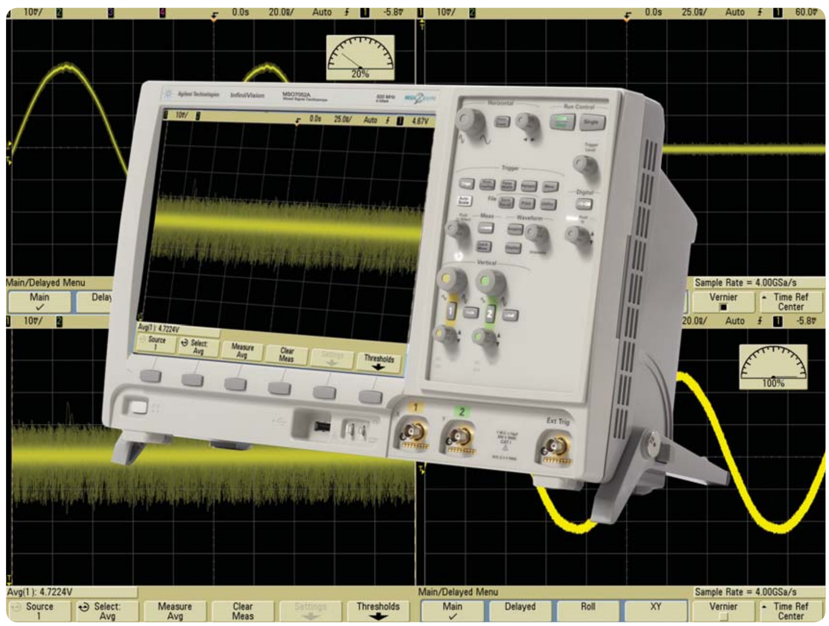
Evaluating Oscilloscope Vertical Noise Characteristics

Application Note 1558



Introduction

All oscilloscopes exhibit one undesirable characteristic: vertical noise in the scope's analog front-end and digitizing process. Measurement system noise will degrade your actual signal measurement accuracy, especially when you are measuring low-level signals and noise. Since oscilloscopes are broadband measurement instruments, the higher the bandwidth of the scope, the higher the vertical noise will be – in most situations. Although engineers often overlook vertical noise characteristics when they evaluate oscilloscopes for purchase, these characteristics should be carefully evaluated as they can impact signal integrity measurements in several ways. Vertical noise:

1. Induces amplitude measurement errors
2. Induces sin(x)/x waveform reconstruction uncertainty
3. Induces timing errors (jitter) as a function of input signal edge slew rates
4. Produces visually undesirable "fat" waveforms

Unfortunately, not all scope vendors provide vertical noise specifications/characteristics in their data sheets. And when they do, the specs are often misleading and incomplete. This document compares vertical noise characteristics of oscilloscopes ranging in bandwidth from 500-MHz to 1-GHz made by Agilent Technologies, Tektronix, Inc, and LeCroy Corporation. In addition, this document provides valuable hints on how to more accurately perform noise and interference measurements on low-level signals in the presence of relatively high levels of measurement system noise (oscilloscope noise).

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Understanding Noise and How it Should Be Measured

Random noise, sometimes referred to as white noise, is theoretically unbounded and exhibits a Gaussian distribution. Unbounded simply means that because of the random nature of noise, the more data you collect in noise characterization measurements, the higher the peak-to-peak excursions will grow. For this reason, random phenomenon such as vertical noise and random jitter should be measured and specified as an RMS (one standard deviation) value. Table 1 and Table 2 shows RMS noise floor measurements of six competitively priced oscilloscopes with bandwidths ranging from 500 MHz to 1 GHz. Each scope was terminated into 50-Ω and was set up to acquire waveforms with no input signal connected, using each scope's maximum specified sample rate.

What is often considered the "base-line noise floor" of an oscilloscope is the level of noise when the scope is set at its most sensitive V/div setting (lowest V/div). But many scopes on the market today have reduced bandwidth characteristics when they are used at the most sensitive V/div settings. As we mentioned earlier, scopes are broadband instruments and the higher the bandwidth, the higher the noise floor – typically. So if you compare base-line noise floor characteristics at each scope's most sensitive V/div setting, you may be comparing a lower-bandwidth scope against a higher-bandwidth scope, which is not an apples-to-apples comparison. The base-line noise floor of each scope of equal bandwidth should be compared at each scope's most sensitive V/div setting that provides full bandwidth.

Many oscilloscope evaluators make the mistake of only testing the base-line noise floor characteristic at the scope's most sensitive V/div setting, and then assuming this amplitude of noise applies to all V/div settings. There are actually two components of noise inherent in oscilloscopes. One component of noise is a fixed level of noise contributed primarily by the scope's front-end attenuator and amplifier. The base-line noise floor at the scope's most sensitive full-bandwidth V/div setting is a good approximation of this component of noise. This component of noise dominates at the most sensitive settings, but it is negligible when the scope is used on the least sensitive settings (higher V/div).

The second component of noise is a relative level of noise based on the scope's dynamic range, which is determined by the specific V/div setting. This component of noise is negligible when the scope is used on the most sensitive settings, but it dominates on the least sensitive settings. Even though the waveform may appear to be less noisy when the scope is set at high V/div settings, the actual amplitude of noise can be quite high, as you can see by comparing the noise measurements in Table 1 at 1-V/div to the level of noise at 10-mV/div. For the Agilent MSO7054A, this relative RMS noise component is approximately 2% of the V/div setting. The relative component of RMS noise on the Tektronix 500-MHz and LeCroy 600-MHz bandwidth scopes appears to be in the range of 3% to 4%.

After determining the fixed component of noise (approximate base-line noise floor) and the relative component of noise, you can estimate the amount of noise at intermediate V/div settings by using a square-root-of-the-sum-of-the-squares formula. And as you can see from the noise measurement results documented in Table 1 and Table 2, Agilent's InfiniiVision Series MSOs provide the lowest overall noise characteristics when used on most full-bandwidth V/div settings.

Understanding Noise and How it Should Be Measured (continued)

	Tektronix MSO4054	LeCroy WaveSurfer 64Xs w/MS500	Agilent MSO7054A
1 mV/div	100 µV[1]	N/A	N/A
2 mV/div	140 µV[1]	140 µV[2]	190 µV[3]
5 mV/div	190 µV	400 µV	210 µV
10 mV/div	300 µV	510 µV	250 µV
20 mV/div	560 µV	800 µV	390 µV
50 mV/div	1.4 mV	1.8 mV	1.0 mV
100 mV/div	3.1 mV	4.4 mV	1.8 mV
200 mV/div	5.7 mV	7.6 mV	3.7 mV
500 mV/div	14 mV	18 mV	9.8 mV
1 /div	26 mV	35 mV	19 mV
2 V/div	N/A	N/A	43 mV
5 V/div	N/A	N/A	93 mV

1. Bandwidth limited to 200 MHz at 1 mV/div and limited to 350 MHz at 2 mV/div
2. Bandwidth limited to 150 MHz at 2 mV/divv
3. Waveform expansion used below 5 mV/div

Table 1: RMS noise comparisons of 500-MHz and 600-MHz bandwidth MSOs

	Tektronix MSO4104	LeCroy WaveRunner 104Xi w/MS500	Agilent MSO7104A
1 mV/div	95 µV[1]	N/A	N/A
2 mV/div	130 µV[1]	300 µV[2]	260 µV[3]
5 mV/div	230 µV	420 µV[2]	280 µV
10 mV/div	340 µV	550 µV	310 µV
20 mV/div	570 µV	800 µV	440 µV
50 mV/div	1.4 mV	1.7 mV	1.7 mV
100 mV/div	3.3 mV	5.2 mV	2.0 mV
200 mV/div	5.7 mV	7.8 mV	4.4 mV
500 mV/div	14 mV	17 mV	12 mV
1 V/div	26 mV	34 mV	20 mV

1. Bandwidth limited to 200 MHz at 1 mV/div and 350 MHz at 2 mV/iv
2. Bandwidth limited to 350 MHz at 2 mV/div and limited to 800 MHz at 5 mV/div
3. Waveform expansion used below 5 mV/div

Table 2: RMS noise comparisons of 1-GHz bandwidth MSOs

Measuring Peak-to-Peak Noise

Although for best results you should evaluate and compare noise as an RMS value because of the random and unbounded nature of noise, it is often desirable to measure and compare peak-to-peak noise. After all, it is the peak excursions of noise that are viewed on the oscilloscope's screen and induce the highest amplitude errors in real-time/non-averaged measurements. For this reason, many oscilloscope users prefer to compare and measure noise as a peak-to-peak value. But since random vertical noise is theoretically unbounded, you must first establish a criterion of how much data to collect, and then realize that peak-to-peak measurement results of noise will be qualified on this criterion. Table 3 and Table 4 shows peak-to-peak noise measurements on the six 500-MHz to 1-GHz scopes tested based on collecting 1-M points of digitized data.

Since it is possible that one particular acquisition of 1-M points of data could produce either high or low peak-to-peak measurements, we repeated these 1-M point peak-to-peak noise measurements ten times at each V/div setting. These measurement results were then averaged to produce a "typical" peak-to-peak noise figure based on 1-M points of acquired data.

As these tables show, the Agilent InfiniiVision series MSOs oscilloscope produced the lowest overall level of peak-to-peak noise (based on 1-M points of data) at most full-bandwidth V/div settings. Again, both the Tektronix and LeCroy oscilloscopes produced significantly higher levels of peak-to-peak noise on most V/div settings.

Although it may be tempting to just set each scope at equal time/div settings and then collect data using the infinite persistence display mode for a set amount of time, such as 10 seconds, you should be cautioned not to use this more intuitive method of peak-to-peak noise testing. Not only can memory depths be significantly different when the scopes are set up at the same timebase setting, but update rates also can be significantly different. For instance, if you initially begin with a default setup condition and then set the WaveRunner 104Xi and Agilent MSO7104A to 20-ns/div, the LeCroy scope will acquire and update waveforms at a rate of approximately 30 waveforms per second. Because of Agilent's 6000 Series' extremely fast waveform update rates, the Agilent scope with MegaZoom III technology, will update waveforms at a rate of approximately 100,000 waveforms per second. This means that if you collect infinite persistence waveforms for 10 seconds, the Agilent scope will collect approximately 3000 times more data for these peak-to-peak noise measurements. And as we mentioned earlier, the more data you collect, the more the peak-to-peak measurements will grow because of the random and Gaussian nature of random vertical noise.

Measuring Peak-to-Peak Noise (continued)

	Tektronix MSO4054	LeCroy WaveSurfer 64Xs w/MS500	Agilent MSO7054A
1 mV/div	1.0 mV[2]	N/A	N/A
2 mV/div	1.4 mV[2]	1.3 mV[3]	2.0 mV[4]
5 mV/div	1.8 mV	3.8 mV	2.1 mV
10 mV/div	2.9 mV	4.5 mV	2.3 mV
20 mV/div	4.9 mV	6.5 mV	3.8 mV
50 mV/div	12 mV	15 mV	8.9 mV
100 mV/div	26 mV	37 mV	16 mV
200 mV/div	50 mV	60 mV	30 mV
500 mV/div	120 mV	140 mV	89 mV
1 V/div	240 mV	280 mV	160 mV
2 V/div	N/A	N/A	390 mV
5 V/div	N/A	N/A	770 mV

1. Typical peak-to-peak noise measurements based on 1 M points of acquired data
2. Bandwidth limited to 200 MHz at 1 mV/div and limited to 350 MHz at 2 mV/div
3. Bandwidth limited to 150 MHz at 2 mV/div
4. Waveform expansion used below 5 mV/div

Table 3: Typical peak-to-peak noise[1] comparisons of 500-MHz and 600-MHz bandwidth MSOs

	Tektronix MSO4104	LeCroy WaveRunner 104Xi w/MS500	Agilent MSO7104A
1 mV/div	0.9 mV[2]	N/A	N/A
2 mV/div	2.1 mV[2]	2.9 mV[3]	2.8 mV[4]
5 mV/div	2.2 mV	4.1 mV[3]	3.1 mV
10 mV/div	3.3 mV	5.4 mV	3.1 mV
20 mV/div	5.6 mV	7.7 mV	4.2 mV
50 mV/div	13 mV	17 mV	12 mV
100 mV/div	30 mV	52 mV	19 mV
200 mV/div	55 mV	75 mV	38 mV
500 mV/div	140 mV	170 mV	130 mV
1 V/div	220 mV	320 mV	190 mV

1. Typical peak-to-peak noise measurements based on 1 M points of acquired data
2. Bandwidth limited to 200 MHz at 1 mV/div and 350 MHz at 2 mV/iv
3. Bandwidth limited to 350 MHz at 2 mV/div and limited to 800 MHz at 5 mV/div
4. Waveform expansion used below 5 mV/div

Table 4: Typical peak-to-peak noise[1] comparisons of 1-GHz bandwidth MSOs

Noise Measurements with Probes

Most oscilloscopes come supplied with 10:1 passive probes, which can provide up to 600-MHz system bandwidth (for 600-MHz oscilloscopes or higher). In addition, active probes also can be used to achieve higher bandwidth in higher bandwidth scopes. Whether you are using a passive or active probe, the probe itself will add an additional component of random noise. Today's digital scopes will automatically detect the probe attenuation factor and re-adjust the scope's V/div setting to reflect the input signal's attenuation induced by the probe. So if you are using a 10:1 probe, the scope will indicate a V/div setting that is ten times the actual setting inside the scope. In other words, if the scope is set at 20-mV/div with a 10:1 probe attached, the scope's input attenuator and amplifier will actually be set at 2-mV/div. This means that you will probably observe a fairly high level of noise relative to the screen height since the base-line noise floor is effectively multiplied by a factor of ten. If you need to perform critical low-level signal measurements, such as measuring the ripple of a power supply, you might consider using a 1:1 passive probe. In addition, if the scope employs bandwidth limiting on its more sensitive V/div ranges, just be aware that bandwidth limiting may now apply to higher V/div settings, based on the particular probe attenuation factor.

Making Measurements in the Presence of Noise

When you use an oscilloscope on its most sensitive V/div settings, inherent random oscilloscope noise sometimes can mask real signal measurements. However, there are measurement techniques you can use to minimize the effects of the scope's noise. If you are measuring the level of noise and ripple on your power supply, you may need to use a scope at or near its more sensitive V/div setting. First, try using a 1:1 probe, as discussed above, rather than using the standard 10:1 passive probe that was probably shipped with your instrument. Secondly, if you are attempting to measure the RMS noise of your power supply, your measurements will also include noise contributed by your scope/probe system, which may be significant. But with careful characterization of both your signal (power supply) and your measurement system, you can back out the measurement system noise component to provide a more accurate estimate of actual power supply noise (RMS).

Using approximately 4.7 V of DC offset in the Agilent 7000 Series oscilloscope, Figure 1 shows a power supply noise measurement at 10 mV/div using a 1:1 passive probe. Note that the 500-MHz and 1-GHz Tektronix and LeCroy scopes documented in this paper are all incapable of offsetting an input signal by more than +/- 1 V at settings lower than 50 mV/div with a 1:1 passive probe attached. This means that performing this noise measurement on a 5-V power supply using one of the Tektronix or LeCroy oscilloscopes requires the use of AC coupling. But if you must use AC coupling because of oscilloscope DC offset limitations, then the DC component of the power supply will be eliminated and cannot be accurately measured.

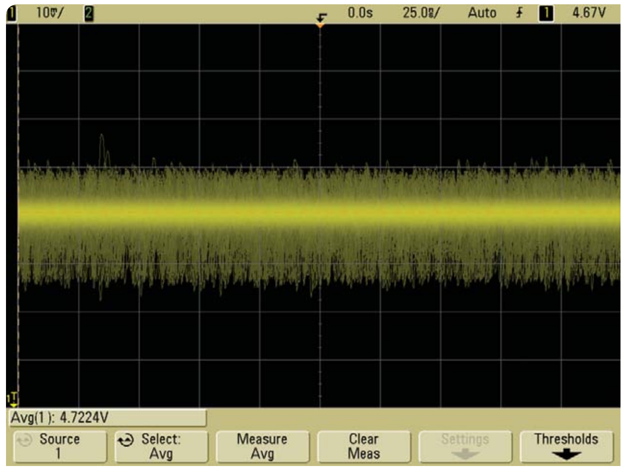

Figure 1. Noise measurement of power supply and scope/probe measurement system

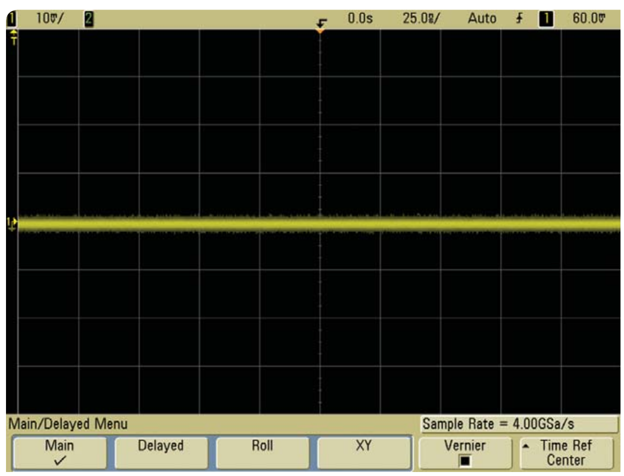

Figure 2. Noise measurement of just the measurement system (scope + 1:1 passive probe)

Making Measurements in the Presence of Noise (continued)

Using a 1:1 passive probe on the Agilent MSO/DSO7000 series oscilloscope, we measured approximately 1.5-mV RMS of noise on this noisy 5-V power supply. Figure 2 shows a noise characterization measurement of just the measurement system using the same 1:1 passive probe. With the ground lead of the probe connected to the probe’s tip, we measured approximately 480-µV RMS of system measurement noise at 10-mV/div. You will see that this measurement of oscilloscope/probe noise is significantly higher than the figure shown in Table 1 (250-µV RMS) because we used a 1:1 probe, which adds an additional component of noise. Plus, we used a 1-MΩ input termination rather than the original 50-Ω termination (used for the base-line RMS noise measurements documented in Table 1). Now, using a square-root-of-the-sum-of-the-squares formula, we can back out this component of measurement system noise, which indicates approximately 1.4-mV RMS of power supply noise.

Although the measurement on this particular power supply may include deterministic/systematic components of interference/noise in addition to a random component, if the deterministic components are non-correlated to the scope's auto triggering, using this technique to back out the measurement system error component will provide a very close approximation of the total RMS noise of your power supply.

Individual deterministic/systematic components of interference, such as power supply switching or digital system clock interference, also can be measured accurately in the presence of fairly large random measurement system noise. By triggering on suspect sources of interference using a separate channel of the oscilloscope, you can repetitively acquire input signals and then average-out all random and non-correlated components of noise and interference contributed by both the scope/probe and input signal. The result will be a high-resolution measurement of a particular component of interference of your power supply, even when you are using the scope on a very sensitive V/div setting such as 2-mV/div, as shown in Figure-3. Again, making an accurate measurement of the average DC component of the power supply requires sufficient oscilloscope DC offset range (only available in the Agilent oscilloscopes documented in this application note).

Using this averaged measurement technique on the same noisy power supply signal, we measured approximately 4.9-mVp-p of interference induced by the system's 10-MHz clock (lower/green waveform). To find all sources of deterministic (non-random) interference/ripple, you need to perform multiple averaged measurements using various suspected sources of interference as your oscilloscope trigger source.

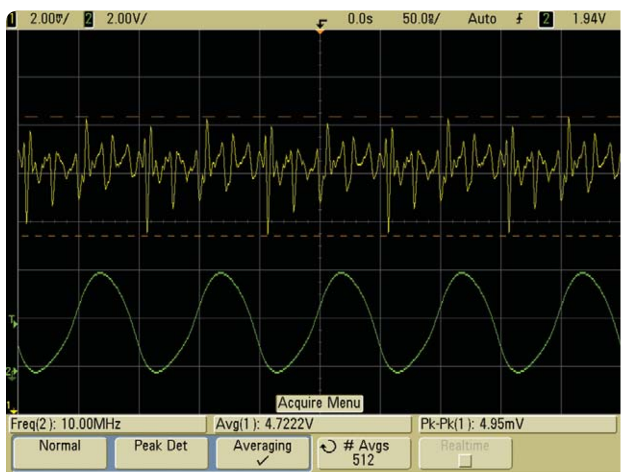

Figure 3: Peak-to-peak interference/noise contributed by an embedded system clock

Viewing the “Fat” Waveform

Some oscilloscope users believe that digital storage oscilloscopes (DSOs) induce a higher level of random vertical noise than older analog oscilloscopes do. They reach this conclusion because a trace on a DSO typically appears wider than a trace on an older analog oscilloscope. But the actual noise level of DSOs is no higher than noise levels in older analog oscilloscopes of equal bandwidth. With analog oscilloscope technology, random extremes of vertical noise are either displayed dimly or not at all because of the infrequent occurrence of signal extremes. Although engineers often think of oscilloscopes as simple two-dimensional instruments that display volts versus time, older analog oscilloscopes actually show a third dimension as a result of the swept electron beam technology they use. The third dimension shows the frequency-of-occurrence of signals using trace intensity modulation, which means that older analog oscilloscopes actually hide or visually suppress extremes of random vertical noise.

Traditional digital oscilloscopes lack the ability to show the third dimension (intensity modulation). But some of today’s newer digital oscilloscopes have intensity gradation capability that closely emulates the display quality of older analog oscilloscopes. Agilent’s new InfiniiVision Series oscilloscopes with MegaZoom III technology provide the highest level of intensity grading in the oscilloscope industry with 256 levels of intensity mapped to an XGA color display. Figure 4 shows a low-level 10-MHz signal captured at 10 mV/div with the intensity adjusted to 100%. This screen is representative of older digital oscilloscope displays that lack intensity gradation capability. Without intensity gradation, the scope shows a “fat” waveform that reveals the peak-to-peak extremes of noise. But the “thickness” of this relatively

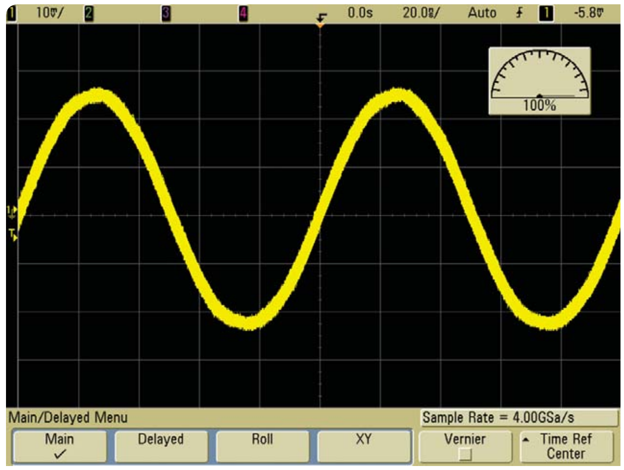

Figure 4. 100% intensity display with no intensity gradation

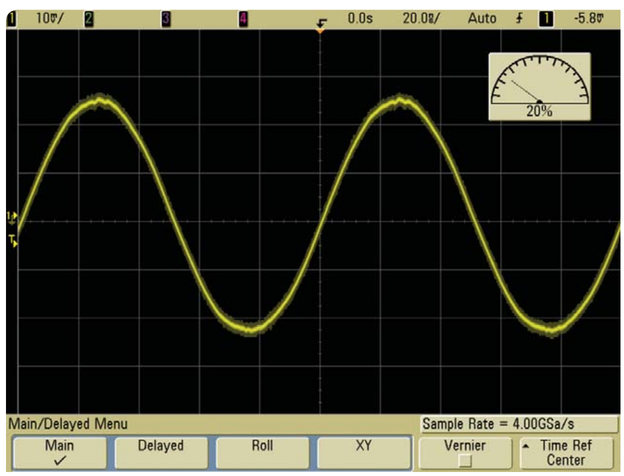

Figure 5. 20% intensity display with 256 levels of intensity gradation

Viewing the “Fat” Waveform (continued)

low-level input signal (approximately 50 mVp-p) measured at 10 mV/div is primarily due to inherent oscilloscope noise – not due to input signal noise. Figure-5 shows the same 10-MHz signal, but now with the intensity adjusted to
20% to more closely emulate the display of analog oscilloscopes that naturally suppress extremes of noise. We can now view a more “crisp” waveform without viewing the effects of the scope’s inherent noise at this relatively sensitive V/div setting. In addition, we now can see waveform details, such as “wiggles” on the positive peak of the sine wave, that were previously masked when viewed with a constant level of intensity (100%) due to the relatively high level of scope noise.

Alternatively, you can eliminate measurement system and random signal noise using waveform averaging if you are acquiring a repetitive input signal, as illustrated in the example shown in Figure 3. For real-time/single-shot applications (when repetitive averaging cannot be used), some scopes also have a high-resolution acquisition mode.

This technique can be used on single-shot acquisitions to filter out high-frequency components of noise and interference using DSP/digital filtering to increase vertical resolution up to 12-bits, but at the expense of measurement system bandwidth.

Summary

When you evaluate various oscilloscopes for purchase, be sure to carefully consider the inherent noise characteristic of the oscilloscopes. Not all oscilloscopes are created equal. Not only can vertical random noise in a scope degrade measurement accuracy, but it also can degrade the viewing quality of digitized signals. When you are evaluating oscilloscope noise characteristics, it is important that you carefully setup oscilloscopes to be tested under the same measurement criteria including same bandwidth scope, same V/div setting (with full bandwidth), same sample rate, same memory depth, and same number of acquisitions.

Agilent's InfiniiVision Series oscilloscopes provide the lowest overall noise characteristics in the industry compared to other 500-MHz to 1-GHz oscilloscopes, as shown in this document. In addition, Agilent's InfiniiVision Series oscilloscopes with MegaZoom III technology provide the highest resolution display quality with 256 levels of intensity grading that can be used to visually suppress random extremes of inherent oscilloscope noise.

You can use various measurement techniques, such as mathematical calculations, waveform averaging, DSP filtering, and display intensity gradation to minimize or eliminate measurement system noise components in order to make more accurate measurements of low-level random and deterministic noise components in your system.

Although this document has focused on noise measurements comparisons between just 500-MHz to 1-GHz bandwidth oscilloscopes, the principles presented in this document apply to any bandwidth oscilloscope – higher or lower. In fact, Agilent's higher-bandwidth 13-GHz DSO90000 Infiniium Series oscilloscope has the lowest inherent internal measurement system noise of any oscilloscope in this bandwidth range with noise levels not that much higher than current 1-GHz oscilloscopes on the market. Agilent is able to achieve lower measurement noise performance primarily because of higher levels of integration using lower-power integrated-circuit (IC) technologies.

It should be noted that a very limited sample size of oscilloscopes was chosen for this characterization of random vertical oscilloscope noise. All scopes selected for testing were recent production units from each vendor. Only channel 1 was tested because this is the channel engineers most often use. Although we don't know for sure if the measurements documented in this paper are typical, we have assumed that these measurement results are representative of all current units in production by each scope vendor.

Glossary

Base-line Noise Floor the level of RMS noise measured at a scope's most sensitive, full bandwidth V/div setting

Sin(x)/x Reconstruction characteristics of software filtering that reconstructs a sampled waveform to provide higher data resolution that will more accurately represent the original un-sampled input signal when Nyquist's rules are observed

Noise Floor the level of RMS noise measured at each scope's V/div setting

Random Noise unbounded noise that exhibits a Gaussian distribution

Dynamic Range the full range of a digital storage oscilloscope's (DSO's) analog-to-digital converter that depends on the scope's V/div setting, which usually varies from 8 division peak-to-peak (full screen) to 10 divisions peak-to-peak in most oscilloscopes

Peak-to-peak Noise the peak-to-peak range of noise in an oscilloscope based on a particular criterion such as time, number of acquisitions, and/or acquisition memory depth

RMS Noise random noise measured as one standard deviation

Infinite Persistence a common display mode in digital storage oscilloscopes (DSOs) that accumulates and displays all acquisitions to show worst-case deviations of a signal

Gaussian Distribution a typical bell-shape curve of statistical distribution

Deterministic systematic sources of error/noise that are bounded

Trace Intensity Modulation/Gradation varying the intensity of a scope's display based on frequency-of-occurrence at a particular X-Y pixel location

DSP Digital Signal Processing

MegaZoom III Agilent proprietary technology that provides trace intensity gradation, fast waveform update rates, and responsive deep memory

Related Literature

Publication Title	Publication Type	Publication Number
Agilent Technologies Oscilloscope Family Brochure	Brochure	5989-7650EN
Agilent 7000 Series InfiniiVision Oscilloscopes	Data sheet	5968-7736EN
Agilent 6000 Series InfiniiVision Oscilloscopes	Data sheet	5989-2000EN
Agilent 5000 Series InfiniiVision Oscilloscopes	Data sheet	5989-6110EN
Agilent InfiniiVision Series Oscilloscope Probes and Accessories	Data sheet	5968-8153EN
Choosing an Oscilloscope with the Right Bandwidth for your Applications :	Application note	5989-5733EN
Evaluating Oscilloscope Sample Rates vs. Sampling Fidelity	Application note	5989-5732EN
Evaluating Oscilloscopes for Best Signal Visibility	Application note	5989-7885EN
Debugging Embedded Mixed-Signal Designs Using Mixed Signal Oscilloscopes	Application note	5989-3702EN
Using an Agilent InfiniiVision Series MSO To Debug an Automotive CAN bus	Application note	5989-5049EN

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