instruments with low bandwidth. For an instrument with very wide bandwidth and extremely long memory depth (long acquisition), high quality sample clocks must be used to maintain low-noise performance in 12-bit resolution oscilloscopes. If the phase noise amplitude is above the measureable noise floor of the oscilloscope, the sample clock phase noise (jitter) can mitigate the benefits of an otherwise high-resolution and low-noise acquisition system.

Poor clock distribution design can lead to crosstalk and contamination of an otherwise high-quality sample clock signal. In this case, the phase noise due to crosstalk and contamination will be revealed as higher noise and distortion (lower SINAD and ENOB) at some frequencies compared to others. This effect cannot be measured at the output of the sample clock, but must be inferred from the SINAD or ENOB plots versus frequency, with noticeably worse performance at some frequencies possibly due to sample clock contamination. Extreme examples of poor clock distribution design might be visually apparent (see Figure 8, Figure 9 and Figure 10).

Therefore, high resolution oscilloscopes must utilize both very high quality sample clocks and a noise-immune clock distribution system architecture.

Memory

The digital sample output of the ADC is pipelined to a circular memory buffer. There is usually a setting in the oscilloscope for the user to define how much memory should be acquired in a given acquisition. The circular memory buffer is continuously filled and old data overwritten with new ADC samples until oscilloscope sampling activity is stopped, either by direct user intervention or a satisfied trigger condition. Once the sampling activity is stopped, the memory is read out to a display rendering system, and the acquired data is compacted to fit the pixel size of the oscilloscope grid and written to the display. The key figure of merit is the number of data points or samples that can be stored in memory, typically expressed as Megapoints (Megasamples) or Gigapoints (Gigasamples).

A high resolution oscilloscope requires a large ADC-to-memory digital bandwidth to quickly transfer samples from the ADC to memory. For instance, storing digital samples encoded in 16-bit words when the ADC is outputting 20 GS/s requires a minimum memory bandwidth of 320 Gb/s. In reality, this number is actually higher because of the memory latency constraints.

Trigger Circuit

The trigger circuit may include analog, digital, or serial data functionality. Regardless, the trigger circuit’s function is to monitor the incoming signal for the desired event and stop the acquisition activity when the event is detected. A non-zero trigger delay time may be used to define a positive or negative time delay from the trigger event to the timestamped digital memory data location. The time length of the digital data that is accumulated in the memory buffer is defined by the oscilloscope timebase setting.

Oscilloscope Acquisition System Design

The typical high-bandwidth oscilloscope acquisition system architecture is a single printed circuit assembly (PCA) that contains the key components described above. The total system performance, whether it be timing jitter, vertical resolution, gain accuracy, etc., will depend on the performance of the "least good" component. Multiple components in series with each other (e.g., a front-end amplifier and an ADC) and with similar performance specifications (e.g., SNR or SINAD) will, if identically rated, be derated as part of the system. For example, if a front-end amplifier and an ADC both have a rated SNR of 55 dB, the series combination of them will have a rated SNR of 52 dB—a reduction of 3 dB. Conversely, a 12-bit ADC that driven by a front-end amplifier with an SNR of 42 dB (consistent with the performance typically found in an 8-bit oscilloscope) might have 12-bit resolution at the output of the ADC, but the noise performance will be consistent with that of an 8-bit resolution oscilloscope.

Additionally, the quality of the PCA layout and overall enclosure design will affect system performance. Poor signal routing that leads to signal crosstalk, excessive power distribution network (PDN) noise, and sample clock signal degradation or noise interference will degrade system performance. Unwanted thermal behaviors (e.g., drifts), different ground potentials between the inputs caused by unbalanced ground currents, and susceptibility to external electric or magnetic fields can all contribute to system performance that is far less than what would be expected based on the component level performance.

Thus, it is critically important to focus on the overall performance of the complete oscilloscope acquisition system and not the performance or rating of a single component. Fortunately, this is easy to do and there are some simple observations that can be made to ascertain whether an oscilloscope advertised as "high resolution" contains a single high resolution component or is truly a high resolution system.

Sources of Noise in Oscilloscopes

As described earlier, the maximum vertical resolution is defined by a single component in the acquisition system—the ADC—and it has quantization and other noise components that introduce noise to the measurement and reduce the effective resolution. Other components, and the overall acquisition system integration of components, also contribute noise.

However, the dominant noise source in the oscilloscope tends to be the front-end amplifier, which is why it is critical that a high resolution oscilloscope have a specially designed, low-noise front-end amplifier. As described earlier, the amplifier usually consists of multiple, selectable gain stages, so there is an implementation strategy that can provide the least noise relative to signal size over a wide range of input signal amplitudes.

Figure 7 shows an example of noise sources in an oscilloscope channel. The user input signal V_{IN} is input to the oscilloscope. V_{IN} has noise as it enters the oscilloscope, and the front-end amplifier and ADC also add noise to the signal. In this example, each ADC input drives four internal ADCs which each add noise, mostly in the form of quantization noise. It is important to realize that the often neglected noise source—the noise on the user's signal—cannot be removed because the oscilloscope does not know that the noise is even noise. As far as it is concerned, the noise is signal, and the oscilloscope's function is to faithfully reproduce the signal. The noise added to the signal in the front-end amplifier causes a problem in that it is indistinguishable also from the noise on the user's input signal and is common to all downstream paths. Thus, front-end noise must be minimized to the largest extent possible—it cannot be filtered out or eliminated later with post-processing techniques.

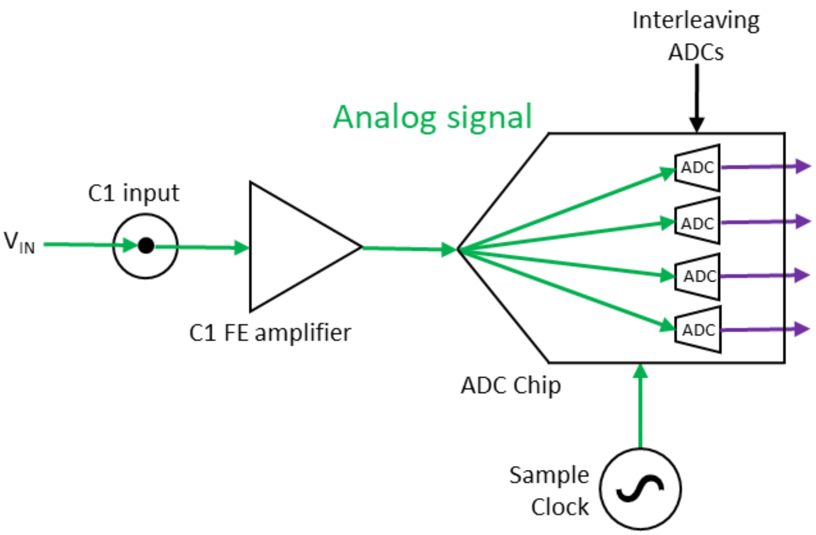


Figure 7 - Input oscilloscope signal path and noise contributors

The job of the ADC is to faithfully digitize the waveform presented to it. However, interleaving one or more ADC chips and interleaving multiple on-chip (internal) ADCs provides opportunities to further reduce noise.

The important parameters of each noise source in the system are:

- The magnitude of the noise
- The correlation between a source and other sources
- The location of the noise source in the signal path and how common the noise source is to the other paths through the system
- The spectral characteristics of the noise

We will talk subsequently about how knowledge of the noise sources can be exploited with software post-processing techniques to improve effective resolution. But one simple fact remains—*starting with the lowest noise, highest resolution hardware acquisition system before applying software post-processing techniques will result in the best effective resolution after software post-processing techniques are applied.* Additional details on software post-processing techniques that can be used to reduce noise in oscilloscopes can be found in "Understanding Vertical Resolution in Oscilloscopes".

Oscilloscope Baseline Noise, Representative Signal and ENOB Measurements

The oscilloscope's complete system performance should be the focus of users interested in understanding how noise-free their oscilloscope is, and whether or not they are getting the resolution and noise performance at the bandwidth and sample rate advertised.

Baseline Noise

Baseline noise is the measured AC RMS value of an oscilloscope input channel with no signal connected to it. A simple baseline noise test will provide a general indication of noise performance when no signal is present on the input to the oscilloscope. While this test is simple and easy to perform, it is not the most realistic test of oscilloscope performance, because most oscilloscopes are used with input signals connected to them. Nonetheless, noise will not decrease when input signals are added, as the added signal amplitude will only add noise to the measurement later. Thus, baseline noise can be a useful test for roughly assessing overall performance.

Representative Signals

Basic, “golden” input signals can reveal a lot about the performance of the front-end amplifier and ADC. Step responses and high-speed serial data signals are commonly used to understand oscilloscope system performance.

Step Response

Step responses can provide useful information about the signal quality and integrity in real-world oscilloscope operating conditions. In addition to showing real-world noise performance, a step-response of sufficient bandwidth for the oscilloscope will also show front-end amplifier performance (rise time, overshoot, linearity, etc.) provided that the input step rise time is much faster than the oscilloscope rise time.

High-speed Non-Return-to-Zero (NRZ) Serial Data Signals

NRZ serial data signals are commonly viewed in an oscilloscope as an eye diagram. An eye diagram is simply a series of step responses corresponding to the 1 and 0 transitions of the NRZ serial data signal. If the serial data signal is at a high enough bit rate, the step response rise time will be fast, and this is a visually informative test of both the step response and noise performance of the oscilloscope. Therefore, eye diagrams are ideal for assessing overall noise and sample clock quality of the oscilloscope.

Reputable high-bandwidth oscilloscopes utilize a software clock-recovery and bit-slicing algorithm to display an eye diagram devoid of the effects of trigger jitter. The resulting 1 and 0 transition width times are solely due to input signal jitter and sample clock jitter. This minimizes reliance on the triggering system to have low trigger jitter—an important benefit, since the random jitter of the trigger circuit can contribute far more jitter to the calculations than may be present in the actual serial data signal. The 1 and 0 (top and base) representation in the eye provides a good indication of noise at the 1 and 0 voltage levels of the NRZ signal.

Jitter is calculated from a calculation of time-interval error—the deviation of the measured period from the actual clock period. Standards define the calculation of random jitter (Rj) and deterministic jitter (Dj) from a measurement of time-interval error jitter, and subsequent calculation of total jitter (Tj) for a bit-error-ratio of $10e^{-12}$ as shown in Equation 8:

$$Tj = 14 \cdot Rj + Dj$$

Equation 8 - Calculation of Tj from Rj and Dj

Thus, large amounts of Rj will result in very large calculations of Tj, and very good (low jitter) Rj performance is highly prized in designs. Therefore, engineers need oscilloscopes that add very little of their own jitter to the measurement.

Oscilloscope System ENOB

Oscilloscope ENOB can be derived from measurement of the oscilloscope SINAD. Refer to Equation 9:

$$Oscilloscope\ ENOB = \frac{SINAD - 1.76}{6.02}$$

Equation 9 - Oscilloscope ENOB calculation from oscilloscope SINAD

If the front-end amplifier is not the dominant source of noise in the system, the system ENOB will approach the ENOB of the ADC. It is important to understand that the ADC ENOB is an upper bound on the system performance, but the system performance is the critical performance to understand. Realistically, the oscilloscope (system) ENOB will always be less than the ADC ENOB.

Equation 9 assumes the input signal is full scale. If not, then the correct calculation is described in Equation 10:

$$ENOB = \frac{SINAD - 1.76 + 20\log\left(\frac{FullScale\ Amplitude}{Input\ Amplitude}\right)}{6.02}$$

Equation 10 - Oscilloscope ENOB calculation for less than full-scale input signal amplitude

Typically, ENOB is measured at 90% of full-scale amplitude and adjusted. However, if no adjustment is made for inputs at less than full-scale amplitude, the ENOB calculation will be lower than it would otherwise be. For example, if a system has 55 dB SINAD measured using a 90% full-scale amplitude signal, the ENOB calculation would be 8.84 bits according to Equation 9 and 9.0 bits according to Equation 10. Thus, it is important to know both the input amplitude used for ENOB measurements and whether or not a correction was made for amplitude.

A “rule-of-thumb” of 6 dB SINAD per effective bit can be inferred from this equation. Thus, improvement of half an effective bit equates to 3 dB (30%) reduction in noise, and improvement of a full effective bit equates to a 6 dB (50%) reduction in noise. Small differences in ENOB mean a lot in terms of vertical (voltage amplitude) noise.

The accepted standard methodology for measuring ENOB is defined in the IEEE-1057-2007 “Standard for Digitizing Waveform Recorders”. However, this measurement method doesn’t adequately address distortion components. An alternative FFT-based method for measuring ENOB, “Computation of Effective Number of Bits, Signal to Noise Ratio, & Signal to Noise and Distortion Ratio using FFT”, addresses both noise and distortion components. The FFT-based method better addresses interleaving errors from the multiple ADCs commonly used in digital oscilloscopes. To the extent that the multiple ADCs aren’t perfectly matched for gain, delay and offset, they tend to degrade the signal. Keep in mind that in a well-designed oscilloscope, the interleave error components are small (about -47 dB) and do not generally affect the ENOB, but their contribution is higher in low-noise, high resolution oscilloscopes with better noise floors than conventional 8-bit resolution oscilloscopes.

When measuring ENOB, we measure with respect to frequency. This is because distortion components are typically a function of frequency. However, SNR and SINAD can also be a function of frequency when sample clock jitter is high. Jitter, when present, increases the noise and distortion at correlated frequencies. This can be seen in Figure 8. Note that the spectral noise power is 10 dB higher around the input 6 GHz sinusoid compared to elsewhere (due to high sample clock jitter in this particular oscilloscope), and the impact was greatest at high bandwidths.

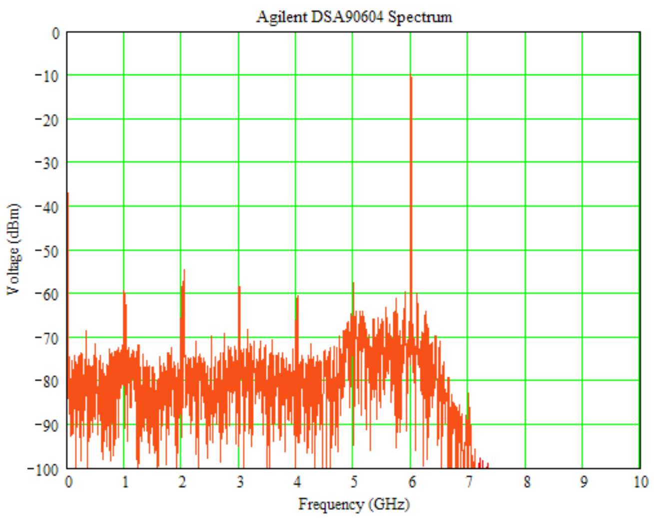


Figure 8 - Noise spectral density with 6 GHz input sinusoid

Figure 9 shows the corresponding SINAD (described as SNR) versus frequency for this same oscilloscope, with the expected degradation of SINAD at higher frequencies.

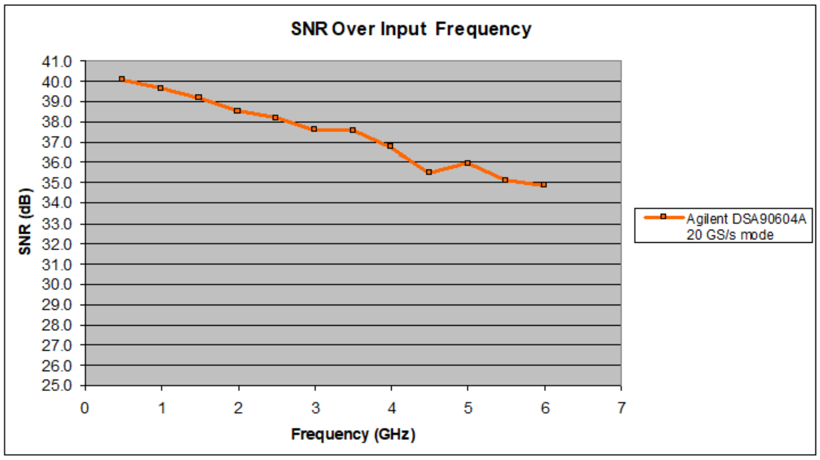


Figure 9 - SINAD vs. frequency for Agilent DSA90604A oscilloscope

Figure 10 shows the impact on a pure sinusoid input at different frequencies. As expected from Figure 8 and Figure 9, the input signal gets noticeably noisier as frequency increases.

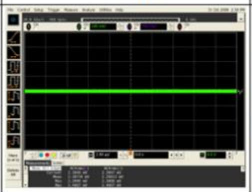
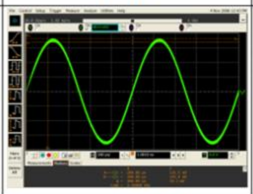
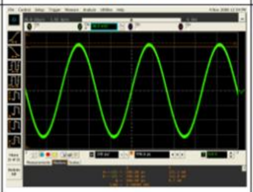
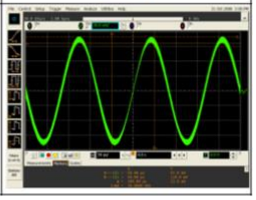
Input Frequency	**None**	**1 GHz**	**3 GHz**	**6 GHz**
SINAD	**42 dB**	**40 dB**	**37 dB**	**35 dB**
Visual Comparison				

Figure 10 - Noise vs. frequency for Agilent DSA90604A oscilloscope

Frequency synthesizers are used as the sinusoid source generator for input to the oscilloscope. Most good quality, commercially available frequency synthesizers have an intrinsic noise floor that is lower than that of an 8-bit oscilloscope acquisition system. However, the frequency synthesizer intrinsic noise floor may not be lower than that of higher resolution oscilloscope acquisition systems. Therefore, bandpass filters are utilized on the output of the frequency synthesizer to remove harmonic content, and the output sinusoid is attenuated as needed to reduce the generator noise floor. If these steps are not taken when measuring ENOB on a 12-bit acquisition system, the ENOB measurements made will be more a reflection of the signal source used than of the acquisition system.

ENOB specifications may be simplified to a single number, but it is important to understand whether this number represents an unusual best-case performance at one single frequency, or whether it is a typical value across a broad range of frequencies. Not surprisingly, oscilloscope manufacturers will usually specify an ENOB number that shows performance in the most favorable light, especially if they are using a lower resolution ADC or a front-end amplifier that has not been optimized for high resolution performance.

Lastly, ENOB would be expected to decrease as bandwidth increases, regardless of resolution. Figure 11 shows typical ENOB values as a function of oscilloscope bandwidth for 8-, 10- and 12-bit resolution oscilloscopes. A trend line is also displayed for reference, as well as lines representing extrapolation to higher bandwidths.

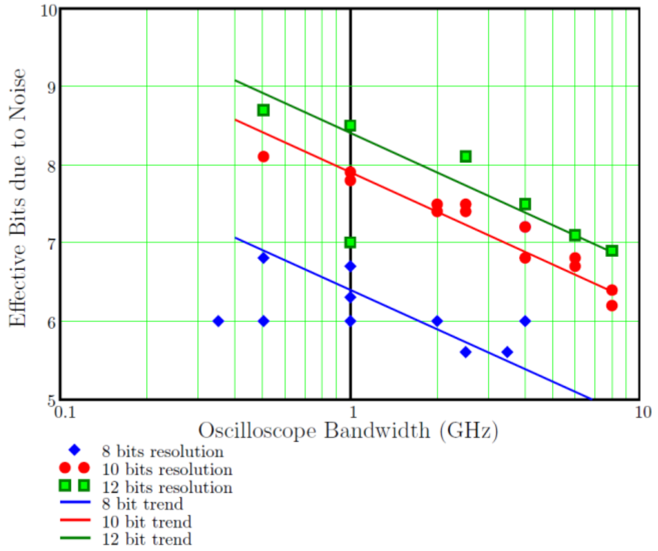


Figure 11 - Typical ENOB vs. bandwidth for 8-, 10-, and 12-bit oscilloscopes

For example, a typical high-quality 8-bit resolution, 1 GHz oscilloscope purchased in 2018 might be expected to have an ENOB of ~6.5 (though the ADC ENOB might be ~7). Ten or more years ago, this would likely have been 0.5 to 1.0 bits less—as technologies mature, performance improves.

Oscilloscope Resolution, Accuracy and Precision

Oscilloscopes are precision measurement devices that convert analog signals into digital samples with time and amplitude values. Oscilloscopes with more resolution will have more accuracy and precision, unless they have poor system implementations.

Time and amplitude values have uncertainty associated with them, and these uncertainties contain both deterministic and random components. The maximum measured uncertainty under the stated operating conditions is less than or equal to the timing or amplitude accuracy specification. In general, the timing uncertainties are much less than the amplitude uncertainties, but as shown in Figure 8, Figure 9 and Figure 10, higher sample clock (timing) jitter can lead to higher vertical (voltage amplitude) noise, so care must be taken in designing the sample clock generation and distribution system.

Note that strictly speaking, accuracy is characterized by the deterministic component and precision by the random component. However, practical oscilloscope gain (vertical amplitude) specifications—in use by all major oscilloscope manufacturers—do not distinguish between deterministic and random contributions for the gain accuracy specifications. A simple gain accuracy specification is typically provided (e.g., ±X%), and this specification includes both deterministic and random components of the gain accuracy.

By itself, more resolution does not automatically result in more accuracy—proper acquisition system design, including use of low-noise and low-jitter components consistent with the resolution throughout the acquisition system is key to achieving the expected accuracy results with improvements in resolution.

Timing Accuracy and Precision

Sample clock timing accuracy is defined by the following specifications:

- Sample Clock Accuracy in absolute parts per million (ppm), with a per year drift component in ppm from data of last calibration (this is the deterministic component of the accuracy)
- Sample Clock (time interval error, or TIE) Jitter in picoseconds (ps) or femtoseconds (fs) root mean square (rms) (sometimes also referred to as aperture uncertainty). This is the random component of the accuracy or precision of the timing measurement.

Deterministic Component Impact

The deterministic component (sample clock accuracy) impacts the measurement accuracy between two sample points, commonly referred to as Delta Time Measurement Accuracy, with the impact proportionally larger for long acquisitions, as described in Equation 11:

$$Delta\ Time\ Measurement\ Accuracy =$$

$$\sqrt{2} * \sqrt{{\frac{Noise}{Slew\ Rate}}^{2} + (Sample\ Clock\ Jitter)^{2}\ (RMS)} + clock\ accuracy \cdot reading\ (seconds)$$

Equation 11 - Delta Time Measurement Accuracy equation

Random Component Impact

The random component (sample clock jitter) impacts the measurement accuracy between two channels. It is typically stated as an absolute (worst-case) value that is typically derived from a statistical assumption and the sample clock jitter value, as shown in Equation 12:

$$Jitter\ Between\ Channels = 5 \cdot \sqrt{2} \cdot Sample\ Clock\ Jitter\ (RMS)$$

Equation 12 - Jitter between channels equation

The factor 5 provides the specification with a 5 sigma certainty (99.99994%), and the $\sqrt{2}$ is the multiplier for the root mean square calculation of two channels that both have identical jitter specifications. Obviously, this is a very conservative specification for jitter between channels.

Voltage (Gain, Amplitude) Accuracy and Precision

Gain accuracy is specified at DC, and the AC gain accuracy is simply a function of the DC gain accuracy and the flatness of the frequency response—the flatter the frequency response and the lesser the deviation from the DC value at a given frequency, the better the AC gain accuracy at that frequency. Fortunately, digital signal processing (DSP) can be used to carefully tailor the frequency response and control this quite well, even if there is no explicit specification for AC gain accuracy. For a thorough explanation of the many ways that DSP is commonly used in oscilloscopes, refer to “Digital Signal Processing (DSP) in Oscilloscopes”. DSP is more broadly applied in oscilloscopes as oscilloscope bandwidth increases, component-to-component variability increases (mostly due to the increased bandwidth), and timing precision becomes more critical. However, even with DSP applied to correct and match frequency response across many gain ranges and channels, the natural frequency response rolloff most engineers expect in their oscilloscope (e.g., Nth-order Bessel) does result in 1 dB (10%) reduction in magnitude response at mid-bandwidth, and 3 dB (30%) reduction at full bandwidth. This will produce larger gain “inaccuracies” at higher frequencies if pure sinusoids are measured. Realistically, most engineers are not measuring pure sinusoids at the bandwidth rating of the oscilloscope, but complex step responses and this tailored, Nth-order Bessel rolloff are ideal for these signals: the response is reasonably flat (~0 dB reduction) to 20% of the bandwidth rating and rolls off gently. This results in accurate voltage magnitude measurements for the base and top of complex signals and minimized additive overshoot on fast rising edges.

ADC resolution and vertical noise have a direct impact on the gain accuracy of the oscilloscope provided an overall high quality acquisition system design is achieved. 12-bit ADC resolution (with good performance characteristics), low noise (in both the ADC and front-end amplifier) and good linearity in the analog signal path will provide gain accuracy specifications that are three or four times better (0.5%) than those found in conventional 8-bit oscilloscopes (2%) or oscilloscopes using only a single high resolution component, such as a 10-bit or 12-bit ADC (1.5% to 2%). The bulk of this gain accuracy improvement is due to much lower noise values, but good sample clock design and distribution play a key role as well.

There is no explicit specification for “precision” in oscilloscopes, but it can be quantified by calculating the standard deviation from the mean value of measurement parameters. All things being equal (acquisition systems with identical sample rate, bandwidth, sample clock, etc.), an oscilloscope with higher precision will return measurement values with less standard deviation around the mean value.

High Definition/High Resolution Design Approaches

“High definition” and “high resolution” are interchangeable terms used by various oscilloscope manufacturers to define vertical resolution of more than 8 bits. By themselves, these terms reveal nothing about the underlying technology employed to achieve higher resolution, any drawbacks associated with it or the overall quality of the approach used. In fact, they have sometimes been used in highly misleading ways to confuse oscilloscope users about actual performance.

As described earlier, high resolution in oscilloscopes is obtained through low-noise high resolution hardware, software post-processing techniques or some combination of both. There are two inviolate rules about the various design approaches:

1. High resolution hardware will always result in better noise performance and higher effective number of bits when equivalent software post-processing techniques are used to improve further upon the hardware noise and resolution.
2. Software post-processing techniques for better noise and higher effective number of bits cannot *replace* high resolution hardware if bandwidth and sample rate are to be maintained at the higher resolution.

Design Approaches Employed

The following are design approaches possible or used in high resolution oscilloscopes:

1. **Design Approach 1: Conventional 8-bit Oscilloscope Hardware**
    - Conventional oscilloscope acquisition system
    - No high resolution components
    - Specialized software post-processing modes to achieve more than rated ADC resolution (with reductions in bandwidth and sample rate when a high resolution/definition “mode” is on)
2. **Design Approach 2: Single High Resolution Component ADC**
    - Conventional oscilloscope acquisition systems with front-end amplifier noise consistent with 8-bit system performance
    - Single high resolution component (usually the ADC, advertised as 10- or 12-bit)
3. **Design Approach 3: Total System Approach (with High Resolution All the Time)**
    - Low-noise front end
    - High resolution ADC (typically 12-bit)
    - Low-noise system architecture
4. **Design Approach 4: Combination**
    - Combination of 1 and 2
    - Combination of 1 and 3

There is nothing inherently wrong with any one approach versus any other, *but software post-processing approaches require the user to accept reductions in bandwidth and sample rate in order to achieve their claimed resolution, or may not have noise performance consistent with claimed resolution.* If these tradeoffs are known and acceptable to oscilloscope users, then any design approach with these limitations is also acceptable.

The characteristics of the design approaches described above are summarized in Table 1:

		High resolution Hardware		
		No high resolution components	High resolution ADC	Low-noise front end High resolution ADC Low-noise system architecture
Software Post-processing	None	Conventional 8-bit oscilloscope	Design Approach 2	Design Approach 3
	Some	Design Approach 1	Design Approach 1 + 2	Design Approach 1 + 3

Table 1 - Hardware and software high resolution design approach characteristics

Expected Performance of High Resolution Design Approaches

Engineers expect their high resolution oscilloscopes to deliver the advertised resolution at the bandwidth, sample rate and number of channels advertised: if a 12-bit, 4 GHz, 4 channel, 10 GS/s oscilloscope is purchased, it should meet all those specifications at the same time, all the time.

An easy way to envision this is with the radar chart shown in Figure 12. This figure has four different axes, one for each of the aforementioned banner specifications (resolution, bandwidth, channel count and sample rate). Resolution is displayed as both bits and ADC levels, with the scale linear to ADC levels.

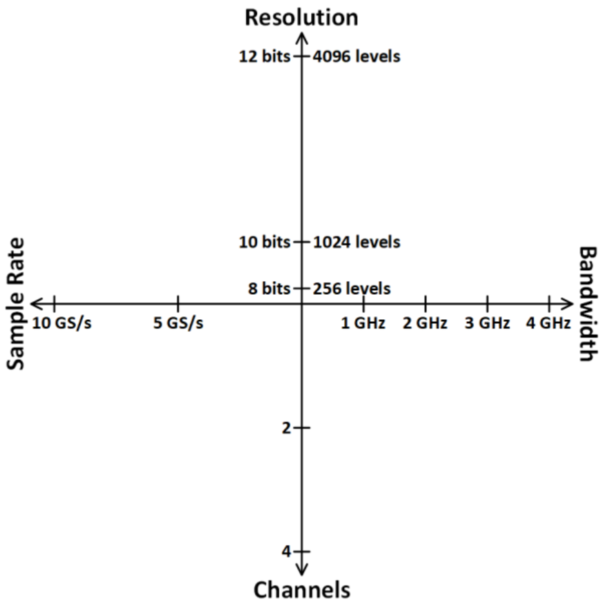


Figure 12 - Radar chart used to understand interplay of oscilloscope banner specifications

Figure 13 is a diagram of a 12-bit resolution, 4 GHz bandwidth, 4 channel, 10 GS/s sample rate oscilloscope resulting from Design Approach 3, with the green area representing the performance that is obtained simultaneously on all four axes, as would generally be expected.

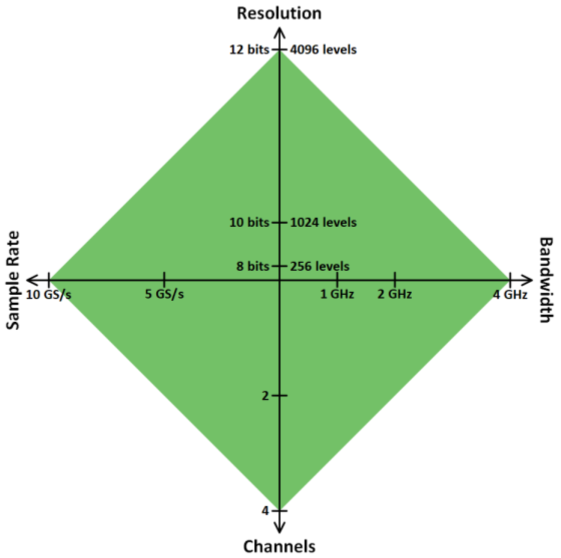


Figure 13 - Radar chart that shows all banner specifications available all the time with no tradeoffs

The performance of an oscilloscope that uses Design Approach 1 (8-bit acquisition hardware with software post-processing for higher resolution) is shown in Figure 14. This oscilloscope operates differently at different bandwidths or operating modes, and the operating compromises may or may not be exposed to the user in an obvious way.

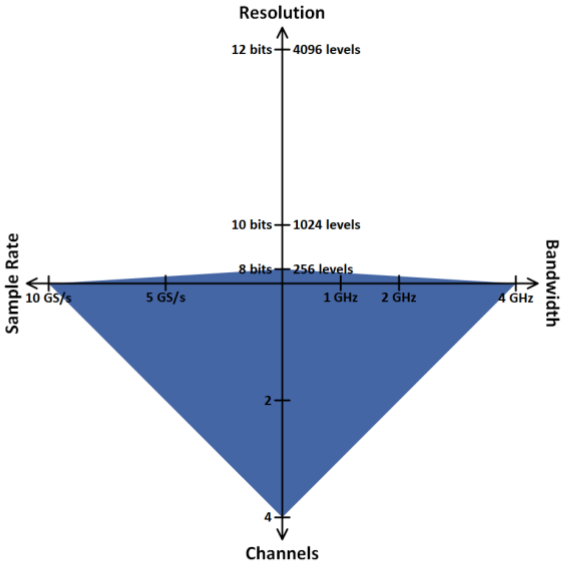


Figure 14 - Radar chart for a conventional 8-bit oscilloscope that uses software post-processing to achieve high resolution

Figure 15 shows how the performance of a Design Approach 1 oscilloscope changes dramatically with an increase in resolution, resulting in a reduction of both bandwidth and sample rate, as is to be expected when relying on software post-processing applied to conventional 8-bit oscilloscope hardware.

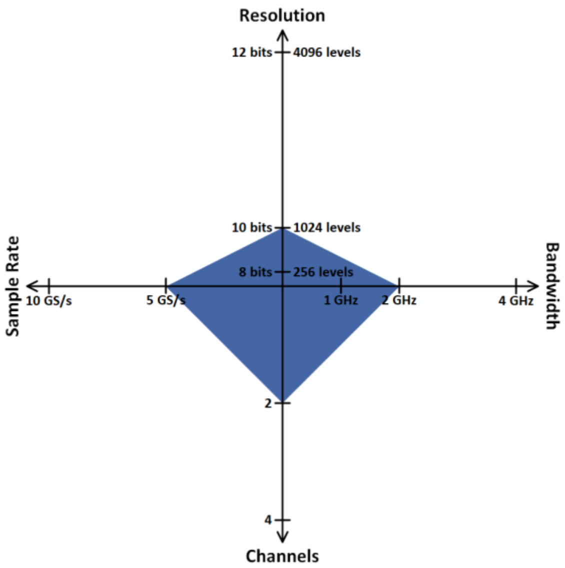


Figure 15 - Same oscilloscope as shown in Figure 14, but with 10-bit resolution using software post-processing of an 8-bit resolution acquisition system

Software Post-processing Techniques for Improved Noise and Resolution

Digital signal processing (DSP) has been used for some time in oscilloscopes for a variety of filtering, frequency response, group delay and other compensations (again, see "Digital Signal Processing (DSP) in Oscilloscopes"). DSP is used in some oscilloscopes to improve noise and resolution, as well as for averaging, filtering and interleaving.

Software post-processing techniques to improve noise and resolution are listed below:

- Acquisition averaging
- ADC sample averaging
- Filtering
- ADC interleaving

Acquisition Averaging

Multiple acquired signals averaged together will significantly reduce random noise, with a larger number of averages resulting in a larger random noise reduction. The signal must be repetitive for this technique to work. Therefore, there is no benefit to this technique for single-shot acquisitions. This is not considered a practical technique for noise reduction in a single-shot, real-time oscilloscope, and in fact it is not currently employed or promoted by any real-time oscilloscope manufacturer as a viable means to reduce noise and improve resolution.

ADC Sample Averaging

As described earlier, many ADC chips contain multiple ADCs, each with a different signal path, that are time interleaved to obtain the full-rated sample rate of the ADC chip. If each time-interleaved ADC has different, uncorrelated noise, the benefit of averaging two different ADC signal paths together, with a corresponding reduction in sample rate, is the equivalent of a maximum half bit of effective resolution. The maximum half bit would be achieved if the noise in the two paths is completely uncorrelated. If the noise in the two paths is completely correlated, the benefit is zero.

ADC sample averaging may be performed on the data as read from the memory buffer or from an FPGA located between the ADC and memory buffer. Regardless, the mathematical result will be the same, though an FPGA-based approach could operate faster. Regardless, these are just two different implementations of a software post-processing filter.

Filtering

If the noise is white (evenly distributed through the bandwidth of the oscilloscope) and we reduce the bandwidth by half, then a noise reduction of 3 dB (half an effective bit) is obtained. Reducing the sample rate by half is mathematically the same as reducing the bandwidth by half. This is the principle behind the Enhanced Resolution (ERES) filter used by Teledyne LeCroy (see "Understanding Vertical Resolution in Oscilloscopes"). Other manufacturers employ similar filtering techniques, though with dubious claims for what can be achieved—*it is not mathematically possible to achieve >3 dB noise reduction (>0.5 effective bit) for every halving of the bandwidth*. Manufacturers that claim more resolution improvement are doing so under misleading pretenses about how effective bits might relate to ADC hardware bits. What is typically seen is a pretense that 0.5 effective bits equals 1 ADC hardware bit.

Filtering may be performed on the data as read-out from the memory buffer or in an FPGA located between the ADC and memory buffer. The mathematical result will be the same, though an FPGA-based approach could operate faster. Regardless, these are just two different implementations of a software post-processing filter.

ADC Vertical Interleaving

Teledyne LeCroy described a technique for ADC vertical and horizontal interleaving for vertical resolution improvement in US patent application "Variable Resolution Oscilloscope" filed on August 21, 2017 as application number 15/682,005 and published on March 1, 2018 as publication number US 2018/0059143 A1. This technique was commercialized in the HDO9000 oscilloscope product line to achieve 10-bit resolution through vertical interleaving of quantity eight 5 GS/s 8-bit ADCs that are part of a single 40 GS/s ADC chip.

Summary of Benefits and Costs

All of the aforementioned techniques take advantage of noise correlation and spectral content to reduce noise and improve resolution, but with reductions in bandwidth, sample rate, channel count or all of the above. It should be noted that some techniques don't directly reduce bandwidth, but if bandwidth is not reduced coincident with the application of that technique, then the Nyquist criteria for SR:BW will no longer be met, and the signal could be aliased. Specifics of implementation and how much improvement can be theoretically or reasonably expected are described in "Understanding Vertical Resolution in Oscilloscopes". Table 2 summarizes these techniques and their impact on oscilloscope performance:

	Impact on Oscilloscope Performance				
Software Post-processing Technique	**Bandwidth**	**Sample Rate**	**Resolution**	**Noise**	**Memory**
ADC Sample Averaging	No Change Nyquist criteria for SR:BW ratio must be satisfied	Reduced	Increased Provided that noise is uncorrelated in different ADC paths	May Be Reduced Provided that the front-end is not the dominant noise source	May Be Reduced Depends on design
Filtering	Usually Reduced	No Change	Increased	May Be Reduced Depends on spectral content of noise	No Change
ADC Vertical Interleaving	No Change However, Nyquist criteria for SR:BW ratio must be satisfied	Reduced Interpolation may be used to maintain SR if a 3x SR:BW ratio is maintained.	Increased	May Be Reduced Depends on front-end noise dominance and spectral content of noise	May Be Reduced Depends on design

Table 2 - Impact on oscilloscope performance of various software post-processing techniques for increasing resolution

High Resolution Oscilloscope Implementations

Most major oscilloscope companies are now marketing oscilloscopes with high definition or high resolution claims. Figure 16 shows the various high resolution oscilloscope product lines and approximate timeline they were released to the market.

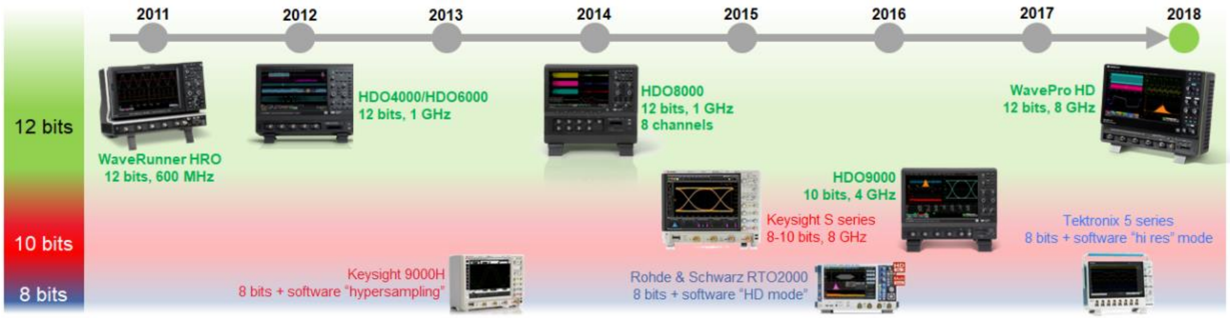


Figure 16 - Release timeline and resolution of various high resolution oscilloscope product lines

Teledyne LeCroy's various HD4096 high definition technology oscilloscopes have led the way with high resolution performance, providing 12-bit resolution all the time regardless of the oscilloscopes' operating mode or configuration.

Teledyne LeCroy

Teledyne LeCroy was first to market with a high resolution oscilloscope with the WaveRunner HRO 6 Zi product line (600 MHz, 2 GS/s, 4 channels, 12-bit resolution), followed by the various 4- and 8-channel HDO series models (HDO4000, HDO6000 and HDO8000) that improved in bandwidth to 1 GHz at 2.5 GS/s (now 10 GS/s with the HDO "A" Series). WavePro HD is the latest Teledyne LeCroy high resolution oscilloscope with bandwidth up to 8 GHz, 20 GS/s (10 GS/s on 4 channels), 4 channels, and 12-bit resolution. All Teledyne LeCroy 12-bit resolution oscilloscopes since 2012 make use of Teledyne LeCroy's HD4096 high definition technology. HD4096 technology is a combination of low-noise front-end amplifiers, 12-bit ADCs and a low-noise system architecture. Therefore, the 12-bit performance is inherent in the hardware design, and with the use of ERes (enhanced resolution filters, standard on the oscilloscopes), up to 15-bit resolution can be achieved (at reduced bandwidths). These oscilloscope platforms all follow Design Approach 3 (or a Design Approach 4 combination of approaches 3 and 1 with the use of ERes). The outcome of Design Approach 3 is that bandwidth, sample rate, and number of channels are not degraded to achieve high resolution, as shown in Figure 17:

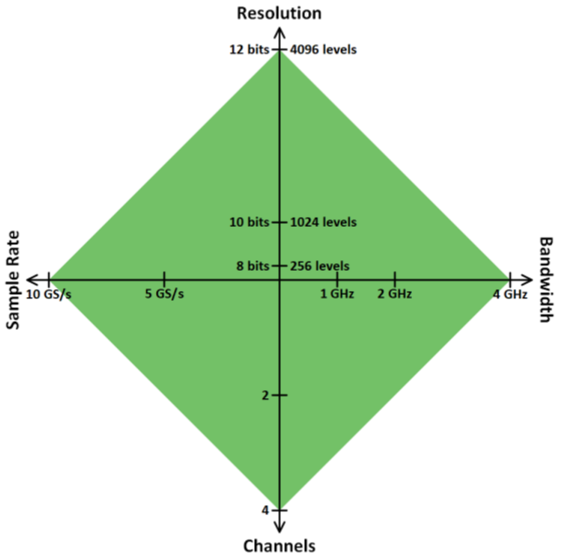


Figure 17 - Teledyne LeCroy WavePro 404HD provides 12-bit resolution all the time at rated banner specifications

Prior to the introduction of the WavePro HD Series, Teledyne LeCroy introduced the HDO9000 oscilloscopes with variable resolution (>8-bit) at over 1 GHz bandwidth. These oscilloscopes are 4 GHz, 4 channels, 20 GS/s (40 GS/s on 2 channels) with an 8-bit ADC. Vertical ADC interleaving was used to achieve 10-bit resolution on 2 channels (9-bit on 4 channels) at 1 GHz, with filtering adding further to resolution. This oscilloscope is a combination of Design Approaches 1 and 2.

Keysight Technologies

Agilent Technologies (now Keysight Technologies) followed Teledyne LeCroy to market by approximately two-and-a-half years with their Infiniium 9000 H-Series High Definition Oscilloscope. This product was essentially the Agilent Technologies Infiniium 9000 Series 8-bit, 4 GHz oscilloscope platform with software post-processing to achieve higher sample rate. The 9000 H-Series was available only in models up to 2 GHz (in 2 channel mode only, limited to 1 GHz in 4 channel mode) with hobbled sample rates (compared to the 9000 Series). The bandwidth and sample rate reductions (compared to the 9000 Series hardware platform capabilities) are as expected with Design Approach 1, simple software post-processing built on an 8-bit platform that lacks native high resolution components.

Agilent Technologies followed the Infiniium 9000 H-Series with a new product platform (the S-Series High definition Oscilloscopes). This platform replaced both the 9000 Series and 9000 H-Series. The S-Series reached to 8 GHz bandwidth and 20 GS/s sample rate (on 2 channels), and is advertised as using a 10-bit ADC and a low-noise front-end amplifier. Noise performance is consistent with that expected of 10-bit resolution when the oscilloscope is operated in 10-bit modes, with more resolution possible through use of filtering techniques. However, this product has operating cases (e.g., 5 GS/s sample rate when the oscilloscope is not in "high resolution mode") where it defaults to 8-bit resolution. That makes this oscilloscope a combination of Design Approaches 1 and 2, as shown in Figure 18:

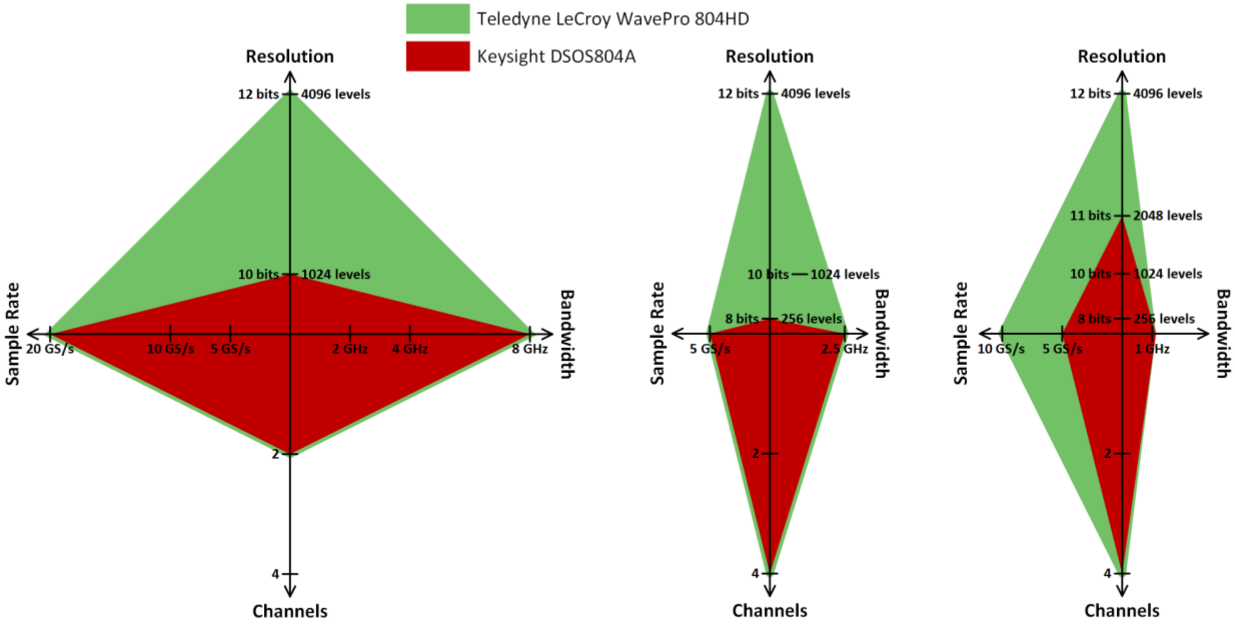


Figure 18 - Banner specification comparison of Keysight DSOS804A to Teledyne LeCroy WavePro 804HD. Note that Keysight resolution changes depending on sample rate and resolution settings.

What Keysight Says

Keysight advertises their S-Series oscilloscope as containing a 10-bit ADC and a low-noise front end. Notwithstanding the several modes where the oscilloscope oddly operates in an 8-bit resolution mode (with commensurate noise performance), the S-Series performs as expected of a 10-bit resolution oscilloscope. High resolution can be selected as an "Automatic" or "Manual" operation, with Manual as the default mode. Keysight is straightforward with their presentation of sample rate and does not intermingle real-time and interpolated sample rate mode as resolution changes.

Examining Keysight Claims

Keysight's claim of a 10-bit ADC and low-noise front-end amplifier is supported at the highest sample rates (20 GS/s and 10 GS/s) and the oscilloscope returns performance consistent with 10-bit operation when it is operating at those sample rates. However, when sample rate is reduced to less than 10 GS/s the ADC may re-configure to an 8-bit operation, without overt warning to the operator (notice is provided if a special display menu is engaged). To prevent this re-configuration, the High Resolution mode (>10 bits) could be enabled. However, an additional bandwidth and/or channel limitation may be imposed without the explicit knowledge of the oscilloscope user. If High Resolution mode is set to "automatic", then the oscilloscope will maximize resolution at the expense of bandwidth and/or number of channels, depending on the configuration. Thus, while the oscilloscope delivers credible 10-bit system performance at the highest operating bandwidths and sample rates, when operated in a more general-purpose way to measure lower-speed signals in typical real-world acquisitions (e.g., long acquisition times), it is highly likely that the user will experience reductions in resolution to 8-bits and/or limitations on channels and bandwidth (depending on acquisition settings) without being overtly warned.

We've operated the Keysight S-Series DSOS804A at several different bandwidth, sample rate and High Resolution Mode settings (referred to as Operating Modes 1 through 9) with each operating mode corresponding to a reduction in bandwidth and/or a reduction in sample rate. Operating modes 1 through 7 are with High Resolution Mode in "Manual" and operating modes 8 and 9 are with High Resolution Mode in "Automatic". The data is summarized in Table 3 (following descriptions of the operating modes). The various operating modes are described below.

Keysight DSOS804A Operating Modes 1, 2, 3, and 5:

8 to 2.5 GHz Bandwidth, 2 Channels, 20 GS/s (Real-time), 10-bit Resolution

1. **Sample Rate:** The maximum 20 GS/s real-time (RT) sample rate on 2 channels indicates a total combined system capability of 4 x 10 GS/s = 40 GS/s
2. **Bandwidth:** Reduced consistent with user-defined bandwidth limits, but not reduced as a function of higher resolution operation.
3. **Resolution:** The displayed system resolution of 10 bits is consistent with their 10-bit system hardware (ADC and front-end amplifier).
4. **Evidence:** Keysight specifies ENOB in these operating modes, and Teledyne LeCroy measurements essentially match the Keysight data. In general, every halving of the bandwidth should result in an improvement of 0.5 effective bit and 3 dB SNR. The improvement is a little better from the 8 GHz baseline, likely due to ADC or front-end amplifier noise and distortion beyond 8 GHz, which would not be present with the 6, 4, or 2.5 GHz brick-wall filters applied.

Keysight DSOS804A Operating Modes 4 and 6:

4 to 2.5 GHz Bandwidth, 2 Channels, 10 GS/s (Real-time), 10-bit Resolution

1. **Sample Rate:** The sample rate is 10 GS/s real-time (RT) sample rate on all 4 channels.
2. **Bandwidth:** Reduced consistent with user-defined bandwidth limits, but not reduced as a function of higher resolution operation.
3. **Resolution:** The displayed system resolution of 10 bits is consistent with their 10-bit system hardware.
4. **Evidence:** Keysight does not report ENOB data in these operating modes. However, we would expect a 3 dB noise (0.5 effective bit) degradation from the 20 GS/s sample rate equivalent bandwidth case if the 10 GS/s interleaving (two channels into one channel to achieve 20 GS/s)

was achieved without interleaving errors. The actual degradation is roughly half what would be expected, indicating that the ideal 20 GS/s performance was not achieved.

Keysight DSOS804A Operating Mode 7:

2.5 GHz Bandwidth, 4 Channels, 5 GS/s (Real-time), 8-bit Resolution

1. **Sample Rate:** The sample rate is 5 GS/s real-time (RT) sample rate on all 4 channels. This sample rate could be manually set, or reached due to memory length limitations.
2. **Bandwidth:** Reduced consistent with user-defined bandwidth limits, but not reduced as a function of higher resolution operation.
3. **Resolution:** The displayed system resolution of 8 bits is inconsistent with their 10-bit system hardware.
4. **Evidence:** SNR degrades by 3 dB compared to the 10-bit resolution, and ENOB degrades by 0.4 bits. When this mode is compared to Teledyne LeCroy's WaveRunner 8404 (an 8-bit resolution oscilloscope) operating in mode 4 (see Table 7) with 2.4 GHz, 5 GS/s and 1 bit of enhanced resolution, the noise and effective bit values are very similar (0.98 mV for Keysight vs. 0.78 mV for Teledyne LeCroy and 6.8 effective bits for both oscilloscopes).

Keysight DSOS804A Operating Mode 8:

1.14 GHz Bandwidth, 4 Channels, 5 GS/s (Real-time), 11-bit Resolution

1. **Sample Rate:** The sample rate is 5 GS/s real-time (RT) sample rate on all 4 channels. This sample rate could be manually set, or reached due to memory length limitations.
2. **Bandwidth:** Reduced by oscilloscope to 1.14 GHz as part of the operation of 11-bit resolution mode.
3. **Resolution:** The oscilloscope is set to "Automatic" High Resolution mode, and when the sample rate is 5 GS/s, the bandwidth limit is automatically set to 1.14 GHz and the reported resolution is 11 bits. The reported resolution does not match expectations for SNR or effective bit improvements.
4. **Evidence:** The improvement in noise and effective bits compared to the 2.5 GHz, 10 GS/s operating mode 6 is only 2.0 dB and 0.3 effective bits, respectively. A simple bandwidth limit filter would achieve 3 dB and 0.5 effective bits improvement. This leads credence to a belief that the S-Series is simply performing a software filtering operation in this operating mode. The reported 11 bit resolution is inconsistent with the measured improvement – reported resolution should be 10.5 bits. In fact, performance falls far short of that provided by a 12-bit resolution Teledyne LeCroy WavePro HD oscilloscope set to a 1 GHz bandwidth limit (0.29 mV baseline noise, 62.8 dB SNR, and 8.1 ENOB).

Keysight DSOS804A Operating Mode 9:

558 MHz Bandwidth, 2 Channels, 5 GS/s (Real-time), 12-bit Resolution

1. **Sample Rate:** The sample rate is 2.5 GS/s real-time (RT) sample rate on only 2 channels. This indicates that two channels are interleaved to one to achieve a higher sample rate (10 GS/s), which is then filtered to 2.5 GS/s to achieve better noise and effective bit performance, while simultaneously limiting the bandwidth to half that of operating mode 8. This maximum sample rate is limited by the 12-bit High Resolution mode setting.
2. **Bandwidth:** Reduced by oscilloscope to 558 MHz as part of the operation of 12-bit resolution mode.

3. **Resolution:** The oscilloscope is set to “Automatic” high resolution mode, and when the sample rate is 2.5 GS/s, the bandwidth limit is automatically set to 558 MHz and the reported resolution is 12 bits.
4. **Evidence:** The improvement in noise and effective bits compared to the 1.14 GHz, 5 GS/s operating mode 8 is only 2.2 dB and 0.2 effective bits, respectively. A simple bandwidth limit filter would achieve 3 dB and 0.5 effective bits improvement. Clearly, claiming 12-bit resolution is a stretch because performance falls far short of that provided by a 12-bit resolution Teledyne LeCroy WavePro HD oscilloscope set to a 500 MHz bandwidth limit (0.21 mV baseline noise, 65.6 dB SNR, and 8.5 ENOB). The Teledyne LeCroy oscilloscope has 4 channel performance as well.

Comparison to Teledyne LeCroy 12-bit Resolution HD4096 Techology Oscilloscopes

Table 3 shows data for the different Keysight DSOS-804A operating modes described above. Areas of yellow shading indicate odd behaviors for a 10-bit resolution oscilloscope and areas of red shading indicate operating modes with excessive claims.

Keysight DSOS-804A (8 GHz, 10 GS/s on 4 channels, 20 GS/s on 2 channels, 10-bit resolution)										
Operating Mode	High-Resolution Mode	Band-width	Available Channels	Displayed Sample Rate RT=Real-time	Keysight Displayed System Resolution (Bits)	Effective Bits @ 50 mV/div	Cumulative Effective Bit Improvement	Measured Baseline Noise @ 50 mV/div	Signal to Noise Ratio @ 50 mV/div[1]	Cumulative Signal to Noise Ratio Improvement
1	Manual	8 GHz	2	20 GS/s RT	10	6.4		1.29 mV	49.8 dB	
2	Manual	6 GHz	2	20 GS/s RT	10	6.8	0.4	1.02 mV	51.9 dB	2.1 dB
3	Manual	4 GHz	2	20 GS/s RT	10	7.2	0.8	0.83 mV	53.7 dB	3.9 dB
4	Manual	4 GHz	4	10 GS/s RT	10	7.0		0.90 mV	53.0 dB	
5	Manual	2.5 GHz	2	20 GS/s RT	10	7.4	1	0.68 mV	55.4 dB	5.6 dB
6	Manual	2.5 GHz	4	10 GS/s RT	10	7.2		0.69 mV	55.2 dB	
7	Manual	2.5 GHz	4	5 GS/s RT	8	6.8		0.98 mV	52.2 dB	
8	Automatic	1.14 GHz	4	5 GS/s RT	11[†]	7.5	1.1	0.55 mV	57.2 dB	7.4 dB
9	Automatic	558 MHz	2	2.5 GS/s RT	12[†]	7.7	1.3	0.43 mV	59.4 dB	9.6 dB

[1] Calculated on the basis of 8 vertical divisions for oscilloscope full scale

[†] Keysight claimed system resolutions and performance do not match industry competitors

Table 3 - Keysight DSOS-804A Performance by Operating Mode

The Teledyne LeCroy HDO4000A, HDO6000A, HDO8000A (350 MHz to 1 GHz) and WavePro HD products (2.5 GHz to 8 GHz) all utilize HD4096 technology for 12-bits all the time with no bandwidth, sample rate or channel count tradeoffs. ERES may also be used to increase resolution beyond 12-bits, but with bandwidth and sample rate tradeoffs. Table 4 shows data for the closest equivalent Teledyne LeCroy WavePro 804HD operating mode.

Teledyne LeCroy WavePro HD Series (8 GHz, 10 GS/s on 4 channels, 20 GS/s on 2 channels, 12-bit resolution)										
Operating Mode	High Definition Mode	Band-width	Available Channels	Displayed Sample Rate RT=Real-time	Teledyne LeCroy Displayed System Resolution (Bits)	Effective Bits @ 50 mV/div	Cumulative Effective Bit Improvement	Measured Baseline Noise @ 50 mV/div	Signal to Noise Ratio @ 50 mV/div[1]	Cumulative Signal to Noise Ratio Improvement
1	HD4096 hardware technology "always ON"	8 GHz	2	20 GS/s RT	12	7.0		0.86 mV	53.4 dB	
2		6 GHz	2	20 GS/s RT	12	7.2	0.2	0.74 mV	54.7 dB	1.3 dB
3		4 GHz	2	20 GS/s RT	12	7.5	0.5	0.56 mV	57.1 dB	3.7 dB
4		4 GHz	4	10 GS/s RT	12	7.2		0.65 mV	55.8 dB	
5		2.5 GHz	2	20 GS/s RT	12	7.9	0.9	0.40 mV	60.0 dB	6.6 dB
6		2.5 GHz	4	10 GS/s RT	12	7.5		0.47 mV	58.6 dB	
7		2.5 GHz	4	5 GS/s RT	12	7.6		0.49 mV	58.2 dB	
8		1 GHz	4	10 GS/s RT	12	8.1	1.1	0.29 mV	62.8 dB	9.4 dB
9		500 MHz	4	10 GS/s RT	12	8.5	1.5	0.21 mV	65.6 dB	12.2 dB

[1] Calculated on the basis of 8 vertical divisions for oscilloscope full scale

Table 4 - Teledyne LeCroy WavePro HD Performance by Operating Mode

Note that as bandwidth is reduced from 8 GHz to 500 MHz in both oscilloscopes, we would expect an improvement of 2.0 ENOB and 12 dB SNR. The Teledyne LeCroy HD4096 technology essentially delivers this expected performance improvement while the Keysight falls a little short of expectations.

Figure 19 shows an SNR comparison for each operating mode in Table 3 and Table 4. The Teledyne LeCroy oscilloscope shows superior results in all operating modes.

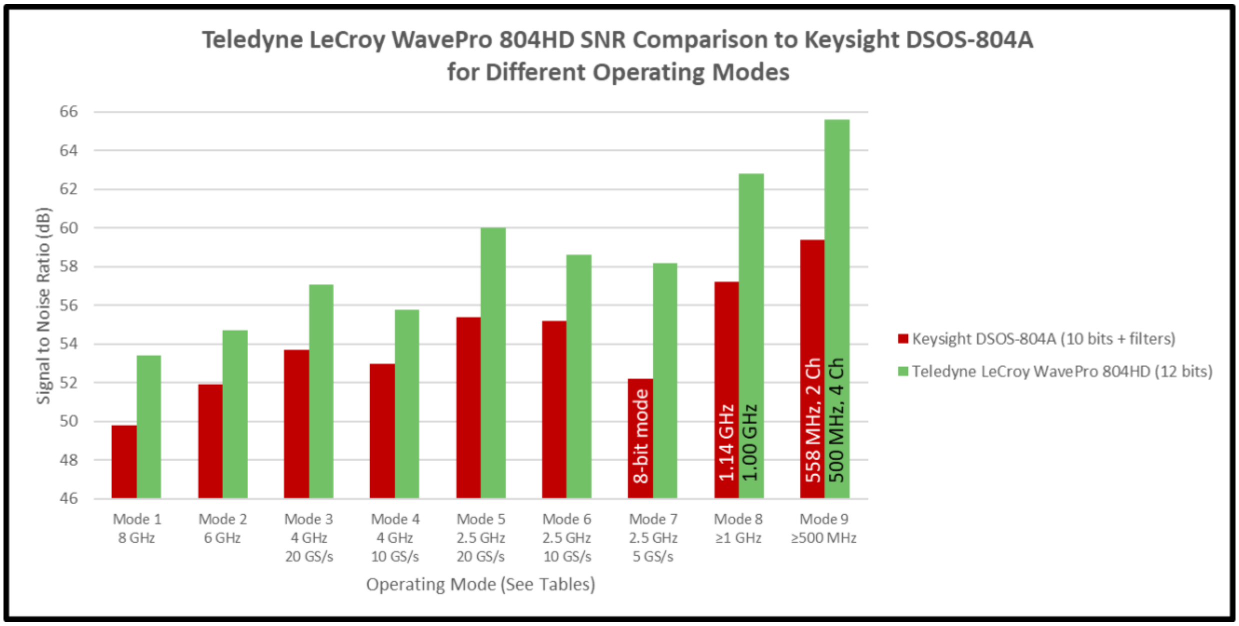


Figure 19 - Teledyne LeCroy and Keysight SNR comparison by Operating Mode

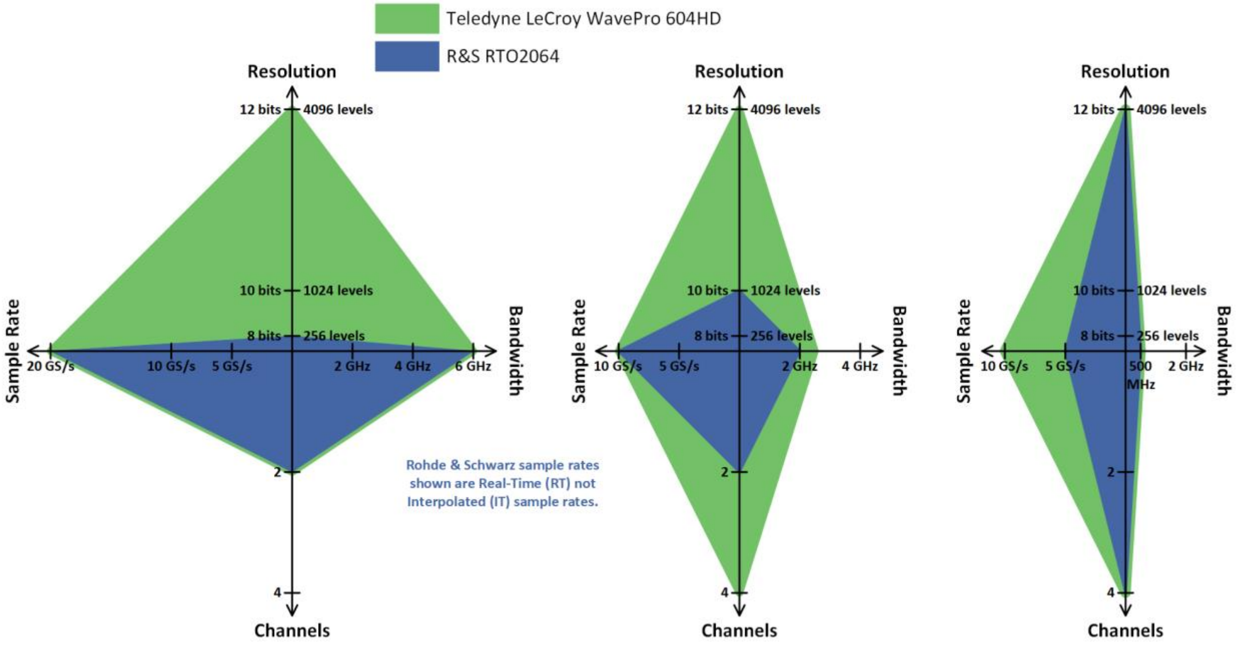
Conclusions

Figure 11 previously introduced a plot of typical oscilloscope system ENOB vs. bandwidth for 8-bit, 10-bit, and 12-bit resolution oscilloscope platforms. The Keysight S-Series is a credible 10-bit performer at high sample rates, but suffers from odd ADC operations which can result in 8-bit resolution at lower sample rates. Claimed 11-bit and 12-bit resolution at 1.14 GHz and 558 MHz bandwidths respectively are not SNR or effective bit equivalent to competitive products that utilize 12-bit technologies, especially considering that the 558 MHz bandwidth mode only provides 2 input channels. In fact, these High Resolution modes are simple software filters that are utilized to achieve better noise performance with corresponding reductions in bandwidth, sample rate and number of channels.

Rohde & Schwarz

Rohde & Schwarz released their high definition (HD) mode software options for RTO and RTE oscilloscopes in late 2014. These Rohde & Schwarz RTO and RTE oscilloscopes are 8-bit oscilloscope platforms that provide 2 channels at 6 GHz and 20 GS/s, or 4 channels at 4 GHz and 10 GS/s. The HD mode (K17 software option) increases resolution to the claimed 16 bits through use of filtering with upsampling (interpolation, or IT mode) to maintain perceived sample rates. 10 bits is claimed at 1 GHz, 12 bits is claimed at 500 MHz, and 16 bits is claimed at much lower bandwidths. The 10 bit, 12 bit and 16 bit claims are dubious (at the bandwidths specified), since their claims don't follow mathematically for noise/resolution improvements with bandwidth and sample rate reduction, and don't come close to matching noise performance for industry competitors with similar resolution achieved with one or more high resolution components. Furthermore, marketing claims are made for ENOB performance only for the ADC component and not for the entire oscilloscope acquisition system, and ENOB is not specified at full-rated bandwidth.

Realistically, the R&S oscilloscope product lines are decent 8-bit resolution oscilloscopes with software capabilities to improve resolution to what would be expected of a 9-bit or lesser 10-bit resolution (when in HD modes) oscilloscope, with marketing claims that imply much, much more. This oscilloscope is an example of Design Approach 1 with performance shown in Figure 20:



Rohde & Schwarz sample rates shown are Real-Time (RT) not Interpolated (IT) sample rates.

Figure 20 - Rohde & Schwarz RTO2064 compared to Teledyne LeCroy WavePro 604HD. Note how Rohde & Schwarz's bandwidth, sample rate and channel count change depending on the desired resolution.

The advertised performance is not consistent with 10-bit or 12-bit performance as achieved by Keysight or Teledyne LeCroy.

What Rohde & Schwarz Says

Rohde & Schwarz published an application note “High-Resolution Measurements with R&S Oscilloscopes” (document number 4.2015-1TD06_0e). The application note describes their approach to noise reduction (resolution improvement with bandwidth reduction) using filtering. Formula 2-4 in their paper describes the SNR improvement (through noise power reduction) that can be achieved by increased sampling rate while maintaining bandwidth. Formula 2-5 describes the noise reduction that can be achieved by applying a moving average filter (MAF) to the sampled signal (which reduces the sample rate and bandwidth). Simply put:

- An ADC with twice the sample rate of another ADC that is the same in every other aspect will have 3 dB better SNR. ADC sample rate could be doubled by interleaving two channels into one, with the penalty of one less input channel. If the interleaved ADCs had no performance tradeoffs due to the interleaving, the noise performance will improve by 3 dB.
- A moving average filter applied to sampled data will provide a 3 dB noise improvement when the sample rate and bandwidth are halved.

R&S employs both of these techniques to reduce noise (and improve resolution) with tradeoffs in the bandwidth, SR and number of channels available for use. The effectiveness of these techniques can be limited by the characteristics of the front end, ADC, and system architecture – there is no guarantee of the full 3 dB improvement. From Equation 7 in this document, we know that 6 dB is one effective bit, so a 3 dB improvement is 0.5 effective bits improvement.

The techniques for noise and resolution improvement that are described in their paper are mathematically sound (and widely used), though there are some implications in the R&S paper that twice the mathematically possible improvements may be achieved (this is not the case). Specifically, when Rohde & Schwarz describes an increase in resolution (in bits), the improvement is not in *effective bits*, but in some other type of (undefined) bit.

Examining the R&S HD Mode Claims

The R&S RTO2044 (4 GHz, 10 GS/s on 4 channels, 8 bit resolution) oscilloscope is used as an example. As would be expected of an 8-bit oscilloscope with software post-processing for higher resolution, significant tradeoffs in bandwidth, sample rate, and number of channels will be made to achieve the claimed higher resolution. All of the R&S RTE, RTO and RTP series oscilloscopes with HD Modes operate in a similar way.

The R&S claims for resolution are excessive and far exceed what is realistically achieved, specifically:

- R&S performance can be reasonably credited as 10-bit resolution in HD Modes. Their claims of 10-bit resolution at 1 and 2 GHz are consistent with what Keysight achieves in the S Series oscilloscopes. However, R&S oscilloscopes sacrifice both sample rate and/or channels to achieve the 10-bit resolution, clear evidence that simple software filtering is being used to achieve higher resolution.
- Claims of 12-bit resolution at 500 MHz are egregious – a credible 10-bit resolution is obtained at 1 GHz, and a further halving of bandwidth to 500 MHz results in 0.3 effective bits improvement.

Instead, R&S claims to achieve 12 bits of resolution (an additional 2 bits). The as measured results absolutely do not support this resolution claim.

- Claims of 16-bit resolution at 50 MHz are equally nonsensical. Each additional halving of the bandwidth from 500 MHz to 50 MHz would result in 0.5 effective bits improvement. Bandwidth reduction from 500 MHz to 50 MHz could theoretically result in 20 dB SNR (3.3 effective bits). There is no credible math to demonstrate how R&S can claim to achieve 16 bits of resolution at 50 MHz.
- R&S HD Mode results in no better performance of the basic 8-bit acquisition system than can be achieved with simple bandwidth filtering, such as offered by Teledyne LeCroy's enhanced resolution (ERES) on the 8-bit resolution WaveRunner 8404 4GHz oscilloscope. R&S claims of superior low-noise front-end amplifiers are not supported by the actual operating data.

We've operated the RTO2044 at several different bandwidth, sample rate and HD Mode settings (referred to as Operating Modes 1 through 6) with each operating mode equating to the application of one or more filtering techniques to achieve higher resolution. The data is summarized in Table 5 (following the descriptions of the operating modes). The various operating modes are described below.

RTO2044 Operating Mode 1:
4 GHz Bandwidth, 4 Channels, 10 GS/s (RT), 8-bit Resolution

1. **Sample Rate:** The maximum 10 GS/s real-time (RT) sample rate on all 4 channels indicates a total combined system capability of 4 x 10 GS/s = 40 GS/s
2. **Resolution:** The displayed system resolution of 8 bits is consistent with their 8-bit system hardware.
3. **Evidence:** R&S doesn't report data on ENOB at 4 GHz in this operating mode. Teledyne LeCroy measurements of ENOB for the R&S oscilloscope return a value of 6.3 near DC (much less than the advertised "above 7 for an input frequency range right up to 4 GHz" as described in their "The Effective Number of Bits (ENOB)) of my R&S Digital Oscilloscope" technical paper (document number April2011-1ER03_1e, page 7). Oscilloscope system ENOB must be less than ADC ENOB, but this is a rather large difference, indicating a non-optimized front-end amplifier or some other system performance issue.

RTO2044 Operating Mode 2:
4 GHz Bandwidth, 2 Channels, 20 GS/s (RT), 8-bit Resolution

1. **Sample Rate:** Two channels are combined into one to provide 20 GS/s (real-time) per channel. This would be expected to provide close to a 3 dB SNR (0.5 effective bit) improvement.
    a. Using a measured RMS (baseline) noise comparison, an improvement of only 0.7 dB (but 0 effective bits) is provided. This could be caused by noise and distortion well beyond the Nyquist bandwidth of 5 GHz and/or some noise and distortion caused by the interleaving.
2. **Resolution:** The displayed system resolution of 8 bits is consistent with how most oscilloscope companies would report their resolution after interleaving two channels – the same as without interleaving channels.
4. **Evidence:** R&S doesn't report data on ENOB at 4 GHz in this operating mode. Teledyne LeCroy measurements of ENOB for the R&S oscilloscope return a value of 6.3 near DC (again, much less than the claimed "above 7 for an input frequency range right up to 4 GHz."

RTO2044 Operating Mode 3:
2 GHz Bandwidth, 2 Channels, 20 GS/s (RT), 8-bit Resolution

1. **Sample Rate:** Two channels remain combined into one to provide 20 GS/s (real-time) per channel.
2. **Bandwidth:** Halved from 4 GHz to 2 GHz (compared to operating mode 2). This should result in a 3 dB reduction in noise and a 0.5 effective bit in resolution. Given that the sample rate is not reduced (compared to Operating Mode 2) and is still reported as real-time sample rate, the bandwidth reduction is presumably achieved with an analog bandwidth filter.
3. **Resolution:** The displayed system resolution of 8 bits is consistent with how most oscilloscope companies would report their resolution after interleaving two channels and applying a bandwidth limit – the same as without interleaving channels or applying bandwidth limits.
4. **Evidence:** Rohde & Schwarz claims 6.8 ENOB and Teledyne LeCroy confirms this claim. This is a 2.6 dB SNR and 0.5 effective bit improvement compared to operating mode 2, as expected. It is this operating mode that Rohde and Schwarz reports ENOB data for their 2GHz bandwidth RTO1024 oscilloscope. See their "The Effective Number of Bits (ENOB) of my R&S Digital Oscilloscope" technical paper (document April2011-1ER03_1e). Teledyne LeCroy measurements of the RTO2044 substantially match this data. A typical 6.8 ENOB can be reasonably assumed for the plot shown in their Figure 5 in their document.

RTO2044 Operating Mode 4:
2 GHz Bandwidth, 2 Channels, 20 GS/s (IT), 10-bit Resolution (HD Mode = ON)

1. **Sample Rate:** The displayed sample rate is now 20 GS/s interpolated (IT) on two channels. The actual real-time sample rate must be 10 GS/s real-time on two channels based on:
    a. There is no available Real-Time (RT) sample rate at 2 GHz in this operating mode – only Interpolated (IT) sample rate. When the oscilloscope is adjusted to RT sample rate (available at 5 GS/s), the oscilloscope further bandwidth limits to 1 GHz. Thus, the RT sample rate cannot be 5 GS/s with 2 GHz bandwidth.
    b. Digital triggering requires a 5x SR:BW ratio to maintain proper operation of the digital triggering system. Thus, the real-time sample rate must be maintained at 10 GS/s.
2. **Bandwidth:** Unchanged at 2 GHz (compared to operating mode 3)
    a. However, there is likely a digital brick-wall bandwidth limit filter to eliminate noise and distortion that is present and not eliminated by a slower rolloff 2 GHz analog bandwidth limit (as in operating mode 3). Such a filter would presumably be performed digitally on 20 GS/s data. This would provide some additional noise and resolution improvement if noise and distortion was present at higher frequencies.
        i. Based on R&S 4 GHz ENOB performance, ENOB averages ~6.1 bits from 0-2 GHz and ~5.8 bits from 2 to 4 GHz
        ii. A 2 GHz brick-wall filter, as described, could be expected to improve the ENOB by 0.3 bits (the difference in average ENOB between the 0-2 GHz and 2-4 GHz frequency ranges).
3. **Resolution:** The displayed system resolution is 10 bits, but this would have to be considered a "round-up" from the best possible mathematical resolution of 9 bits.
    a. Mathematically, a halving of the sample rate and a halving of the bandwidth are essentially the same operation. Thus, no additional noise or resolution improvement

could be expected compared to operating mode 3. The noise (resolution) improvement that is achieved is likely due to a faster rolloff brick-wall bandwidth limit.

4. **Evidence:** There is a cumulative total 0.8 effective bit improvement (5.5 dB noise improvement) achieved from operating mode 2 to 4, slightly less than the theoretically possible 1.0 effective bit (6 dB SNR) improvement.

RTO2044 Operating Mode 5:

1 GHz Bandwidth, 4 Channels, 5 GS/s (RT) and 20 GS/s (IT), 10-bit Resolution, HD Mode = ON

1. **Sample Rate:** Reported as 5 GS/s real-time, and four channels at 5 GS/s each is still a total combined system sample rate of 20 GS/s.
2. **Bandwidth**: Halved compared to operating mode 4. The expectation would be a 3 dB reduction in noise and a 0.5 effective bit improvement (when combined with sample rate reduction).
3. **Resolution:** The displayed system resolution is 10 bits. This performance does match that of the 10-bit resolution Keysight DSOS-804A operated in 1.14 GHz High Resolution mode.
4. **Evidence:** A 2.0 dB improvement in baseline noise and a 0.4 effective bit improvement near DC is measured, consistent with the theoretical expectations.

RTO2044 Operating Mode 6:

500 MHz Bqndwidth, 4 Channels, 5 GS/s (RT) and 20 GS/s (IT), 12-bit Resolution, HD Mode = ON

1. **Sample Rate:** Reported as 5 GS/s real-time, but four channels at 5 GS/s each is still a total combined system sample rate of 20 GS/s. Thus, no noise reduction or effective bit improvement due to sample rate filtering should be expected compared to Operating Mode 5.
2. **Bandwidth**: Halved compared to operating mode 5. The expectation would be a 3 dB reduction in noise and a 0.5 effective bit improvement.
3. **Resolution:** Displayed system resolution is claimed as 12 bits. This does not credibly compare to what is provided by a Teledyne LeCroy 12-bit HD4096 technology oscilloscope.
4. **Evidence:** A 3.2 dB improvement in noise and a 0.3 effective bit improvement is measured.

Comparison to Teledyne LeCroy 12-bit Resolution HD4096 Technology Oscilloscopes

Table 5 shows data for the different Rohde & Schwarz RTO2044 operating modes described above. Areas of red shading indicate operating modes with excessive claims.

Rohde & Schwarz RTO2044 (4 GHz, 10 GS/s on 4 channels, 20 GS/s on 2 channels, 8-bit resolution)											
Operating Mode	HD Mode	Band-width	Available Channels	Displayed Sample Rate RT=Real-time, IT=Interpolated	Mathematically Possible Real-time Sample Rate	R&S Displayed System Resolution (Bits)	Effective Bits @ 50 mV/div	Cumulative Effective Bit Improvement	Measured Baseline Noise @ 50 mV/div	Signal to Noise Ratio @ 50 mV/div[3]	Cumulative Signal to Noise Ratio Improvement
1	OFF	4 GHz	4	10 GS/s RT	10 GS/s	8	6.3	-	1.77 mV	49.0 dB	
2	OFF	4 GHz	2	20 GS/s RT	20 GS/s	8	6.3	0	1.63 mV	49.7 dB	0.7 dB
3	OFF	2 GHz	2	20 GS/s RT	20 GS/s	8	6.8[1]	0.5	1.22 mV[2]	52.3 dB	3.3 dB
4	ON	2 GHz	2	20 GS/s IT[2]	10 GS/s	10	7.1	0.8	0.87 mV	55.2 dB	6.2 dB
5	ON	1 GHz	4	5 GS/s RT	5 GS/s	10	7.5	1.2	0.69 mV	57.2 dB	8.2 dB
6	ON	500 MHz	4	5 GS/s RT	5 GS/s	12†	7.8	1.5	0.48 mV	60.4 dB	11.4 dB

[1] Data provided by R&S. Other ENOB data as measured by Teledyne LeCroy to IEEE-1057 specifications for ENOB.

[2] Data taken from the R&S RTO Digital Oscilloscope Specifications datasheet

[3] Calculated on the basis of 10 vertical divisions for oscilloscope full scale

† R&S claimed system resolutions are not supported by their technical papers, and performance does not match industry competitors.

Table 5 - Rohde & Schwarz RTO2044 Performance by Operating Mode

The Teledyne LeCroy HDO4000A, HDO6000A, HDO8000A (350 MHz to 1 GHz) and WavePro HD products (2.5 GHz to 8 GHz) all utilize HD4096 technology for 12-bits all the time with no bandwidth, sample rate or channel count tradeoffs. ERES may also be used to increase resolution beyond 12-bits, but with bandwidth and sample rate tradeoffs. Table 6 displays the different operating modes of Teledyne LeCroy HD4096 technology (12-bit resolution) oscilloscopes, numbered to correlate with the closest equivalent R&S RTO2044 operating mode.

Teledyne LeCroy WavePro 404HD (4 GHz, 10 GS/s on 4 channels, 20 GS/s on 2 channels, 12-bit resolution), or Teledyne LeCroy HDO6104A or HDO6054A (1 GHz or 500 MHz, 10 GS/s ESR on 4 channels, 12-bit resolution)											
Operating Mode	High Definition Mode	Band-width	Available Channels	Displayed Sample Rate RT=Real-time, ESR = Enhanced Sample Rate	Mathematically Possible Real-time Sample Rate	Teledyne LeCroy Displayed System Resolution (Bits)	Effective Bits @ 50 mV/div	Cumulative Effective Bit Improvement	Measured Baseline Noise @ 50 mV/div	Signal to Noise Ratio @ 50 mV/div[1]	Cumulative Signal to Noise Ratio Improvement
1	HD4096 hardware tech-nology "always ON"	4 GHz	4	10 GS/s RT	10 GS/s	12	7.2		0.65 mV	55.8 dB	
2		4 GHz	2	20 GS/s RT	20 GS/s	12	7.5	0.3	0.56 mV	57.1 dB	1.3 dB
3		2.5 GHz	2	20 GS/s RT	20 GS/s	12	7.9	0.7	0.40 mV	60.0 dB	4.2 dB
4		2.5 GHz	4	10 GS/s RT	10 GS/s	12	7.5		0.47 mV	58.6 dB	
5		1 GHz	4	10 GS/s RT	10 GS/s	12	8.1	0.9	0.29 mV	62.8 dB	7 dB
5		1 GHz	4	10 GS/s ESR	2.5 GS/s	12	8.4		0.28 mV	62.8 dB	
6		500 MHz	4	10 GS/s RT	10 GS/s	12	8.5	1.3	0.21 mV	65.6 dB	9.8 dB
6		500 MHz	4	10 GS/s ESR	2.5 GS/s	12	8.6		0.25 mV	64.1 dB	

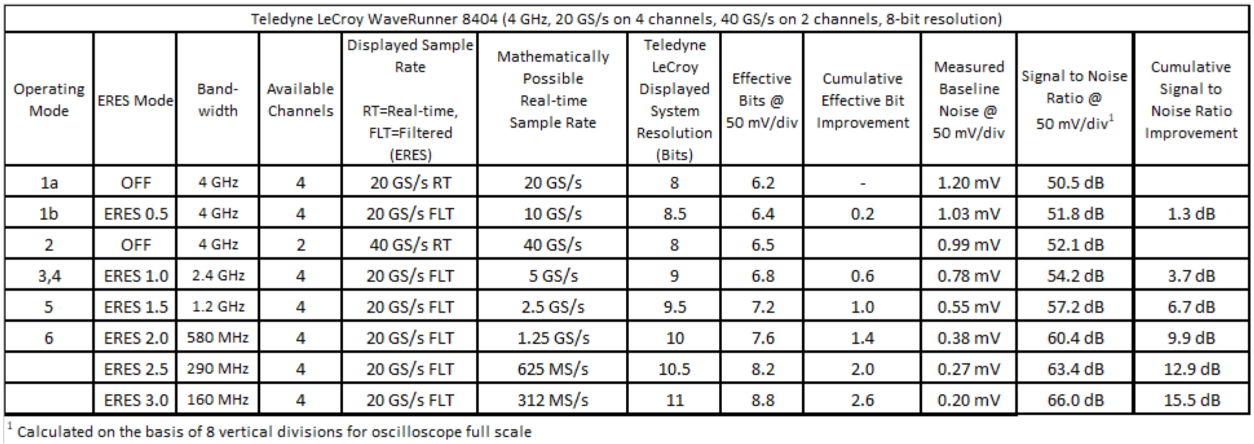
[1] Calculated on the basis of 8 vertical divisions for oscilloscope full scale

Table 6 - Teledyne LeCroy HD4096 Technology 12-bit Oscilloscope Performance Data

Note that while R&S shows a higher cumulative SNR improvement (11.4 dB) compared to Teledyne LeCroy (9.8 dB), it is only because they are beginning from an 8-bit resolution baseline and have more room to improve. The Teledyne LeCroy absolute SNR in this same operating mode (6) is 5.2 dB better than R&S.

Comparison to Teledyne LeCroy 8-bit Resolution WaveRunner 8404 (4 GHz) with ERES

The Teledyne LeCroy WaveRunner 8404 oscilloscope has 4 GHz bandwidth with 20 GS/s on all four channels. The WaveRunner 8404 (as do all Teledyne LeCroy oscilloscopes) provide capability to apply an enhanced resolution filter (ERes) to any or all channels. The ERES filter provides simple software moving average filtering to the sampled data with each halving of sample rate and bandwidth resulting in a theoretical 3 dB noise and 0.5 effective bit improvement. The selection is for improvement in bits of resolution, in 0.5 effective bit steps, up to 3 effective bits improvement. Table 7 displays the different operating modes numbered to correlate with the closest equivalent R&S RTO2044 operating mode.



Teledyne LeCroy WaveRunner 8404 (4 GHz, 20 GS/s on 4 channels, 40 GS/s on 2 channels, 8-bit resolution)

Operating Mode	ERES Mode	Band-width	Available Channels	Displayed Sample Rate RT=Real-time, FLT=Filtered (ERES)	Mathematically Possible Real-time Sample Rate	Teledyne LeCroy Displayed System Resolution (Bits)	Effective Bits @ 50 mV/div	Cumulative Effective Bit Improvement	Measured Baseline Noise @ 50 mV/div	Signal to Noise Ratio @ 50 mV/div[1]	Cumulative Signal to Noise Ratio Improvement
1a	OFF	4 GHz	4	20 GS/s RT	20 GS/s	8	6.2	-	1.20 mV	50.5 dB	
1b	ERES 0.5	4 GHz	4	20 GS/s FLT	10 GS/s	8.5	6.4	0.2	1.03 mV	51.8 dB	1.3 dB
2	OFF	4 GHz	2	40 GS/s RT	40 GS/s	8	6.5		0.99 mV	52.1 dB	
3,4	ERES 1.0	2.4 GHz	4	20 GS/s FLT	5 GS/s	9	6.8	0.6	0.78 mV	54.2 dB	3.7 dB
5	ERES 1.5	1.2 GHz	4	20 GS/s FLT	2.5 GS/s	9.5	7.2	1.0	0.55 mV	57.2 dB	6.7 dB
6	ERES 2.0	580 MHz	4	20 GS/s FLT	1.25 GS/s	10	7.6	1.4	0.38 mV	60.4 dB	9.9 dB
	ERES 2.5	290 MHz	4	20 GS/s FLT	625 MS/s	10.5	8.2	2.0	0.27 mV	63.4 dB	12.9 dB
	ERES 3.0	160 MHz	4	20 GS/s FLT	312 MS/s	11	8.8	2.6	0.20 mV	66.0 dB	15.5 dB

[1] Calculated on the basis of 8 vertical divisions for oscilloscope full scale

Table 7 - Teledyne LeCroy 8-bit Resolution, 4 GHz Bandwidth WaveRunner 8404 Performance Data

By comparing the effective bits and the measured RMS noise of the WaveRunner 8404 to the R&S RTO2044 in the various operating modes, it is easy to see that the 4 GHz, 8-bit resolution WaveRunner 8404 with ERES performs functionally the same (or slightly better) than the R&S RTO2044 with HD Modes ON. It should be noted that the ERES capability is standard in Teledyne LeCroy oscilloscopes whereas R&S charges extra for their HD Mode option, and that the bandwidth settings for the two oscilloscopes don't exactly correlate (Teledyne LeCroy provides more bandwidth with a commensurate noise increase). But the comparison does provide additional evidence that R&S HD Mode approach provides no benefits that are not already available in other 8-bit oscilloscopes and that the advertised R&S 12-bit resolution at 500 MHz is not a credible claim.

Comparison to Teledyne LeCroy - Summary

Figure 21 shows an SNR comparison for each operating mode described in Table 5, Table 6 and Table 7. The Teledyne LeCroy HD4096 12-bit resolution oscilloscopes show superior results in all operating modes, and the Teledyne LeCroy WaveRunner 8404 8-bit resolution oscilloscope shows comparable SNR performance when software (ERES) filters are used, especially when differences in bandwidth are accounted for.

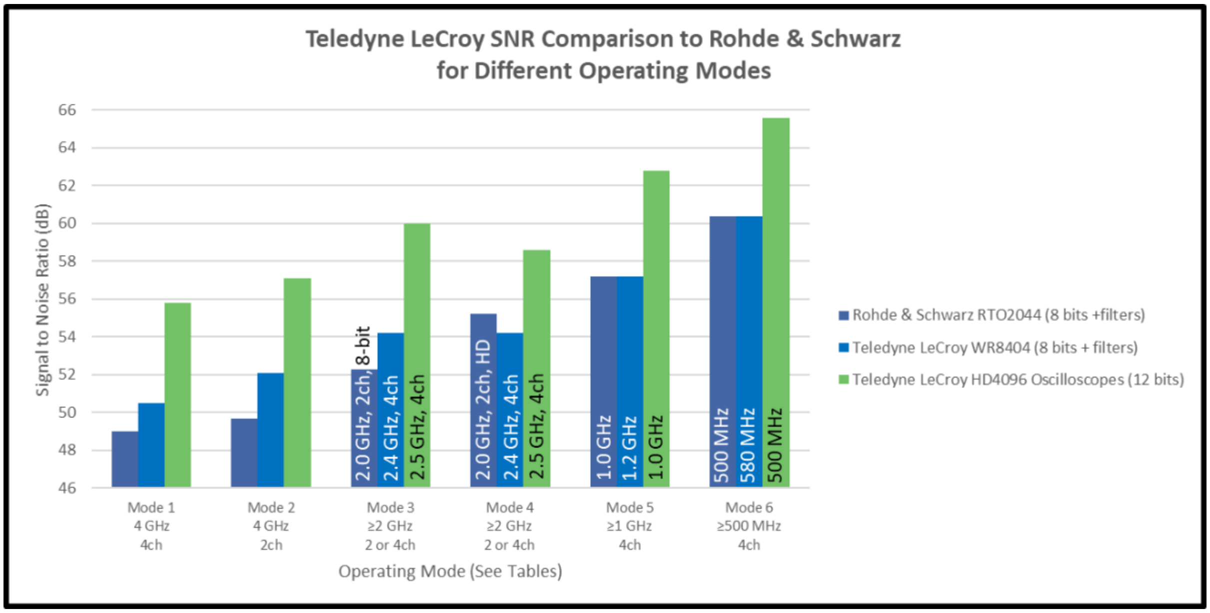


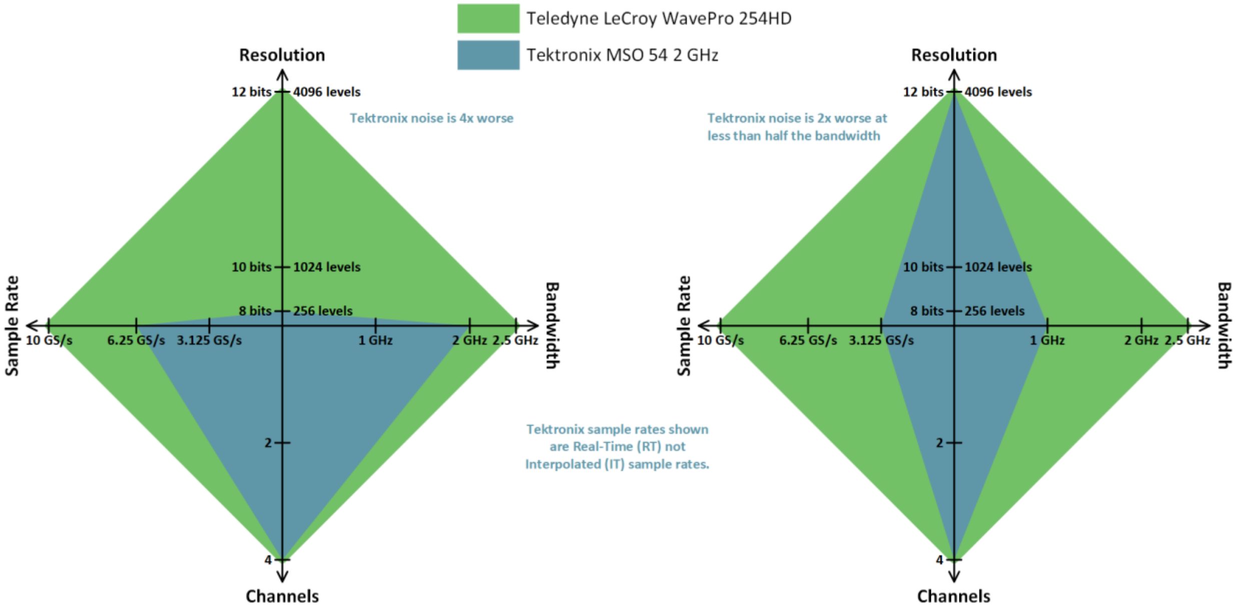
Figure 21 - Teledyne LeCroy and Rohde & Schwarz SNR comparison by operating mode

Conclusions

Figure 11 previously introduced a plot of typical oscilloscope system ENOB vs. bandwidth for 8-bit, 10-bit, and 12-bit resolution oscilloscope platforms. The performance of the RTO2044 when in HD Mode is slightly below the 10-bit resolution trendline, indicating performance somewhat below a 10-bit resolution oscilloscope, and substantially less than provided by 12-bit technologies (e.g., Teledyne LeCroy's HD4096 technology-based oscilloscopes). Performance at higher bandwidths (when the R&S oscilloscopes are not in high resolution mode) is consistent with an 8-bit oscilloscope performance. A direct comparison of the Teledyne LeCroy WaveRunner 8404 with and without software filtering for noise reduction provides further evidence that the performance of the R&S oscilloscopes is basically that of an 8-bit oscilloscope with an added cost software option to provide simple software filtering – something that Teledyne LeCroy oscilloscopes provide at no added charge.

Tektronix

Tektronix was the last major oscilloscope manufacturer to release a product— the 5 Series MSO — with claims of high resolution performance. This product is available with up to 8 channels, 2 GHz bandwidth and 6.25 GS/s real-time sample rate, and it claims to use a 12-bit ADC. The caveats on this oscilloscope are endless: the default resolution is 8-bits, even though Tektronix claims it uses a 12-bit ADC; at 3.125 GS/s or less it defaults to 12-bit mode, but with an aliased bandwidth of 2 GHz; if a special "High Res" mode is entered, bandwidth is limited to 1 GHz, sample rate defaults to 3.125 GS/s (though a 6.25 GS/s or higher interpolated "IT" sample rate mode may occur, as well) and resolution is indicated as 12 bits (though noise performance is consistent with an 8-bit oscilloscope). Up to 16-bit resolution is claimed through the use of additional software filters. Realistically, the noise performance of this oscilloscope series is nowhere near even the better performing 10-bit oscilloscopes (Keysight S-Series, Teledyne LeCroy HDO9000 Series), and is exceeded by some 8-bit oscilloscopes (e.g. Teledyne LeCroy WaveRunner 8404) and claims of 12-bit performance should be taken lightly. Based on manufacturer claims, this oscilloscope is representative of Design Approaches 1 and 2, but the performance is more like a poorly implemented Design Approach 1. Refer to Figure 22.



Tektronix noise is 4x worse

Tektronix noise is 2x worse at less than half the bandwidth

Tektronix sample rates shown are Real-Time (RT) not Interpolated (IT) sample rates.

Figure 22 - Tektronix MSO 54 Series with 2 GHz bandwidth compared to Teledyne LeCroy WavePro 254HD. Note how the Tektronix oscilloscope does not deliver rated resolution at rated bandwidth, and also suffers from bandwidth reduction in high resolution mode.

More recently, Tektronix has announced the 6 Series oscilloscopes. These oscilloscopes essentially use the same design approach as the 5 Series but with what appears to be an improved front-end amplifier with more bandwidth and more ADCs. When this product begins shipping, an evaluation of actual performance can be done.

What Tektronix Says about the 5 Series

Tektronix's marketing material indicates two key vertical resolution specifications:

- 12-bit ADC
- Up to 16 bits in High Res mode

Their datasheet specifications indicate vertical resolution of 8 bits at 6.25 GS/s (the full, all channel sample rate), 12 bits at 3.125 GS/s in High Res mode, 13 bits at 1.25 GS/s in High Res mode, and an additional bit of resolution for each further halving of sample rate.

ENOB is specified separately for 2 GHz and <2 GHz models. ENOB is listed as 7.0 at 1 GHz in High Res mode, and there is explicitly no specification for ENOB during 2 GHz operation. ENOB is specified as 7.6 for 1 GHz models when operated in 1 GHz High Res mode (which requires 3.125 GS/s sample rate). ENOB is specified as 7.9 and 8.2 for 500 MHz and 350 MHz models, respectively.

Examining the Tektronix MSO 5 Series Claims

The detail of the bandwidth, sample rate, resolution and ENOB/noise tradeoffs are deep in the 5 Series datasheet. The advertised banner specs on page 2 indicate maximum bandwidth of 2 GHz, real-time sample rate of 6.25 GS/s, 12-bit ADC with up to 16 bits in High Res mode, and no mention of ENOB or noise performance. The clear implication is that:

- All of the banner specs can be achieved at the same time (they cannot)
- The oscilloscope has low noise performance, consistent with 12-bit resolution (it does not)

Given that Tektronix was last to the market with a high resolution oscilloscope, it is easy to understand that the Tek MSO 5 Series marketing materials needed to:

- Indicate “12 bit” to have a message against Teledyne LeCroy
- Indicate “up to 16 bits” to have a message against Rohde & Schwarz
- Not overtly promise low noise performance since the performance is not what most would consider low noise.

The overall operation of the oscilloscope to achieve high resolution operation is somewhat confusing. High Res mode is activated through a front panel button. Resolution is indicated through an on-screen display, and the indicated resolution changes from 8 bits to 12 bits as sample rate is reduced from 6.25 GS/s to 3.125 GS/s, though in some instances bandwidth remains at 2 GHz (for the 2 GHz model), which results in an aliased signal. Bandwidth is reduced to 1 GHz when the oscilloscope is put in High Res mode, with corresponding sample rate reduction to 3.125 GS/s. In some High Res operating cases, sample rate will remain at 6.25 GS/s and is indicated as interpolated (IT) sampling mode. There are several different controls in the Horizontal pop-up setup dialog that interact with each other in confusing ways, making it difficult to attain the desired resolution and sample rate in an easily understandable way. Sample rate cannot be interleaved from two channels to one to obtain higher real-time sample rate.

We’ve operated the Tektronix 5 Series at several different bandwidth, sample rate and High Resolution Mode settings (referred to as Operating Modes 1 through 5) with each operating mode equating to the application of one or more filtering techniques to achieve higher resolution. The data is summarized in Table 8 (following the descriptions of the operating modes). The various operating modes are described below.

Tektronix MSO 54 2 GHz Model Operating Mode 1 and 2:
2 GHz Bandwidth, 4 Channels, 6.25 GS/s (RT), 8-bit Resolution

1. **Sample Rate:** The maximum 6.25 GS/s real-time (RT) sample rate on all 4 channels indicates a total combined system capability of 4 x 6.25 GS/s = 25 GS/s
2. **Resolution:** The displayed system resolution of 8 bits is consistent with their datasheet, but it is unusual that a purported 12-bit ADC would operate in an 8-bit mode.
3. **Evidence:** Tektronix doesn't report data on ENOB at 2 GHz in this operating mode. Teledyne LeCroy measures 6.3 ENOB – consistent with 8-bit resolution.

Tektronix MSO 54 2 GHz Model Operating Mode 3:
2 GHz Bandwidth, 4 Channels, 3.125 GS/s (RT), 12-bit Resolution

1. **Sample Rate:** The 3.125 GS/s real-time (RT) sample rate on all 4 channels indicates that sample rate has been halved, but without a corresponding halving of the bandwidth. The oscilloscope is operating in an undersampled and aliased mode.
2. **Bandwidth:** Bandwidth is not halved with sample rate, as would be required to achieve a noise reduction and resolution improvement.
3. **Resolution:** The displayed system resolution is 12 bits but the noise performance is the same as Operating Mode 2, which is described as 8 bits.
4. **Evidence:** Tektronix doesn't report data on ENOB in this operating mode. Teledyne LeCroy measures 6.3 ENOB — unchanged from previous operating mode. Likewise, baseline noise SNR is only slightly (0.6 dB) improved. All this indicates that nothing was substantially done to improve the performance from 8-bit to 12-bit resolution, despite the on-screen indication of 12-bit resolution.

Tektronix MSO 54 2 GHz Model Operating Mode 4:
1 GHz Bandwidth, 4 Channels, 3.125 GS/s (RT), 12-bit Resolution

1. **Sample Rate:** The 3.125 GS/s real-time (RT) sample rate on all 4 channels is unchanged from the previous operating mode 2.
2. **Bandwidth:** Bandwidth is halved, consistent with a sample rate that would prevent aliasing. With this halving of bandwidth, we expect a 3 dB noise and 0.5 effective bit improvement. In fact, we observe slightly more improvement, likely due to a boosted front-end amplifier response above 1 GHz (which is now attenuated by the bandwidth limit filter).
3. **Resolution:** The displayed system resolution of 12 bits is not consistent with noise performance for a 12-bit resolution, 1 GHz bandwidth oscilloscope.
4. **Evidence:** Tektronix reports data on ENOB for the 2 GHz model and <2 GHz models in this operating mode. The 2 GHz model operating in this model has a Tektronix reported value of 7.0 effective bits (measured by Teledyne LeCroy as 6.8), which is about 1.5 effective bits lower (9 dB worse SNR) than would be expected for a 12-bit oscilloscope. The 1 GHz model operating in this mode has a Tektronix reported value of 7.6 effective bits, which is about 1 effective bit worse than would be expected. While SNR and ENOB are slightly improved from the previous 2 GHz bandwidth operating modes, the improvement is not enough to justify a claim of 12-bit resolution.

Tektronix MSO 54 2 GHz Model Operating Mode 5:

500 MHz Bandwidth, 4 Channels, 1.5625 GS/s (RT), 13-bit Resolution

1. **Sample Rate:** The 1.5625 GS/s real-time (RT) sample rate on all 4 channels is halved compared to the previous operating mode 3.
2. **Bandwidth:** Bandwidth is halved, consistent with a sample rate that would prevent aliasing. With this halving of bandwidth, we expect a 3 dB noise and 0.5 effective bit improvement. In fact, we observe slightly less improvement (2.1 dB SNR and 0.3 effective bits).
3. **Resolution:** The displayed system resolution of 13 bits is not consistent with noise performance for a 13-bit resolution, 500 MHz bandwidth oscilloscope.
4. **Evidence:** Tektronix does not report data on ENOB for the 2 GHz model in this mode, but does report data for the <2 GHz models in this operating mode. We measure 6.8 effective bits for the 2 GHz model, which is about 1.5 effective bits lower (9 dB worse SNR) than would be expected for a 12-bit oscilloscope. The 1 GHz model operating in this mode has a Tektronix reported value of 7.9 effective bits, which is about 1 effective bit worse tha would be expected. While SNR and ENOB are slightly improved from the previous 1 GHz bandwidth operating modes, the improvement is not enough to justify a claim of 13-bit resolution.

Comparison to Teledyne LeCroy 12-bit Resolution HD4096 Techology Oscilloscopes

Table 8 shows data for the different Tektronix MSO 54 oscilloscope operating modes described above. Areas of yellow shading indicate odd behaviors for an oscilloscope with claims to use a 12-bit ADC, and areas of red shading indicate operating modes with excessive claims.

Tektronix MSO 54 (2 GHz, 6.25 GS/s on 4 channels, 12-bit ADC)										
Operating Mode	High-Resolution Mode	Band-width	Available Channels	Displayed Sample Rate RT=Real-time	Tektronix Displayed System Resolution (Bits)	Effective Bits @ 50 mV/div	Cumulative Effective Bit Improvement	Measured Baseline Noise @ 50 mV/div	Signal to Noise Ratio @ 50 mV/div[1]	Cumulative Signal to Noise Ratio Improvement
1	Automatic	2 GHz	4	6.25 GS/s RT	8	6.3		1.86 mV	48.6 dB	
2	Automatic	2 GHz	4	6.25 GS/s RT	8	6.3		1.86 mV	48.6 dB	
3	Automatic	2 GHz	4	3.125 GS/s RT	12[†]	6.3		1.73mV	49.2 dB	0.6 dB
4	High Res	1 GHz	4	3.125 GS/s RT	12[†]	6.8	0.5	1.17 mV	52.6 dB	4.0 dB
5	High Res	500 MHz	4	1.5625 GS/s RT	13[†]	7.1	0.8	0.92 mV	54.7 dB	6.1 dB

[1] Calculated on the basis of 10 vertical divisions for oscilloscope full scale

[†] Tektronix claimed system resolution and performance do not match industry competitors

Table 8 - Tektronix 5 Series 2 GHz Model Performance Data

The Teledyne LeCroy HDO4000A, HDO6000A, HDO8000A (350 MHz to 1 GHz) and WavePro HD products (2.5 GHz to 8 GHz models) all utilize HD4096 technology for 12-bits all the time with no bandwidth, sample rate or channel count tradeoffs. ERES may also be used to increase resolution beyond 12-bits, but with bandwidth and sample rate tradeoffs. Table 9 displays the different operating modes numbered to correlate with the closest equivalent Tektronix MSO 54 operating mode.

Teledyne LeCroy WavePro HD Series (2.5 GHz, 10 GS/s on 4 channels, 20 GS/s on 2 channels, 12-bit resolution) Teledyne LeCroy HDO6104A or HDO6054A (1 GHz or 500 MHz, 10 GS/s ESR on 4 channels, 12-bit resolution)										
Operating Mode	High Definition Mode	Band-width	Available Channels	Displayed Sample Rate RT=Real-time, ESR = Enhanced Sample Rate	Teledyne LeCroy Displayed System Resolution (Bits)	Effective Bits @ 50 mV/div	Cumulative Effective Bit Improvement	Measured Baseline Noise @ 50 mV/div	Signal to Noise Ratio @ 50 mV/div[1]	Cumulative Signal to Noise Ratio Improvement
1	HD4096 hardware technology "always ON"	2.5 GHz	2	20 GS/s RT	12	7.9		0.40 mV	60.0 dB	
2		2.5 GHz	4	10 GS/s RT	12	7.5		0.47 mV	58.6 dB	
3		2.5 GHz	4	10 GS/s RT	12	7.5		0.47 mV	58.6 dB	
4		1 GHz	4	10 GS/s RT	12	8.1	0.6	0.29 mV	62.8 dB	4.2 dB
4		1 GHz	4	10 GS/s (ESR)	12	8.4		0.28 mV	62.8 dB	
5		500 MHz	4	10 GS/s RT	12	8.5	1.0	0.21 mV	65.6 dB	7.0 dB
5		500 MHz	4	10 GS/s (ESR)	12	8.6		0.25 mV	64.1 dB	

[1] Calculated on the basis of 8 vertical divisions for oscilloscope full scale

Table 9 - Teledyne LeCroy HD4096 12-bit Oscilloscope Performance Data

Figure 23 shows an SNR comparison for each operating mode in Table 8 and Table 9. The Teledyne LeCroy HD4096 12-bit resolution oscilloscopes show superior results in all operating modes.

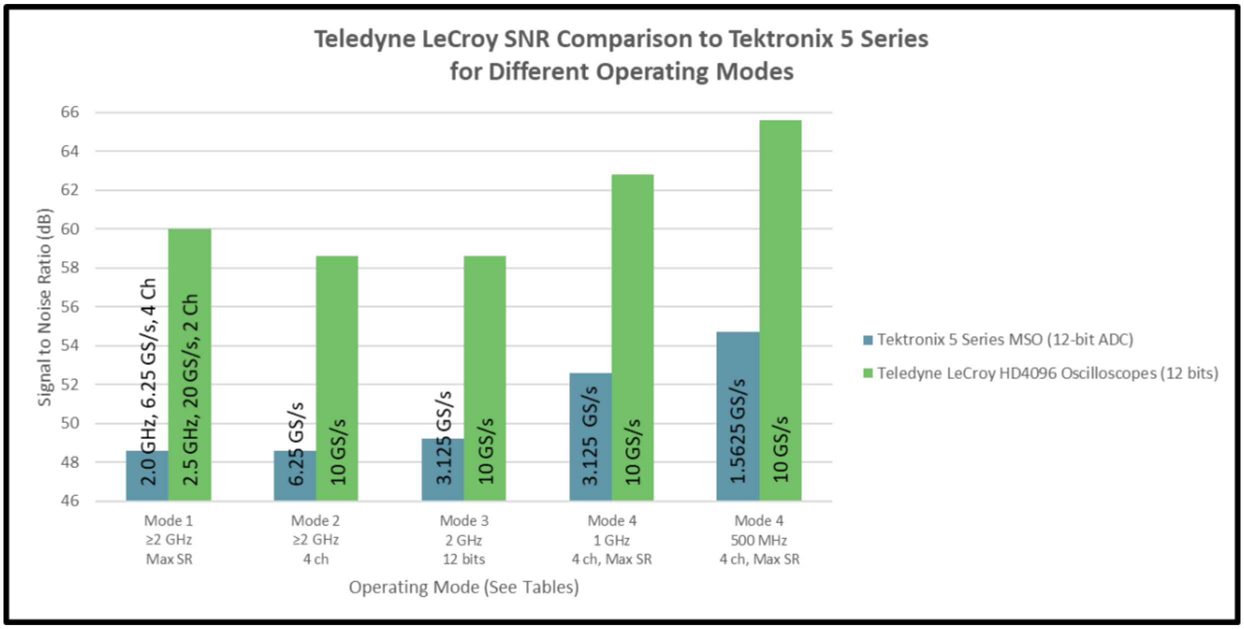


Figure 23 - Teledyne LeCroy and Tektronix SNR comparison by operating mode

Conclusions

Figure 11 previously introduced a plot of typical oscilloscope system ENOB vs. bandwidth for 8-bit, 10-bit, and 12-bit resolution oscilloscope platforms. The performance of the Tektronix MSO 54 2 GHz oscilloscope when in High Resolution mode is consistent with the performance of an 8-bit resolution oscilloscope, and substantially less than provided by 12-bit technologies (e.g., Teledyne LeCroy's HD4096 technology-based oscilloscopes).

Summary of Oscilloscopes and Design Approaches Used

Table 10 shows how each oscilloscope manufacturer and product line uses hardware or software to achieve high resolution. It is based on manufacturer's claims (however dubious), published datasheets, and technical articles. Table 10 follows the same "Design Approach" format described in Table 1.

		High Resolution Hardware		
		No High Resolution Components	**High Resolution ADC**	**Low-noise Front End High Resolution ADC Low-noise System Architecture**
Software Post-processing	**None**	**Conventional 8-bit oscilloscopes**		**Teledyne LeCroy HDO4000A** **Teledyne LeCroy HDO6000A** **Teledyne LeCroy HDO8000A** **Teledyne LeCroy WavePro HD**
	Some	**Keysight 9000H Series** **Rohde & Schwarz RTE1000** **Rohde & Schwarz RTO2000** **Rohde & Schwarz RTP Series**	**Keysight S-Series (10-bit)** **Tektronix 5 Series (12-bit)**[1] **Teledyne LeCroy HDO9000**[2]	**With Enhanced Resolution ON** **Teledyne LeCroy HDO4000A** **Teledyne LeCroy HDO6000A** **Teledyne LeCroy HDO8000A** **Teledyne LeCroy WavePro HD**

Table 10 - Hardware and software post-processing approaches to high resolution used by various oscilloscope manufacturers

[1] Baseline noise performance does not match claims about ADC resolution

[2] 8-bit ADC that is dynamically configured to 10 bits in HD modes

Oscilloscope High Resolution Detailed Comparisons

Two fairly simple tests can reveal the basic noise performance of the oscilloscope—a baseline noise test and an NRZ serial data eye diagram.

Teledyne LeCroy has two high definition oscilloscope product lines:

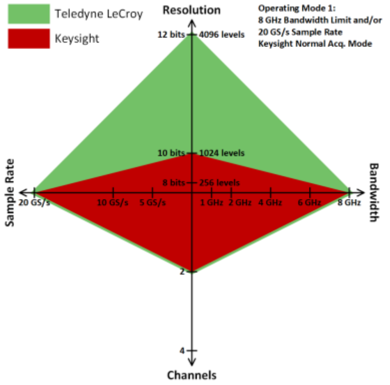
- The 12-bit resolution HDO Series, available from 350 MHz to 1 GHz and from 4 to 8 channels
- The 12-bit resolution WavePro HD Series, available from 2.5 to 8 GHz

The tables below compare the Teledyne LeCroy WavePro HD Series and Teledyne LeCroy HDO Series to similar bandwidth high resolution oscilloscopes from other vendors. Both product series use similar HD4096 technology and also provide 12-bit resolution all the time. Because the bandwidth is lower on the HDO Series oscilloscopes, the noise performance (baseline noise, ENOB) is better, and the presence of 12-bit hardware (front-end amplifier, high resolution ADC and low-noise system architecture) becomes even more important.

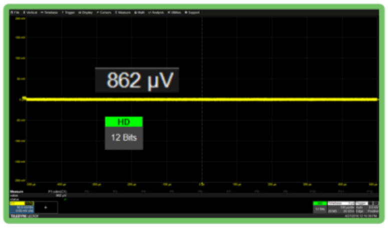
All tables contain a radar graph of the resolution, bandwidth, number of channels and sample rate performance for a given configuration, followed by an image of each oscilloscope display in that configuration. The oscilloscopes are operated under identical conditions (sample rate, bandwidth, input coupling, etc.) and represent what a knowledgeable engineer with a thorough operating knowledge of each oscilloscope would be able to achieve (i.e., they do not represent a best-case condition for one vendor versus a worst-case condition for another vendor). Display comparisons are created to be as equivalent as possible (e.g., equivalent waveform trace intensity settings), so that there is no visual difference that is not due solely to the oscilloscope's performance. From the data, it is easy to observe the performance tradeoffs that occur as resolution is increased on some oscilloscopes.

Teledyne LeCroy WavePro HD vs. Keysight S-Series

Baseline Noise Performance



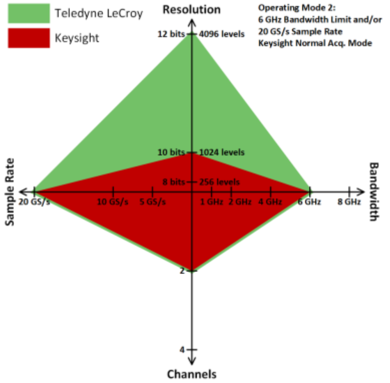
Teledyne LeCroy WavePro 804HD @ 8 GHz



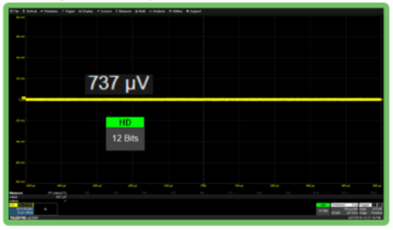
12-bit resolution

Keysight DSOS804A @ 8 GHz

10-bit resolution



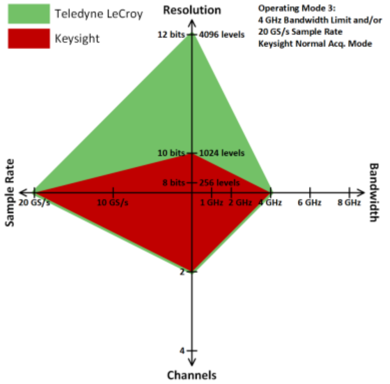
Teledyne LeCroy WavePro 804HD @ 6 GHz



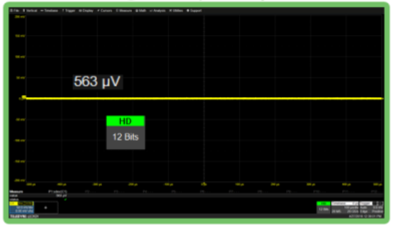
12-bit resolution

Keysight DSOS804A @ 6 GHz

10-bit resolution



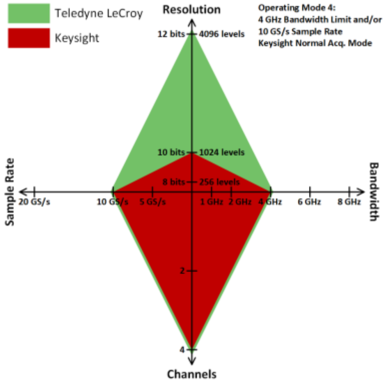
Teledyne LeCroy WavePro 804HD @ 4 GHz, 20 GS/s



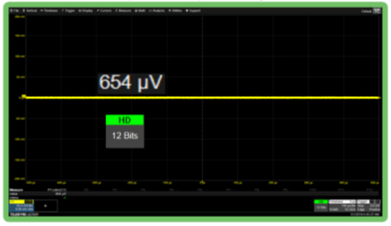
12-bit resolution

Keysight DSOS804A @ 4 GHz, 20 GS/s

10-bit resolution



Teledyne LeCroy WavePro 804HD @ 4 GHz, 10 GS/s



12-bit resolution

Keysight DSOS804A @ 4 GHz, 10 GS/s

10-bit resolution

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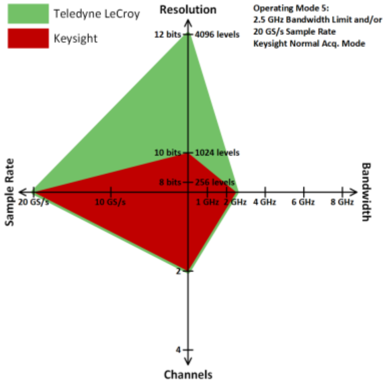

Operating Mode 5:
2.5 GHz Bandwidth Limit and/or
20 GS/s Sample Rate
Keysight Normal Acq. Mode
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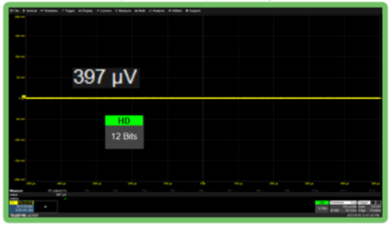
<td>
Teledyne LeCroy WavePro 804HD
@ 2.5 GHz, 20 GS/s



397 µV

HD
12 Bits

12-bit resolution
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<td>
Keysight DSOS804A @ 2.5 GHz, 20 GS/s

683.57 µV

10-bit resolution
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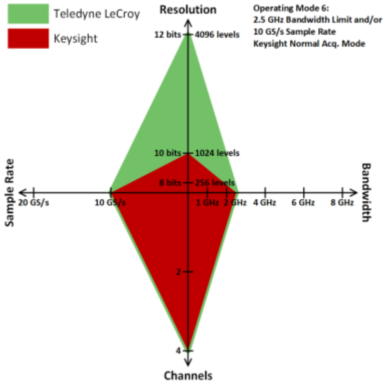

Operating Mode 6:
2.5 GHz Bandwidth Limit and/or
10 GS/s Sample Rate
Keysight Normal Acq. Mode
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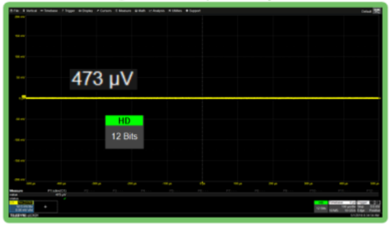
Teledyne LeCroy WavePro 804HD
@ 2.5 GHz, 10 GS/s



473 µV

HD
12 Bits

12-bit resolution
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Keysight DSOS804A @ 2.5 GHz, 10 GS/s

694.87 µV

10-bit resolution
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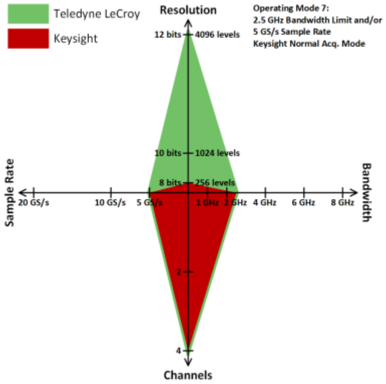

Operating Mode 7:
2.5 GHz Bandwidth Limit and/or
5 GS/s Sample Rate
Keysight Normal Acq. Mode
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<td>
Teledyne LeCroy WavePro 804HD
@ 2.5 GHz, 5 GS/s

453 µV

HD
12 Bits

12-bit resolution
</td>
<td>
Keysight DSOS804A @ 2.5 GHz, 5 GS/s

981.822 µV

Bits of Resolution 8 bits
Chan 1 Scope BW 2.50 GHz

8-bit resolution
It’s unknown why the scope reverts to 8-bits.
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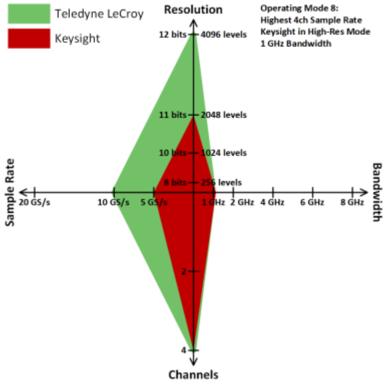

Operating Mode 8:
Highest 4ch Sample Rate
Keysight in High-Res Mode
1 GHz Bandwidth
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<td>
Teledyne LeCroy WavePro 804HD
@ 1 GHz, 10 GS/s

292 µV

HD
12 Bits

12-bit resolution
</td>
<td>
Keysight DSOS804A @ 1.14 GHz,
5 GS/s, Hi-Res

553.262 µV

Bits of Resolution 11 bits
Chan 1 Scope BW 1.14 GHz

11-bit resolution (claimed) with software post-processing, loss of bandwidth
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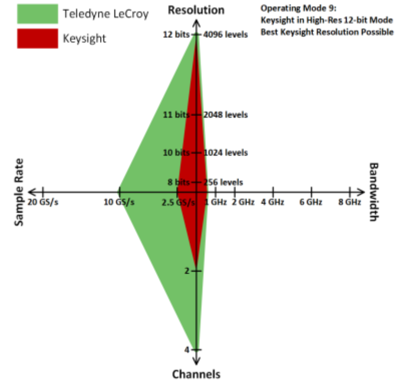
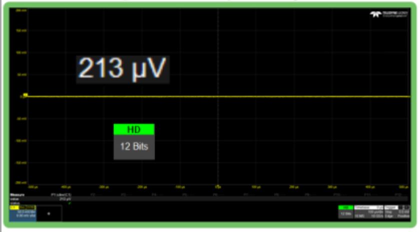


Teledyne LeCroy WavePro 804HD @ 500 MHz, 10 GS/s



213 µV

HD

12 Bits

12-bit resolution
WavePro HD has less noise, more sample rate, and twice the number of channels

Keysight DSOS804A 558 MHz, 2.5 GS/s, Hi-Res

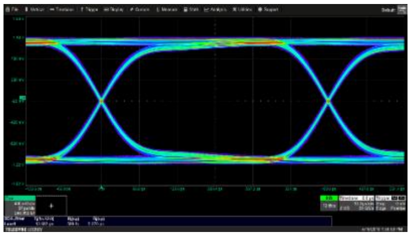
432.555 µV

Bits of Resolution 12 bits

Chan 1 Scope BW 558 MHz

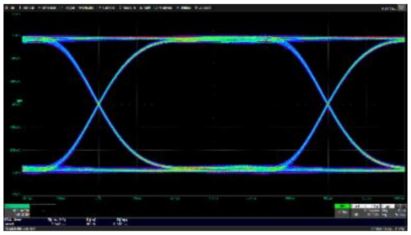
12-bit resolution (claimed) with software post-processing, loss of bandwidth and channels

Eye Diagram



12-bit resolution
2.5 Gb/s PRBS-7 pattern
Rj = 599 fs, Dj = 5.270 ps,
Tj = 13.692 ps

10-bit resolution
2.5 Gb/s PRBS-7 pattern
Rj = 720 fs, Dj = 8.55 ps,
Tj = 18.69 ps

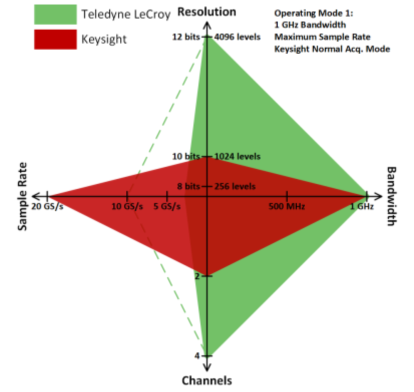


12-bit resolution
1.25 Gb/s PRBS-7 pattern
Rj = 661 fs, Dj = 10.352 ps,
Tj = 19.643 ps

10-bit resolution
1.25 Gb/s PRBS-7 pattern
Rj = 860 fs, Dj = 12.63 ps,
Tj = 24.70 ps

Teledyne LeCroy HDO4104A and HDO6104A vs. Keysight S-Series

Baseline Noise Performance

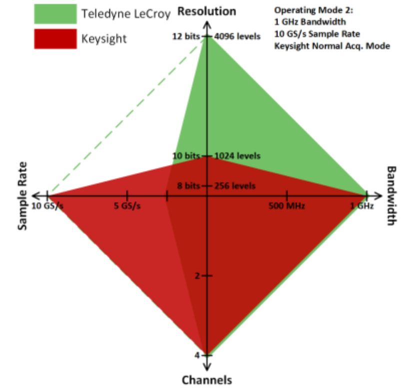


Teledyne LeCroy HDO6104A, 1 GHz, 10 GS/s

12-bit resolution

Keysight DSOS104A 1 GHz, 20 GS/s, 10 bits

10-bit resolution

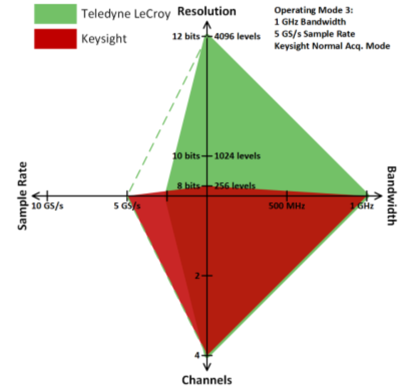


Teledyne LeCroy HDO6104A, 1 GHz, 10 GS/s

12-bit resolution

Keysight DSOS104A 1 GHz, 10 GS/s, 10 bits

10-bit resolution

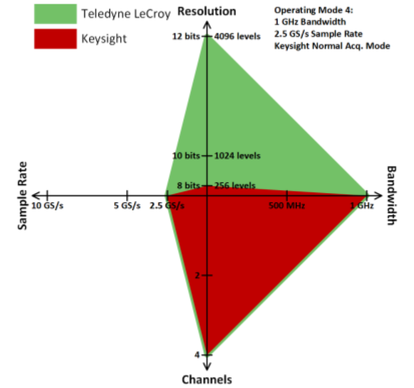


Teledyne LeCroy HDO6104A, 1 GHz, 5 GS/s

12-bit resolution

Keysight DSOS104A 1 GHz, 5 GS/s, 8 bits

8-bit resolution

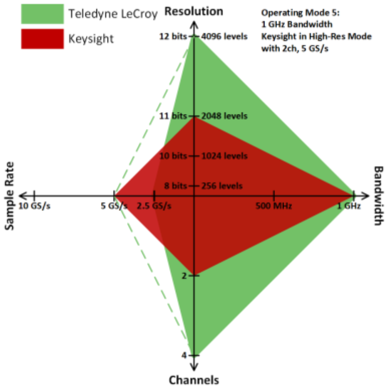


Teledyne LeCroy HDO6104A, 1 GHz, 2.5 GS/s

12-bit resolution

Keysight DSOS104A 1 GHz, 2.5 GS/s, 8 bits

8-bit resolution



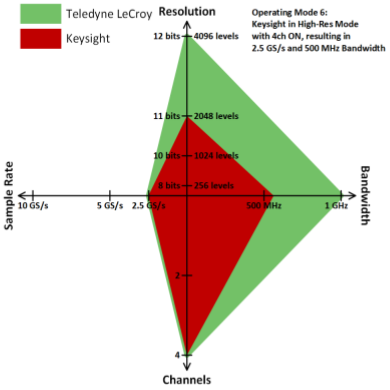
Operating Mode 5:
1 GHz Bandwidth
Keysight in High-Res Mode
with 2ch, 5 GS/s

Teledyne LeCroy
HDO6104A, 1 GHz, 5 GS/s

12-bit resolution

Keysight DSOS104A 1 GHz, 5 GS/s, 11 bits

11-bit resolution (claimed)



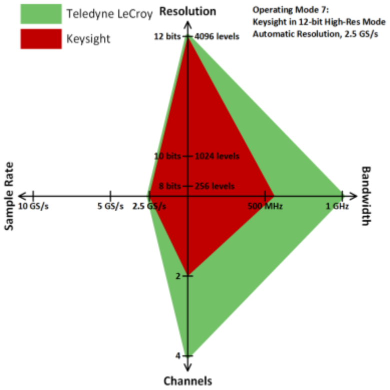
Operating Mode 6:
Keysight in High-Res Mode
with 4ch ON, resulting in
2.5 GS/s and 500 MHz Bandwidth

Teledyne LeCroy
HDO6104A, 1 GHz, 2.5 GS/s

12-bit resolution

Keysight DSOS104A 500MHz, 2.5 GS/s, 11 bits

11-bit resolution (claimed)



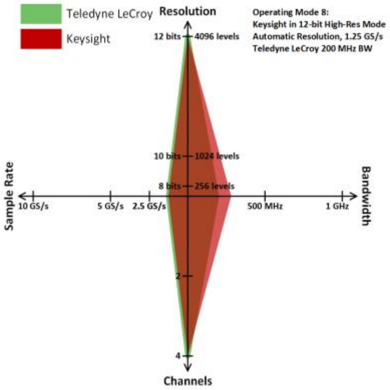
Operating Mode 7:
Keysight in 12-bit High-Res Mode
Automatic Resolution, 2.5 GS/s

Teledyne LeCroy
HDO6104A, 1 GHz, 2.5 GS/s

12-bit resolution

Keysight DSOS104A 500 MHz, 2.5 GS/s, 12 bits

12-bit resolution (claimed)



Operating Mode 8:
Keysight in 12-bit High-Res Mode
Automatic Resolution, 1.25 GS/s
Teledyne LeCroy 200 MHz BW

Teledyne LeCroy
HDO6104A, 200 MHz, 1.25 GS/s

12-bit resolution

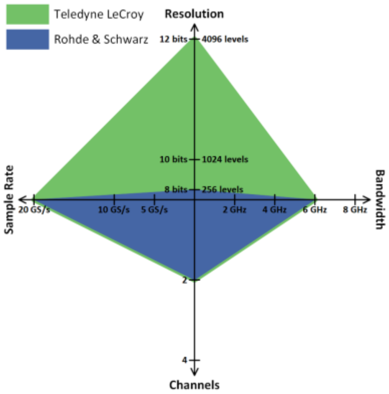
Keysight DSOS104A 277 MHz,
1.25 GS/s, 12 bits

12-bit resolution (claimed)

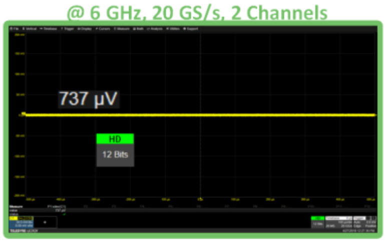
Teledyne LeCroy WavePro HD vs. Rohde & Schwarz RTO2044

Baseline Noise Performance

H



Teledyne LeCroy WavePro 804HD @ 6 GHz, 20 GS/s, 2 Channels

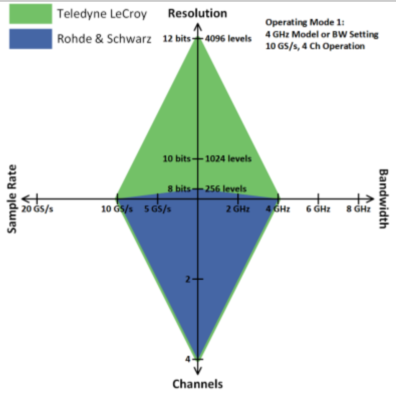


12-bit resolution

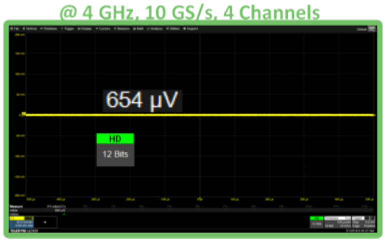
Rohde & Schwarz RTO2000 Series @ 6 GHz, 20 GS/s, 2 Channels

No screen image available. Datasheet specification for this operating condition is **1.96 mV**

8-bit resolution

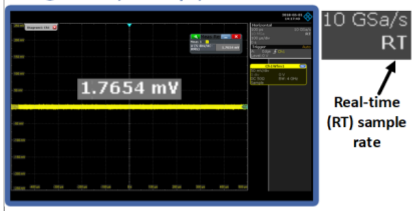


Teledyne LeCroy WavePro 804HD @ 4 GHz, 10 GS/s, 4 Channels



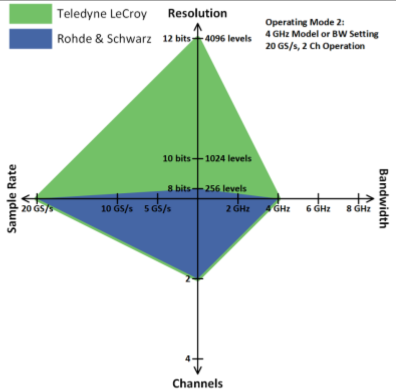
12-bit resolution

Rohde & Schwarz RTO2000 Series @ 4 GHz, 10 GS/s, 4 Channels

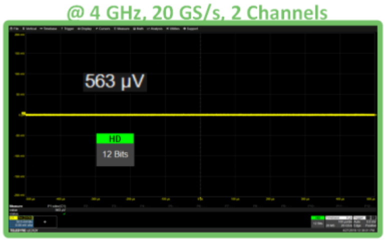


Real-time (RT) sample rate

8-bit resolution

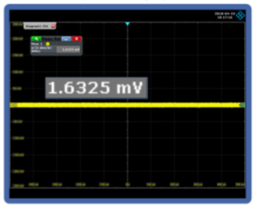


Teledyne LeCroy WavePro 804HD @ 4 GHz, 20 GS/s, 2 Channels

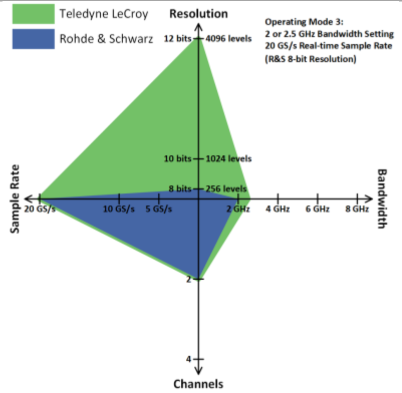


12-bit resolution

Rohde & Schwarz RTO2044 @ 4 GHz, 20 GS/s, 2 Channels

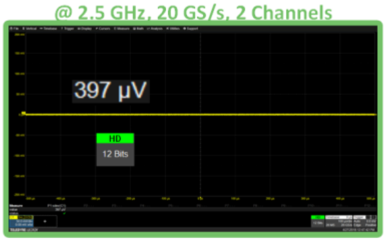


8-bit resolution



Operating Mode 3:
2 or 2.5 GHz Bandwidth Setting
20 GS/s Real-time Sample Rate
(R&S 8-bit Resolution)

Teledyne LeCroy WavePro 404HD
@ 2.5 GHz, 20 GS/s, 2 Channels

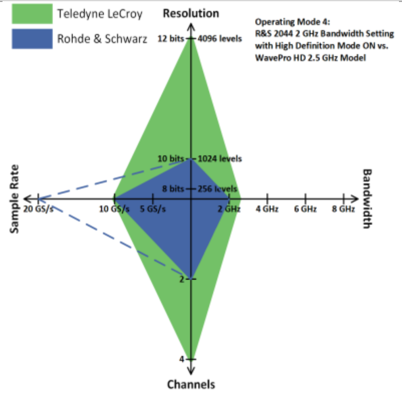


12-bit resolution

Rohde & Schwarz RTO2044
@ 2 GHz, 20 GS/s, 2 Channels

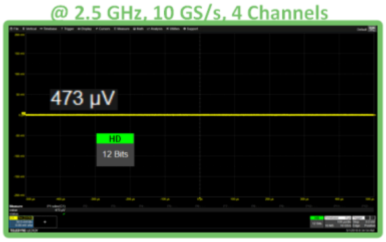
No screen image available.
Datasheet specification for
this operating condition is
1.22 mV

8-bit resolution



Operating Mode 4:
R&S 2044 2 GHz Bandwidth Setting
with High Definition Mode ON vs.
WavePro HD 2.5 GHz Model

Teledyne LeCroy WavePro 804HD
@ 2.5 GHz, 10 GS/s, 4 Channels

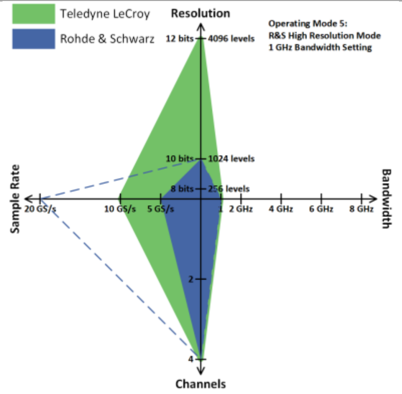


Rohde & Schwarz RTO2000 Series
@ 2 GHz, 20 GS/s (IT mode), 2 Channels

Interpolation (IT) Sampling Mode. Real-time Sample Rate of 5 GS/s will lower the bandwidth to 1 GHz with 2 channel operation.

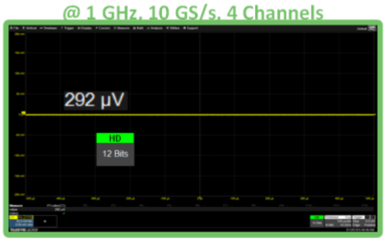
RMS (Baseline) Noise datasheet specification for 2 GHz RTO2024 at 50 mV/div = **1.22 mV**

10-bit resolution (claimed)



Operating Mode 5:
R&S High Resolution Mode
1 GHz Bandwidth Setting

Teledyne LeCroy WavePro 404HD
@ 1 GHz, 10 GS/s, 4 Channels

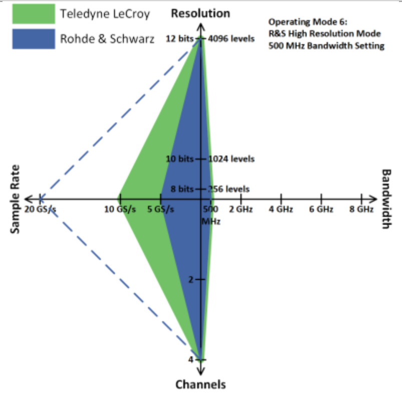


12-bit resolution

Rohde & Schwarz RTO2044
@ 1 GHz, 5 GS/s, 4 Channels, 10 bits

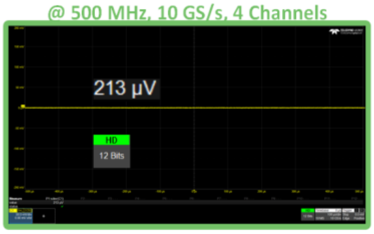
Interpolation (IT) Sampling Mode. Real-time Sample Rate is claimed as 5 GS/s, but this does not logically follow from their white paper. More likely, the real-time SR is 2.5 GS/s and 5 GS/s is interpolated.

10-bit resolution (claimed)



Operating Mode 6:
R&S High Resolution Mode
500 MHz Bandwidth Setting

Teledyne LeCroy WavePro 404HD
@ 500 MHz, 10 GS/s, 4 Channels



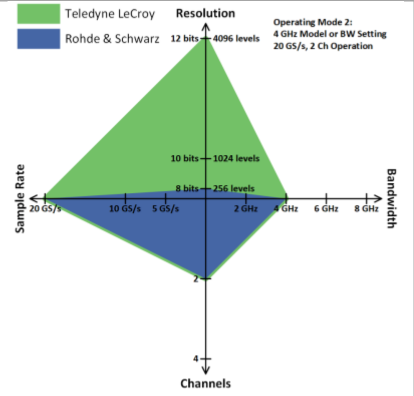
12-bit resolution

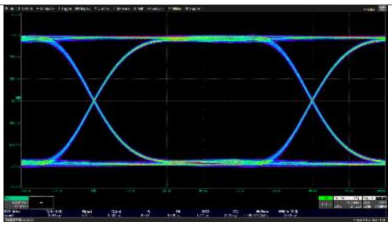
Rohde & Schwarz RTO2044
@ 500 MHz, 5 GS/s, 4 Channels, 12 bits

Interpolation (IT) Sampling Mode. Real-time Sample Rate is a claimed 5 GS/s, but this does not follow logically from their white paper. More likely, it is just 1.25 GS/s Real-Time SR.

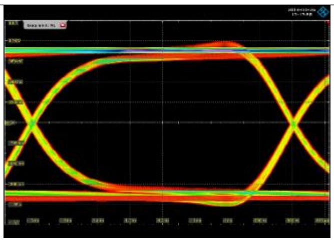
12-bit resolution (claimed)
Noise is >2x that of Teledyne LeCroy

Eye Diagram





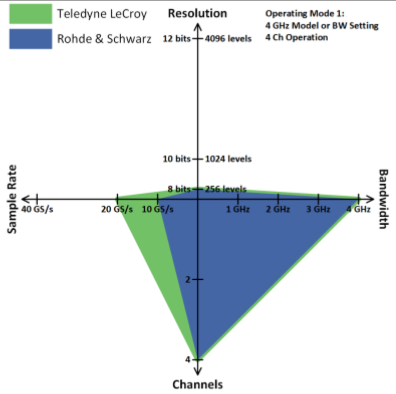
12-bit resolution
1.25 Gb/s PRBS-7 pattern
Rj = 661 fs, Dj = 10.352 ps,
Tj = 19.643 ps



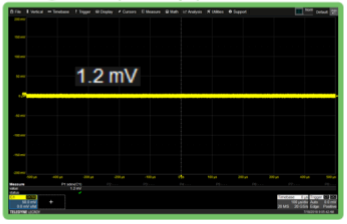
8-bit resolution
1.25 Gb/s PRBS-7 pattern
No application package exists to
measure serial data jitter.

Teledyne LeCroy WaveRunner 8404 vs. Rohde & Schwarz RTO2044

Baseline Noise Performance

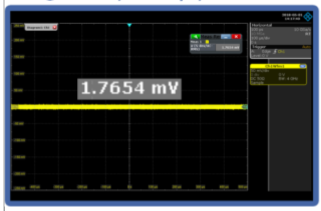


Teledyne LeCroy WaveRunner 8404 @ 4 GHz, 20 GS/s, 4 Channels



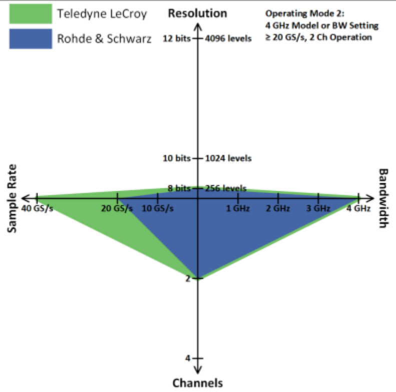
8-bit resolution

Rohde & Schwarz RTO2000 Series @ 4 GHz, 10 GS/s, 4 Channels

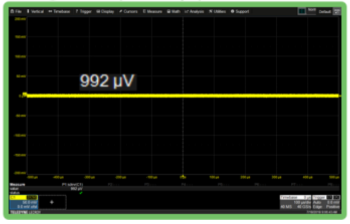


Real-time (RT) sample rate

8-bit resolution

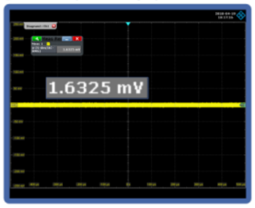


Teledyne LeCroy WaveRunner 8404 @ 4 GHz, 40 GS/s, 2 Channels

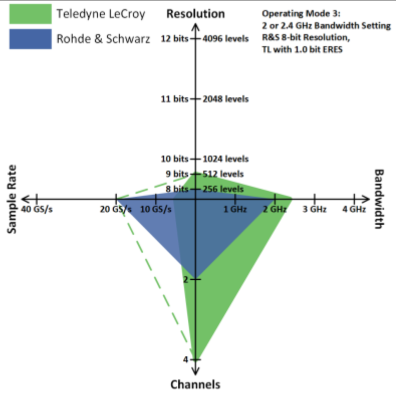


8-bit resolution

Rohde & Schwarz RTO2044 @ 4 GHz, 20 GS/s, 2 Channels



8-bit resolution



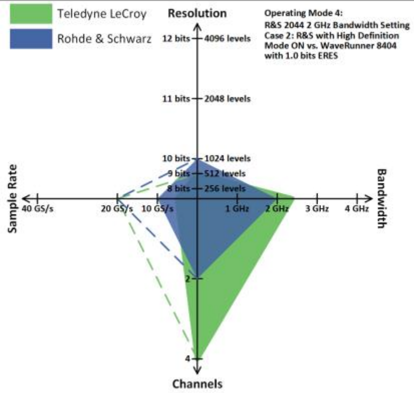
Teledyne LeCroy WaveRunner 8404 @ 2.4 GHz, 20 GS/s (FLT), 4 Channels, 1.0 bits ERES

9-bit resolution

Rohde & Schwarz RTO2044 @ 2 GHz, 20 GS/s, 2 Channels

No screen image available. Datasheet specification for this operating condition is 1.22 mV

8-bit resolution



Teledyne LeCroy WaveRunner 8404 @ 2.4 GHz, 20 GS/s (FLT), 4 Channels, 1.0 bits ERES

9-bit resolution

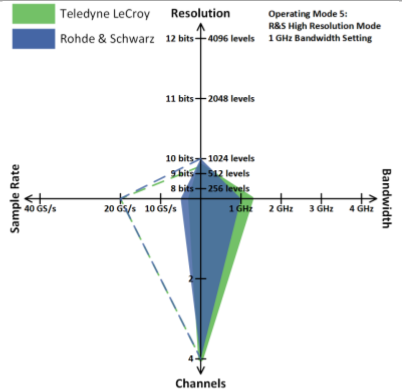
Rohde & Schwarz RTO2000 Series @ 2 GHz, 20 GS/s (IT mode), 2 Channels

Operation Mode: High definition
Bandwidth: 2 GHz
Resolution in bits: 10

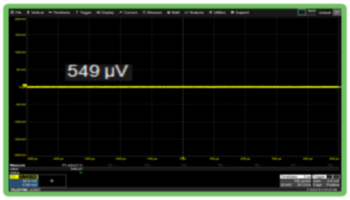
Interpolation (IT) Sampling Mode. Real-time Sample Rate of 5 GS/s will lower the bandwidth to 1 GHz with 2 channel operation.

RMS (Baseline) Noise datasheet specification for 2 GHz RTO2024 at 50 mV/div = **1.22 mV**

10-bit resolution (claimed)

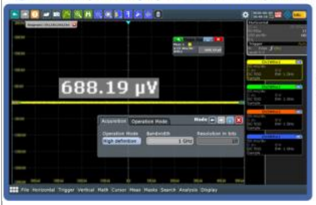


Teledyne LeCroy WaveRunner 8404
@ 1.2 GHz, 20 GS/s (FLT),
4 Channels, 1.5 bits ERES



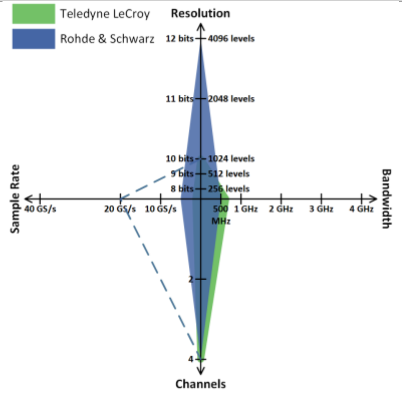
9.5 bit resolution

Rohde & Schwarz RTO2044
@ 1 GHz, 5 GS/s, 4 Channels, 10 bits

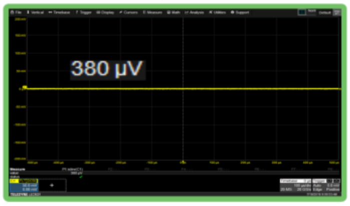


Interpolation (IT) Sampling Mode. Real-time Sample Rate is 5 GS/s

10-bit resolution (claimed)



Teledyne LeCroy WaveRunner 8404
@ 580 MHz, 20 GS/s (FLT),
4 Channels, 2.0 bits ERES



10-bit resolution

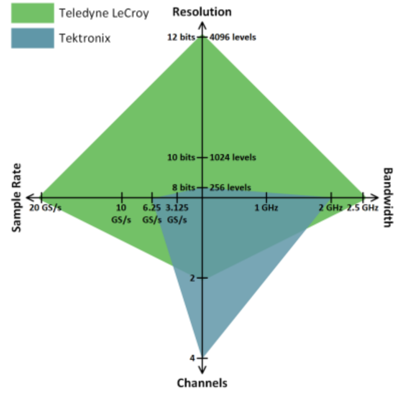
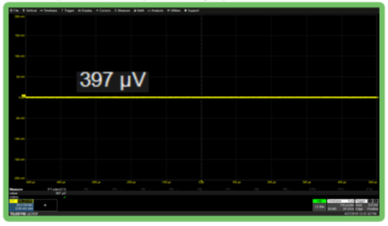
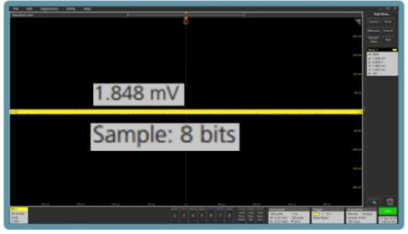
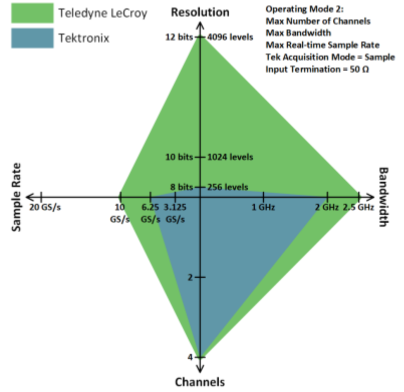
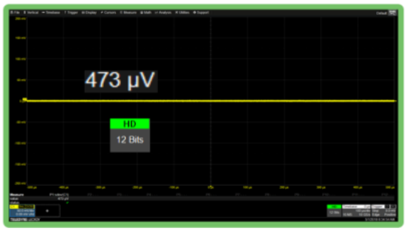
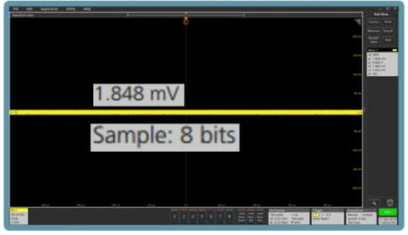
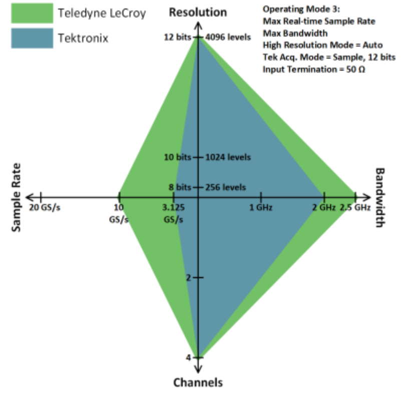
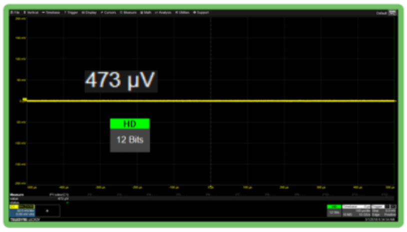
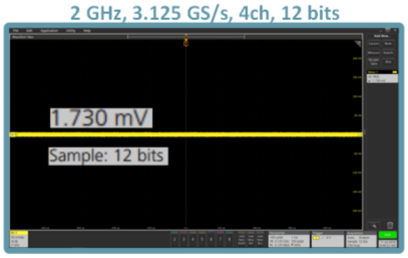
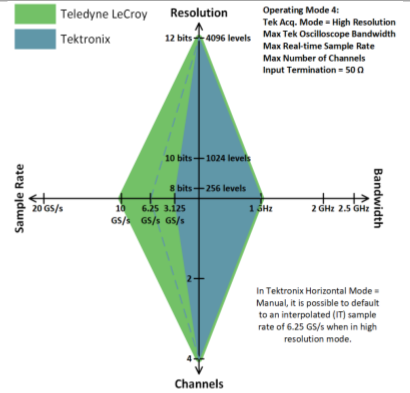
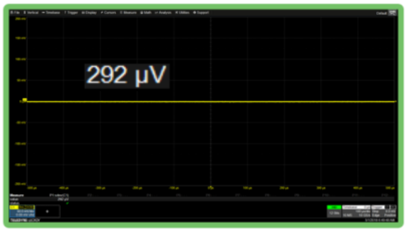
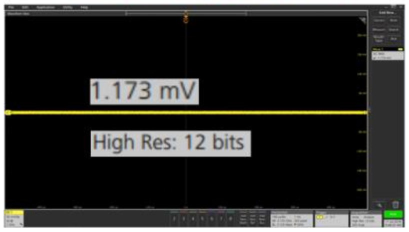
Rohde & Schwarz RTO2044
@ 500 MHz, 5 GS/s, 4 Channels, 12 bits

Interpolation (IT) Sampling Mode. Real-time Sample Rate is a claimed 5 GS/s, but this does not follow logically from their white paper. More likely, it is just 2.5 GS/s Real-Time SR.

12-bit resolution (claimed)
Miracle increase of 2 bits with halving of bandwidth

Teledyne LeCroy WavePro 254HD vs. Tektronix MSO 54 2 GHz Model

Baseline Noise Performance

	**Teledyne LeCroy WavePro 254HD @ 2.5 GHz, 20 GS/s, 2 Channels**  397 µV 12-bit resolution	**Tektronix 54 2 GHz Model 2 GHz, 6.25 GS/s, 4ch, 8 bits**  1.848 mV Sample: 8 bits 8-bit resolution It is unclear why an advertised 12-bit ADC would ever operation in an 8-bit mode
 Operating Mode 2: Max Number of Channels Max Bandwidth Max Real-time Sample Rate Tek Acquisition Mode = Sample Input Termination = 50 Ω	**Teledyne LeCroy WavePro 254HD 2.5 GHz, 10 GS/s, 4ch**  473 µV HD 12 Bits 12-bit resolution	**Tektronix 54 2 GHz Model 2 GHz, 6.25 GS/s, 4ch, 8 bits**  1.848 mV Sample: 8 bits 8-bit resolution Noise is 4x higher than Teledyne LeCroy
 Operating Mode 3: Max Real-time Sample Rate Max Bandwidth High Resolution Mode = Auto Tek Acq. Mode = Sample, 12 bits Input Termination = 50 Ω	**Teledyne LeCroy WavePro 254HD 2.5 GHz, 10 GS/s, 4ch**  473 µV HD 12 Bits 12-bit resolution	**Tektronix 54 2 GHz Model 2 GHz, 3.125 GS/s, 4ch, 12 bits**  1.730 mV Sample: 12 bits 12-bit resolution (claimed) Noise is 4x higher than Teledyne LeCroy, and baseline noise in no way meets resolution claim.
 Operating Mode 4: Tek Acq. Mode = High Resolution Max Tek Oscilloscope Bandwidth Max Real-time Sample Rate Max Number of Channels Input Termination = 50 Ω In Tektronix Horizontal Mode = Manual, it is possible to default to an interpolated (IT) sample rate of 6.25 GS/s when in high resolution mode.	**Teledyne LeCroy WavePro 254HD 1 GHz, 10 GS/s, 4ch**  292 µV 12-bit resolution	**Tektronix MSO 54 2 GHz Model 1 GHz, 3.125 GS/s, 4ch, 12 bits**  1.173 mV High Res: 12 bits 12-bit resolution (claimed) Noise is 4x higher than Teledyne LeCroy, and baseline noise in no way meets resolution claim.

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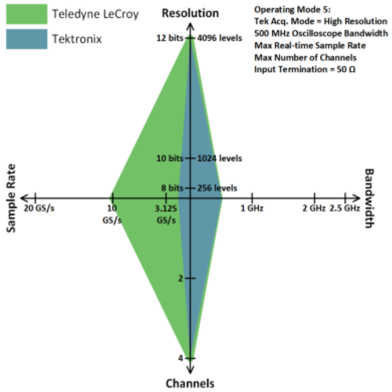

Operating Mode 5:
Tek Acq. Mode = High Resolution
500 MHz Oscilloscope Bandwidth
Max Real-time Sample Rate
Max Number of Channels
Input Termination = 50 Ω
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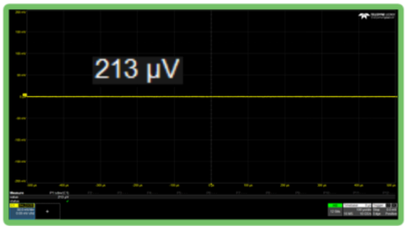
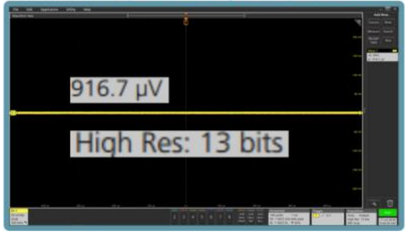
<td>
Teledyne LeCroy WavePro 254HD
500 MHz, 10 GS/s, 4ch



12-bit resolution
</td>
<td>
Tektronix MSO 54 2 GHz Model
500 MHz, 1.5625 GS/s, 4ch, 13 bits



13-bit resolution (claimed)
Noise is >4x higher than Teledyne LeCroy. Again, baseline noise in no way meets resolution claim.
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Teledyne LeCroy HDO6104A vs. Tektronix MSO 54 2 GHz Model

Baseline Noise Performance

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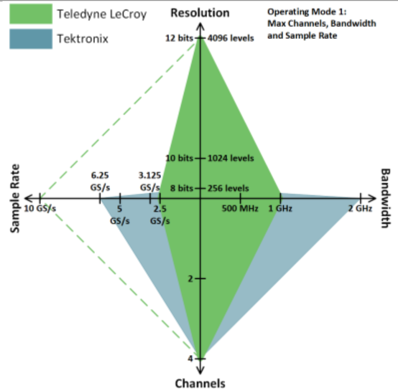

Operating Mode 1:
Max Channels, Bandwidth and Sample Rate
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<td>
Teledyne LeCroy HDO6104A
1 GHz, 10 GS/s

12-bit resolution
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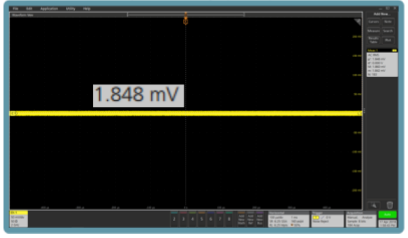
Tektronix 54 2 GHz Model
2 GHz, 6.25 GS/s, 4ch, 8 bits



8-bit resolution
It is unclear why an advertised 12-bit ADC would ever operation in an 8-bit mode
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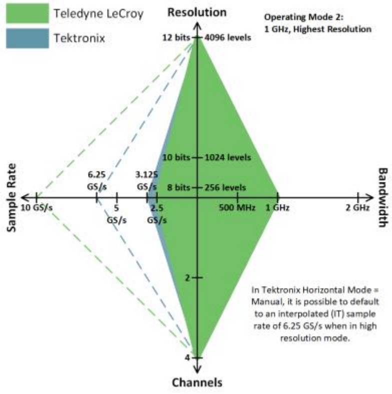

Operating Mode 2:
1 GHz, Highest Resolution

In Tektronix Horizontal Mode = Manual, it is possible to default to an interpolated (IT) sample rate of 6.25 GS/s when in high resolution mode.
</td>
<td>
Teledyne LeCroy HDO6104A
1 GHz, 10 GS/s

12-bit resolution
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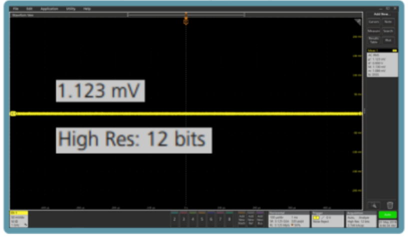
<td>
Tektronix MSO 54 2 GHz Model
1 GHz, 3.125 GS/s, 4ch, 12 bits



12-bit resolution (claimed)
Noise is 4x higher than Teledyne LeCroy, and baseline noise in no way meets resolution claim.
</td>
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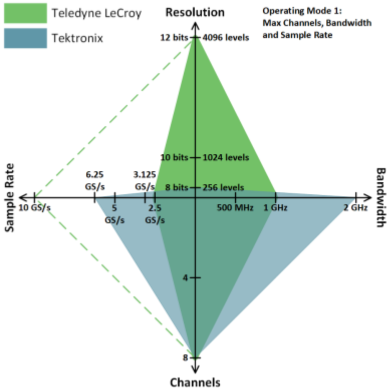
Teledyne LeCroy HDO8108A vs. Tektronix MSO 58 2 GHz Model

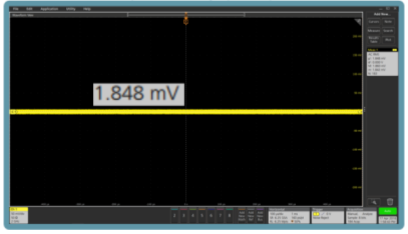
Baseline Noise Performance



Teledyne LeCroy
HDO8108A, 1 GHz, 10 GS/s

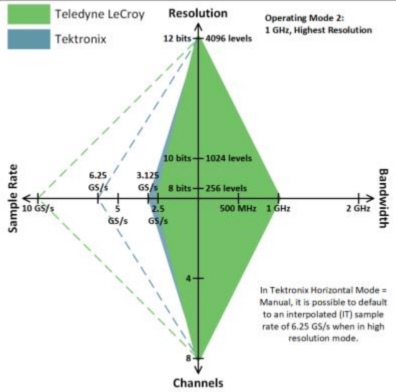
12-bit resolution

Tektronix 58 2 GHz Model
2 GHz, 6.25 GS/s, 4ch, 8 bits



8-bit resolution

It is unclear why an advertised 12-bit ADC would ever operation in an 8-bit mode

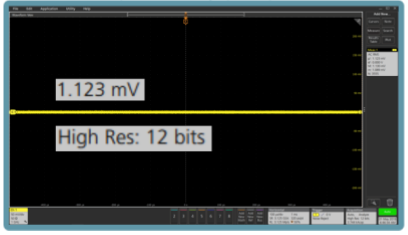


In Tektronix Horizontal Mode = Manual, it is possible to default to an interpolated (IT) sample rate of 6.25 GS/s when in high resolution mode.

Teledyne LeCroy
HDO8108A, 1 GHz, 10 GS/s

12-bit resolution

Tektronix MSO 58 2 GHz Model
1 GHz, 3.125 GS/s, 4ch, 12 bits



12-bit resolution (claimed)

Noise is 4x higher than Teledyne LeCroy, and baseline noise in no way meets resolution claim.

High Resolution Oscilloscope Applications

High resolution and high definition oscilloscopes, if properly designed, can acquire signals with lower noise than conventional 8-bit resolution oscilloscopes. If high resolution is maintained across all operating points (bandwidth, sample rate and number of channels), they are ideal for measuring complex, cross-correlated behaviors between any mix of low-speed and high-speed signals, such as:

- Correlation of power rail behaviors with jitter on associated or contaminating clock signals, and vice-a-versa
- Debugging DDR memory sub-systems, including memory system failures due to power rail dips or transients, or clock-contamination from the same
- Validation of high-speed serial data interfaces, especially in regards to jitter and vertical noise margin, and debug to root-cause of poor performance
- Measurement of power conversion voltage, current and power consumption/delivery at AC line input, DC bus and PWM (inverter) output, and correlation of same to high-speed control or device signals
- Validation of proper system behavior during unusual temperature, humidity, or electromagnetic immunity or conduction (EMI/EMC) events

These use cases are common in the following application segments:

- Embedded systems and embedded computing systems
- Power conversion systems
- EMI/EMC test laboratories

Embedded Computing Systems

Embedded systems and embedded computing systems are ubiquitous and widely used in a broad range of consumer and industrial products, such as automobiles, aircraft and avionics systems; computers and peripherals; consumer electronics and appliances; heating, ventilation and air conditioning systems; inverters and drives; lighting and building automation; medical instruments and devices; motion control equipment; power tools and power supplies. When these systems utilize analog sensors to detect something in the environment, perform a basic level of processing and then take an action, they are referred to as “deeply” embedded systems. These systems also have multiple, distributed, very low-voltage power rails that provide critically stable power to highly sensitive loads, such as central processing units (CPUs), memory chips and analog-to-digital converters (ADCs). These sensors and power rails must be measured with high accuracy and precision and correlated to high-speed system behaviors to properly debug and validate the system operation. Faulty system operation often means coupling between low-bandwidth sensor and power rail signals and associated high-speed serial data signals, high-speed clock signals or high-speed control signal.

Power Conversion Systems

Power conversion systems employ digital pulse-width modulated (PWM) output voltage control. The inverter subsection contains multiple power conversion devices, and the off, on and switching voltage levels must be accurately measured to understand device efficiency and optimization. Sinusoidal AC, DC bus voltages and PWM outputs require accurate voltage measurement for calculation of static and dynamic power consumption and efficiency, and correlation of power section behaviors with high-speed control system signals and commands.

EMI/EMC Test Labs

Pre-compliance or formal compliance testing is performed on many finished products to determine susceptibility to high-frequency radiated or conducted bursts, impulses or transients. Many larger companies have an in-house compliance lab to perform this type of testing. EMI/EMC Lab Managers need equipment in the 1 to 4 GHz range, with high sample rate and low noise (high resolution) to validate the shape and amplitude of the applied pulses prior to applying them to the device under test (DUT). Additionally, once the DUT is subjected to the interference events, DUT performance must be monitored. Any DUT that is also a deeply embedded system must have sensor signal inputs or outputs monitored during interference events to ensure proper system performance. A 12-bit resolution acquisition system with high bandwidth is ideal to monitor the complex range of signals present on such a system and to debug any problems that are found.

Conclusions

Manufacturers make a variety of vertical resolution claims for high bandwidth oscilloscopes, and a variety of design approaches may be used to achieve high resolution. Some design approaches result in significant tradeoffs of bandwidth, sample rate and channel count as resolution is increased. Tradeoffs may or may not be apparent to the user and may result in less oscilloscope performance than is required for a given application. Fortunately, there are some simple tests that can be performed to understand whether resolution claims are legitimate and to understand whether there is bandwidth, sample rate or channel count degradation as channel count is increased.