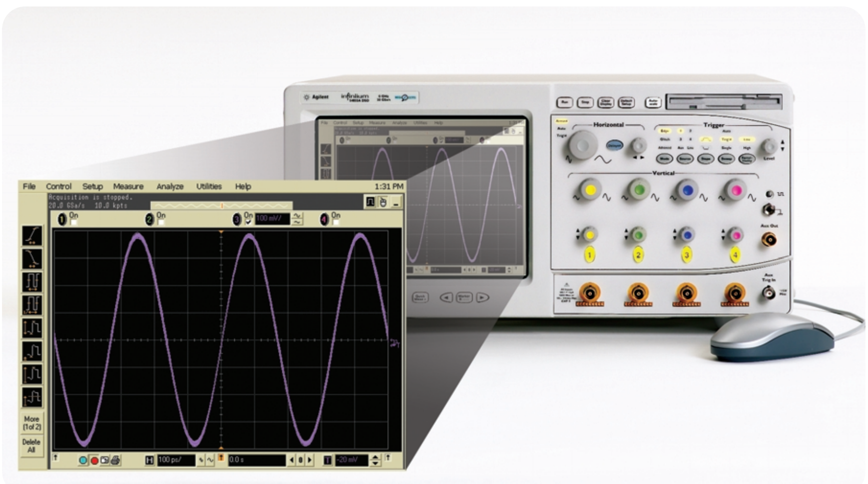
Characterizing High-Speed Oscilloscope Distortion

A comparison of Agilent and Tektronix high-speed, real-time oscilloscopes

Application Note 1493



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Introduction

When real-time oscilloscopes process high-speed signals, the resulting digitized waveforms may exhibit distortions relative to the signal's true wave shape. Distortions usually occur when the scope is operating near the limits of its bandwidth capability. Error sources that can produce waveform distortions primarily include input amplifier non-linearity, instrument noise floor, misalignment of interleaved A/D converters, and A/D converter non-linearity. This application note shows how to properly characterize waveform distortions using various measurement techniques. In addition, this application note documents distortion measurement results of two competitive 6-GHz, 20-GSa/s oscilloscopes, the Agilent 54855A and Tektronix TDS6604.

Agilent Technologies

Establishing characterization test parameters

The first challenge in characterizing oscilloscope high-speed distortions is choosing the right signal to test. Although oscilloscopes in the class of Agilent's and Tektronix' 6-GHz real-time oscilloscopes are primarily used to capture and characterize high-speed digital signals, digital signals are not a good type of signal to use for distortion characterization. Pulse shapes of digital signals, even from the best high-speed pulse/pattern generators, are very unpredictable. In addition, the frequency content of a digital signal is very complex. A better signal to use is a sine wave generated by a high-frequency signal generator. Sine waves have a predictable shape and, theoretically, known timing parameters such as rise times and fall times. Also, the frequency content of a pure sine wave is very simple, consisting of a single component at the fundamental frequency. Using sine waves simplifies the task of looking for distortion components in the frequency domain.

In addition to the type of signal, we also must select the frequency and amplitude of the signal we will use in our characterization test. Given enough time and energy, you could characterize a wide range of signals with various speeds, amplitudes, and oscilloscope setup conditions. But for the analysis documented in this application note, we have chosen to characterize a 3-GHz sine wave acquired on channel 3.

We chose channel 3 because this channel appeared to exhibit the highest levels of distortion on both oscilloscopes. We chose a frequency of 3 GHz because it is a high enough frequency to stress a 6-GHz scope front-end, yet low enough that if amplifier non-linearity produces second-harmonic distortion at 6 GHz, then this element of distortion would still be within the bandwidth of the oscilloscope (6 GHz). We chose amplitudes in the range of 0.8 V_{p-p} to 1.6 V_{p-p} because this is the approximate amplitude range of today's higher-speed LVDS signals, which is a key application for this class of real-time 6-GHz oscilloscopes. In addition, these amplitudes of signals will allow us to stress the dynamic range of each scope with near full-scale deflection when the scope's vertical sensitivities are set at 100 mV/div and 200 mV/div.

To characterize distortion of the Tektronix and Agilent oscilloscopes, we conducted the following four tests to measure distortion and parametrics in both the frequency and time domains:

1. FFT analysis with total distortion computation

2. Rise and fall time measurement

3. V_{p-p} variation measurement

4. Visual distortion test

FFT analysis

To insure that our 3-GHz input signal source generated a pure sine wave with minimal distortion, we first performed a spectral analysis on the signal. We fed the signal directly into a spectrum analyzer, which showed a single frequency component at precisely 3 GHz with a very low noise floor and no harmonics higher than 50 dB below the fundamental. After performing complete front-panel calibrations, we set up both scopes to acquire the 3-GHz reference sine wave at the maximum sample rate (20 GSa/s) and with sufficient memory to perform an FFT math operation to reveal all frequency components of distortion caused by the scopes' front-end and digitizing process including the instrument's noise floor.

Figures 1 and 2 show the results of the FFT analysis on both the Agilent 54855A and the Tektronix TDS6604. Both oscilloscope FFT displays were set up for a center frequency of 5 GHz and frequency span of 10 GHz (1 GHz per division). Looking at the resultant FFT spectral analysis on the Agilent oscilloscope (Figure 1), we can clearly see the fundamental input frequency at 3 GHz, plus we can see a second harmonic distortion spur at 6 GHz, measuring approximately 35 dB down from the fundamental. Averaging the FFT measurement to eliminate the noise floor also revealed two minor distortion components (–53 dB) at ± 500 MHz around the fundamental spur. These compontents of distortion are due to sub-picosecond sub-harmonic distortion in the A/D sample clock. If we change the input signal's frequency, we can see that these two minor distortion components track the fundamental frequency spur. But these distortion components are very insignificant and are essentially buried within the scope's noise floor.

The only significant component of distortion is the second harmonic spur at 6 GHz, which is within the bandwidth of this Agilent 6-GHz oscilloscope. This component of distortion is generated primarily by slight non-linearity of the scope's front-end/amplifier. If this distortion component were sufficiently high in amplitude, SPICE modeling shows that it would manifest itself in the time domain as asymmetry in slew rates of the rising and falling edges.

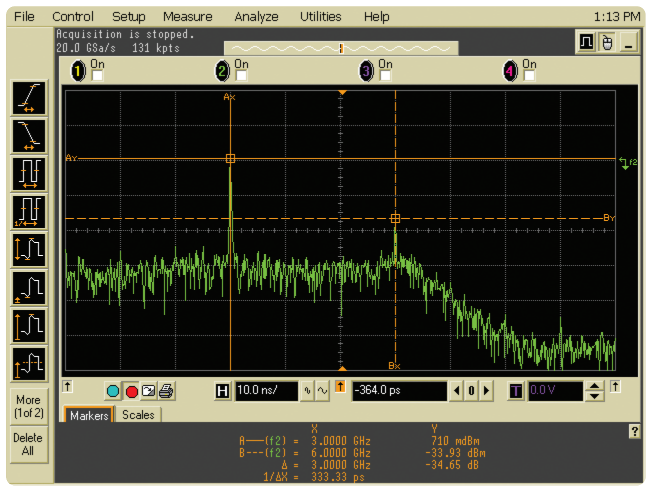

Figure 1. FFT analysis on Agilent oscilloscope

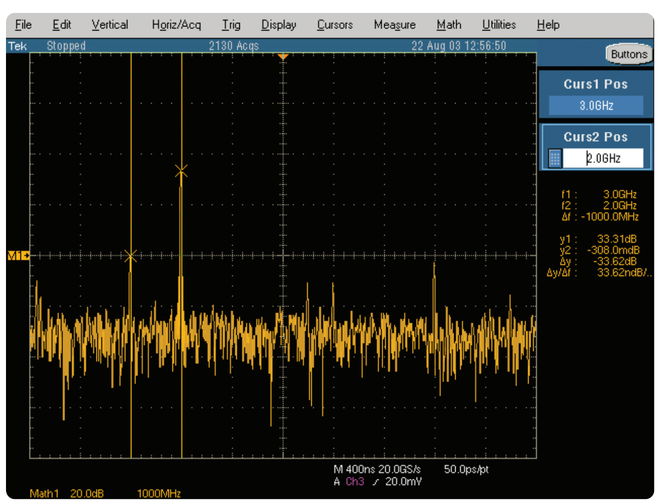

Figure 2. FFT analysis on Tektronix oscilloscope

FFT analysis (continued)

Figure 2 shows the distortion components contributed by the Tektronix oscilloscope. Although the second harmonic spur is well down (–46 dB) relative to the fundamental, the Tektronix scope generates two other major distortion components plus a much higher noise floor. At 2 GHz and 8 GHz, we can see spectral spurs with amplitudes of approximately 34 dB down from the fundamental. The 8-GHz spur is exactly 5 GHz higher than the fundamental, and the 2-GHz spur is exactly 5 GHz below the fundamental, but folded back into the positive frequency domain (ABS[3 GHz – 5 GHz]). Manually varying the frequency of the input sine wave shows that these two components of distortion track the fundamental and always appear at ± 5 GHz around the fundamental input signal. And the worst-case condition appears to be when the fundamental input frequency is set near 3 GHz.

These two distortion components are primarily caused by misalignment of this instrument's interleaved A/D converters. The TDS6604 utilizes four 5-GSa/s A/D converters to achieve an interleaved 20-GSa/s sampling rate on two channels simultaneously, whereas the Agilent scope utilizes a single 20-GSa/s monolithic converter on each channel with much tighter integration of internally interleaved A/D converters within a single chip.

With a 3-GHz input signal, the distortion component at 2 GHz on the Tektronix scope should manifest itself as a modulating/low-frequency "beating" distortion component in the time domain. This means that both timing and amplitude measurements may show higher variability of real-time results from measurement to measurement. In addition, the higher noise floor of the Tektronix oscilloscope (~30 percent higher than the Agilent scope's noise floor) also will contribute to variability in measurement results when you are using real-time sampling.

Next, we computed the total distortion caused by the various elements of frequency distortion on both the Agilent and Tektronix oscilloscopes. By integrating all the distortion spurs (fundamental spur not included), we can easily compute the percentage of total distortion for each scope when capturing this 3-GHz sine wave. But to eliminate the noise-floor effects, we averaged the FFT spectrum results and then considered only frequency spurs more positive than 45 dB below the fundamental. (Distortion components below this level are insignificant.) Table 1 shows the results of this measurement and computation at two different input-signal levels and two different scope vertical-sensitivity settings that are typical when measuring today's high-speed LVDS digital signals.

With a 3-GHz input sine wave the Tektronix oscilloscope generates approximately 25 percent more total distortion than the Agilent oscilloscope. Input signal level and oscilloscope vertical sensitivity settings don't appear to have much effect. However, by varying the input frequency of our sine wave test signal, we found definite "sweet spots" for both the Agilent and Tektronix oscilloscopes. And in some cases, total distortion on the Tektronix scope may be less than the Agilent scope at particular frequency settings. But additional testing at a variety of frequency settings showed that the worst-case distortion on the Agilent scope (at 2.037 GHz) was less than the worst-case distortion on the Tektronix scope (at 3.082 GHz).

Let's now turn our attention to time-domain measurements and see how frequency components of distortion are manifested in the time domain, which is the primary usage of an oscilloscope.

	Input signal level	Scope V/div	Percent distortion
Agilent 54855A	2.5 dBm (300 mV rms)	100 mV/div	1.98%
Agilent 54855A	8.0 dBm (560 mV rms)	200 mV/div	2.05%
Tektronix TDS6604	2.5 dBm (300 mV rms)	100 mV/div	2.47%
Tektronix TDS6604	8.0 dBm (560 mV rms)	200 mV/div	2.47%

Table 1.

Measuring rise and fall times

With a pure sine wave input, theoretical timing parameters are very predictable. A 3-GHz sine wave has rising and falling edge speeds of exactly 98.4 picoseconds, based on a 10 percent to 90 percent criteria. Figure 3 shows the results of 100 successive real-time measurements performed on the Agilent 54855A.

As we predicted, the –35 dB second harmonic distortion component has manifested itself in the time domain as slight asymmetry in the edge speeds of this signal. After 100 measurements, the average rising edge speed measured approximately 3.9 ps fast, and the average falling edge speed measured approximately 3.0 ps slow. But for real-time/single-shot measurements, which is the primary usage model for a fast-sample-rate scope, the repetitive/average measurement should be of less concern. Your highest concern should be the real-time variability of measurements.

In this particular series of 100 measurements, we find from the on-screen statistics that the rise-time measurement had a worst-case error of –7.1 ps, and the fall-time measurement had a worst-case error of +7.2 ps relative to theoretical edge speeds for a 3-GHz input source. With additional measurements beyond a count of 100, worst-case measurements are likely to increase on both scopes due to random error sources, but the standard deviation of

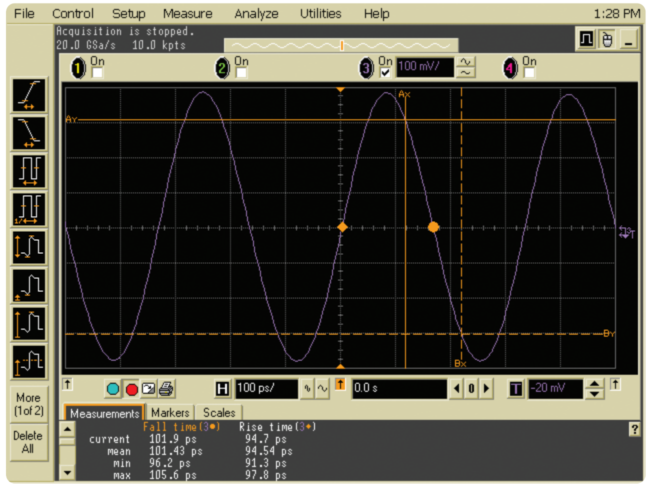

Figure 3. Rise/fall times on the Agilent scope

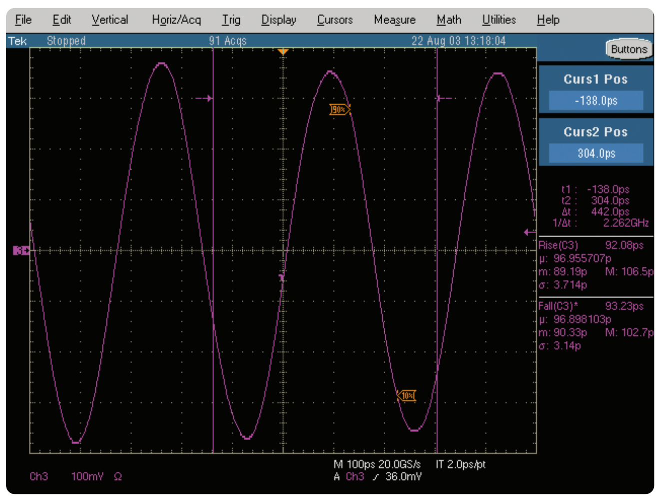

Figure 4. Rise/fall times on the Tektronix scope

approximately 1.5 ps for rise-time measurements and 1.3 ps for fall-time measurements would be fairly stable on the Agilent oscilloscope. Let's now compare these results to measurements made on the Tektronix oscilloscope.

As Figure 4 shows, the Tektronix oscilloscope produced slightly more-accurate average measurements of edge speeds, but much worse real-time measurements in terms of variability. The average measurements for both the rise and fall times were approximately –1.4 ps in error for 100 successive measurements. However, as we previously mentioned, for a high-speed real-time oscilloscope, variability of real-time measurements should be your highest concern, not repetitive-averaged measurements. As predicted from the frequency-domain analysis, the distortion component at 2 GHz, along with the higher noise floor, appears to be inducing a very high variability in measurements. The rise-time measurement showed as much as –9.2 ps error, and the fall-time measurement showed as much as –8.1 ps error. The standard deviation was greater than 3 ps for both rise-time and fall-time measurements, which was significantly higher (~2X) than the standard deviation of real-time measurements performed on the Agilent scope.

So, which scope performed better on the rise/fall-time measurement test? If you are making primarily repetitive-averaged measurements, then the Tektronix scope performed slightly better. But if you are using the scope to make real-time/single-shot measurements, then the Agilent scope produced much more reliable and repeatable measurements with a much lower standard deviation. Let's now take a look at some amplitude measurements.

Measuring volts peak-to-peak

As another time-domain distortion test, we measured the variability of peak-to-peak amplitudes of our test signal. Figure 5 shows the variability of peak-to-peak measurement results on the Agilent 54855A after 100 successive measurements. With an input-signal amplitude of approximately 770 $mV_{p\text{-}p}$, the Agilent scope produced approximately 16 mV of peak-to-peak variation with a standard deviation of 3.2 $mV_{p\text{-}p}$. Let's compare these measurement results to the Tektronix TDS6604.

As Figure 6 shows, the TDS6604 produced 63 mV of peak-to-peak variations performing the same set of 100 consecutive $V_{p\text{-}p}$ measurements with a standard deviation of 13.8 $mV_{p\text{-}p}$. This is more that 4X the peak-to-peak measurement variations produced on the Agilent scope. Again, the large variability in measurements on the Tektronix scope is primarily due to the 2-GHz "beating" frequency caused by interleaved A/D converter misalignment. Effects of the 30 percent higher noise floor of the Tektronix oscilloscope also contributed to higher measurement variability. In fact, you can visually detect the variation in peak-to-peak measurements on the Tektronix scope display. If you look closely at Figure 6, you can actually see variations in acquired-signal amplitudes when comparing adjacent cycles of the 3-GHz sine wave.

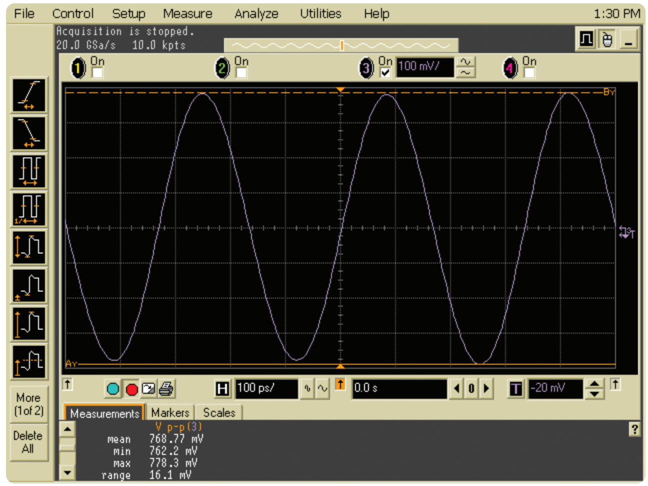

Figure 5. $V_{p\text{-}p}$ measurement on Agilent scope

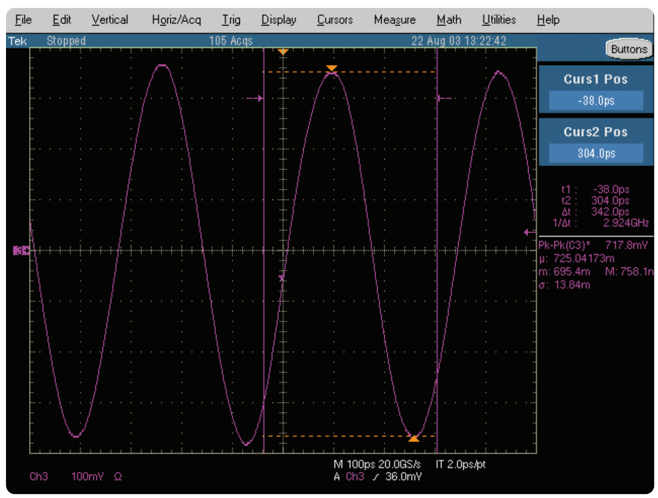

Figure 6. $V_{p\text{-}p}$ measurement on Tektronix scope

Visual distortion test using infinite persistence

In our last test, we looked at visual variability in acquired waveforms to get a more intuitive feel to see if our scope is producing distorted waveform results. Unfortunately, showing real-time variability with "live" display updates in an application note is impossible.

Figure 7 shows worst-case visual variations on the Agilent 54855A using the infinite persistence display mode. The infinite persistence mode accumulates repetitive acquisitions on-screen to show worst-case variations. For this particular test, we accumulated 100 real-time acquisitions on each scope. As you can see, there is very little amplitude and timing variation shown in the infinite persistence display mode for this high-speed signal captured with the Agilent oscilloscope. Although it may be difficult to visually detect distortions in edge speeds, we can see slight modulations in peak-to-peak amplitudes. However, cycle-to-cycle timing variations appear to be extremely stable. This is a due to the Agilent scope's very low trigger jitter characteristic of less than 1 picosecond rms. (Note: The trigger point for both scopes is at center-screen.)

Figure 8 shows the same repetitive infinite persistence measurements using the Tektronix TDS6604. The waveform acquisitions on the Tektronix scope "bounces" significantly both vertically and horizontally as evidenced by the "blurred" infinite persistence display.

The horizontal variations are primarily due to the much-higher trigger jitter characteristic of the Tektronix TDS6604, which is specified at 7 picoseconds rms. This magnitude of trigger jitter quickly translates into more than 40 ps of peak-to-peak timing jitter, as shown in Figure 8. When monitoring high-speed waveforms on fast time base settings, such as 100 ps/div as shown in these examples, you have a choice between viewing a very stable waveform on the Agilent oscilloscope or viewing waveforms that bounce both vertically and horizontally on the Tektronix oscilloscope due to a combination of acquired waveform distortion and trigger jitter.

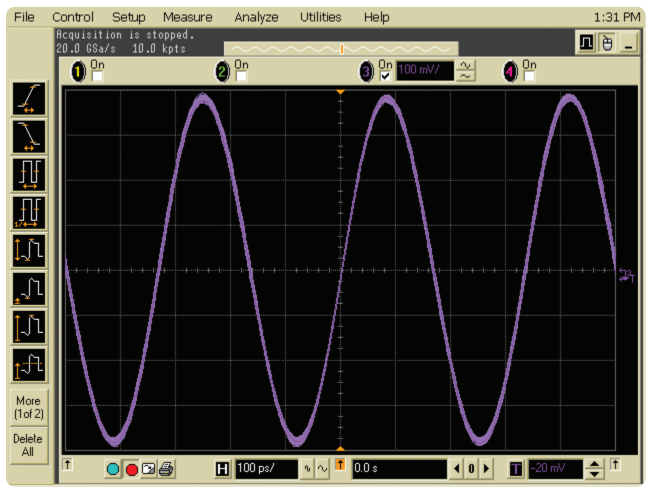

Figure 7. Visual distortion test using infinite persistence mode on the Agilent scope

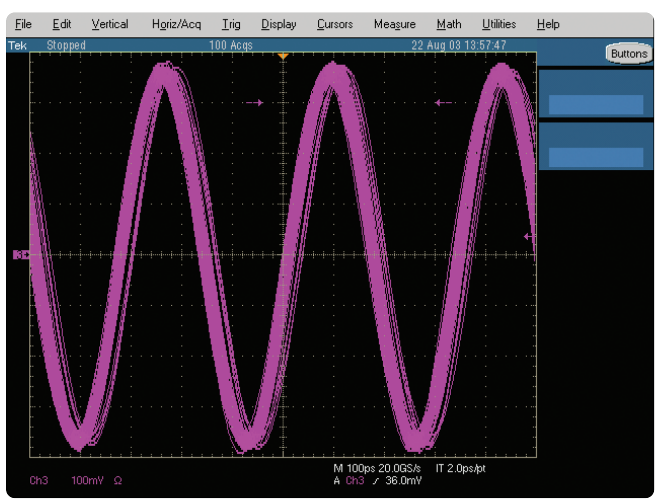

Figure 8. Visual distortion test using infinite persistence on the Tektronix scope

Conclusion

The series of distortion tests documented in this paper were not tuned to show best-case results for the Agilent scope and worst-case results for the Tektronix scope. As pointed out in this paper, the 3-GHz sine wave used as a reference test source is a frequency high enough to stress the upper bandwidth range of these scopes, yet low enough to reveal harmonic distortion if it exists (which it did on the Agilent scope). And since this class of real-time oscilloscopes is primarily used to test high-speed digital signals, 3 GHz represents typical higher fundamental frequency content in today's digital signals. We chose the sine wave because of its predictability in frequency content, wave shape, and timing parametrics. And finally, amplitudes of the test signals were chosen to be in the range of today's higher-speed LVDS digital signals, but scaled for near full-scale deflection in order to stress each scope's dynamic range.

Distortion components on the Agilent and Tektronix scope originate from different sources of error. Distortion on the Agilent scope comes primarily from amplifier/front-end harmonic distortion, which is a systematic/deterministic error source. This type of error translates into slightly less-accurate repetitive-averaged timing measurements. Tektronix scope distortion comes primarily from random (but bounded) sources of error including interleaved A/D converter misalignment and system noise. This type of error translates into a much higher standard deviation in both timing and amplitude measurements. For high-speed digital signal measurements, this higher standard deviation shows up as a higher measurement-system timing jitter floor, which is important because jitter measurements are a key application for both of these competitive oscilloscopes.

Only two units were tested in this side-by-side distortion analysis. The Agilent oscilloscope is representative of production units shipped after August 1, 2003. The Tektronix oscilloscope was obtained from a U.S. instrument-rental company. It is possible that if we tested different units, we might observe slightly different results, but we believe these test results are representative of all units. However, we don't know for sure without testing a large sample size of units from both vendors. But even if test results with additional units produced measurement results with 10 percent to 15 percent differences, the Agilent scopes would still show superior distortion measurement results.

Glossary

ABS absolute value of

Distortion any waveform deviations not present in the input signal that are induced by the oscilloscope

Dynamic range the maximum scaling of a signal that can be accurately measured by an oscilloscope. The typical dynamic range of an oscilloscope is usually “full scale,” or 8 divisions peak-to-peak.

FFT Fast Fourier Transform, a computationally efficient implementation of a discrete Fourier transform, which is an algorithm used to transform time domain data into frequency domain

Interleaved A/D converter a technique often used to increase the sample rate of an oscilloscope by multiplexing multiple precisely phase-delayed discrete analog-to-digital converters, each sampling at sub-rates to achieve an overall higher net real-time sample rate

LVDS low-voltage differential signaling

Trigger jitter uncertainty in the time-placement of the acquired digitized waveform in the scope’s memory and display relative to the trigger event

Related Literature

Publication Title	Publication Type	Publication Number
Agilent Infiniium 54850 Series Oscilloscopes and InfiniiMax 1130 Series Probes	Data Sheet	5988-7976EN
Side-by-Side Comparison of Agilent and Tektronix Probing Measurements	Application Note 1491	5989-0553EN

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