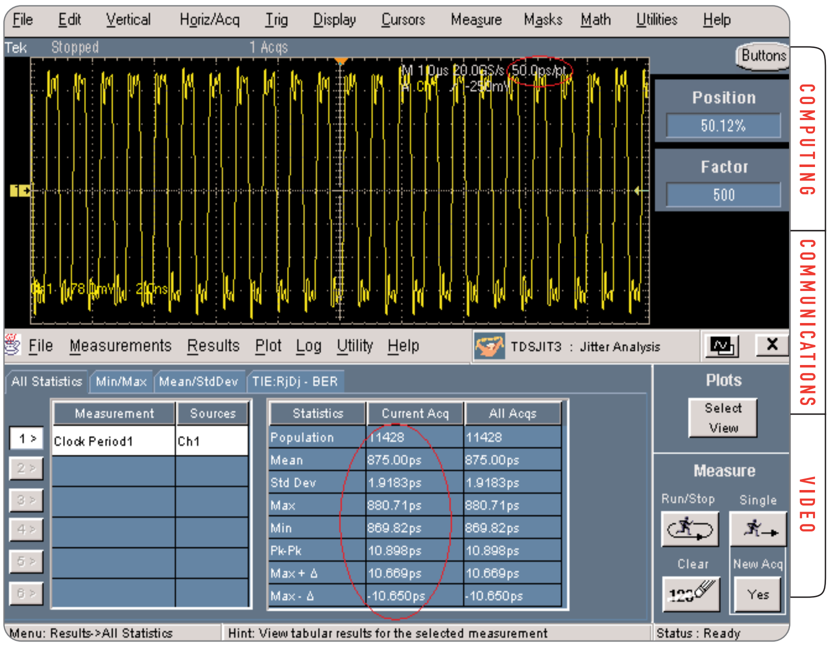
▶ Technical Brief

Delta-Time Accuracy: The Good, The Bad, and The Worst Case



	Measurement	Sources
1 >	Clock Period1	Ch1
2 >		
3 >		
4 >		
5 >		
6 >		

Statistics	Current Acq	All Acqs
Population	11428	11428
Mean	875.00ps	875.00ps
Std Dev	1.9183ps	1.9183ps
Max	880.71ps	880.71ps
Min	869.82ps	869.82ps
Pk-Pk	10.898ps	10.898ps
Max + Δ	10.669ps	10.669ps
Max - Δ	-10.650ps	-10.650ps

Menu: Results->All Statistics

Hint: View tabular results for the selected measurement

Status : Ready

▶ Ensure reliable time measurements with a digital oscilloscope for exceptional delta-time measurement accuracy

When testing high-speed microprocessor designs that incorporate next-generation bus architectures such as DDR II and RapidIO, or testing high-speed serial data communication systems such as Fibre Channel, SONET, Gigabit Ethernet and InfiniBand, design engineers need to see all the details of their high-speed signals. Their test and measurement equipment must provide a clear and accurate display of all the waveform activity, including jitter. How accurately a digital oscilloscope can measure the time interval between two events is an important factor when examining these high-speed signals. To ensure reliable time measurements, an oscilloscope should provide exceptional delta-time measurement accuracy.

The accuracy of delta-time measurements is controlled by the capabilities of the measuring instrument – the stability and accuracy of the time base, its sample rate, its input noise level, etc. When the delta-time measurement is inaccurate, the measurement instrument might report more jitter than is actually there, leading a design engineer to think that the system is not meeting specification, or that components are a problem. Or, it can hide errors in system design, possibly resulting in design problems being overlooked and potentially leading to costly troubleshooting later.

For these reasons, it is extremely important that design engineers use digital oscilloscopes with accurate delta-time measurement capabilities. But determining the accuracy of delta-time measurement is not a trivial task, especially given how highly dependent the measurement is on the signal being examined. Consequently, evaluating delta-time measurement accuracy should be based on worst-case conditions to allow the widest safety margin.

The first place to look when trying to determine the delta-time measurement accuracy is in the specifications. But a word of caution here: Different manufacturers specify delta-time measurement accuracy differently. You should, therefore, know the details about how the specifications were determined. For example, are these numbers typical, worst case, optimized or …? What were the measurement conditions? What signal source was used?

You should also be aware of the different types of delta-time measurements and the various sources of errors that affect their accuracy.

Two Types of Delta-Time Measurements

There are two basic types of delta-time measurements: direct measurements and derived measurements.

Direct Measurements

Direct measurements are any measurements that determine the elapsed time between two events as defined by the crossings of a specific voltage level or levels. This can be a measurement between two levels on a single edge, any two edges of the same signal, or the edges of two different signals. To further complicate matters, it can also be between different levels for each edge. But, essentially, it is an elapsed-time measurement – that is, how much time elapsed between events A and B. Some typical direct measurements include:

- Period
- Pulse width
- Delay time
- Skew
- Rise time
- Fall time

Derived Measurements

Derived measurements are not taken directly. Instead, they are calculated (or derived) from one or more direct measurements. The fact that they are derived means that smaller errors in the direct measurements can, in some cases, be compounded and at other times minimized. Some typical derived measurements include:

- Frequency
- Time interval error
- Cycle-to-cycle jitter
- N-cycle jitter

Sources of Error in Delta-Time Measurements

There are several potential sources of error to be aware of that can affect the delta-time accuracy of a digital oscilloscope. Some of these errors are to be found within the oscilloscope and some in the connection to the design under test. To minimize errors due to connection, use the highest bandwidth, lowest noise probes available and follow the prescribed techniques for acquiring high-quality signals. Also, take all precautions to eliminate any signal degradation as it moves from the device under test to the oscilloscope. For a more detailed description of high-speed probing techniques and equipment, see *TekConnect™ Probes: Signal Fidelity Issues and Modeling* available on the Web at www.tektronix.com.

One must also determine the sources of error within the measuring device and assure oneself that the digital oscilloscope is adequate to the measurement task. These errors are significant threats to delta-time accuracy and are, unfortunately, extremely difficult to determine and minimize. Why? Because many of the errors depend on the measurements being made and the type of signal being examined, including its frequency and period. There are six primary sources of error inherent in the instruments used for timing measurements. They include:

- Time base center frequency accuracy
- Timing instability
- Vertical noise
- Bandwidth effects
- Interleaving or calibration error
- Interpolation (aliasing) error

Time base Center Frequency Accuracy

This is usually the least significant of these error sources. Often quoted in ppm (parts per million), it represents the average frequency error of the instrument's reference clock. Fortunately, time base center frequency accuracy generally has minimal impact on the accuracy of typical delta-time measurements. For example, if a design engineer examines a 100 ps jitter on a clock using a digital oscilloscope with 10 ppm time base center frequency accuracy, this error would introduce only 1 femtosecond of inaccuracy. This particular source of error is generally of concern only when making measurements of an extremely long duration.

Timing Instability

Timing instability in the time base of an oscilloscope is a combination of phase noise in the instrument clock and aperture jitter in the samplers. In modern oscilloscope designs, this inaccuracy is often a significant, but not dominant, source of timing measurement error.

Bandwidth Effects

Oscilloscope bandwidth has more significant effects on certain parametric measurements, such as risetime and certain skew measurements, than on other measurements, such as period measurements. For example, the period of a 500 MHz clock with a 50 ps risetime can be measured with a 500 MHz oscilloscope, however the bandwidth of the oscilloscope acts as a harmonic limiter to the higher frequency components. What is removed is any transient and edge information contained in the original signal. Therefore the oscilloscope should have adequate bandwidth to acquire the higher order harmonics of the signal. The Fibre Channel standard recommends the oscilloscope have a bandwidth of at least 3 to 5 times the frequency of the data signal.

It is also important to consider that both the risetime of oscilloscope and the risetime of the probe or interconnect cabling affect the final risetime measurement. The following formula is a rule of thumb for calculating the effect of multiple risetimes in a signal path:

$$RT_{measured} = \sqrt{RT^2_{scope} + RT^2_{probe} + RT^2_{signal}}$$

It can be applied to make small corrections to the measurement when the risetimes of the oscilloscope and probe are smaller than that of signal. If the risetimes of the oscilloscope and probe are close to or larger than that of signal, using this equation to adjust a measurement may render incorrect results. Also, with today's digital oscilloscopes, the risetime may not fit a Gaussian distribution, thereby making any use of this technique unreliable.

For a more detailed description of bandwidth effects, see *Effect of Bandwidth on Transient Information* available on the Web at www.tektronix.com.

Vertical Noise

Noise is inherent in any oscilloscope's vertical system. Vertical noise can also result from poor probing and acquisition techniques, poor connections, or environmental noise. Vertical noise is often the dominant error in timing measurements, especially for signals with relatively low slew rates. The amount of inherent vertical noise is a measure of the quality of the oscilloscope design. Because this is such an important source of error, Tektronix offers oscilloscopes that have some of the lowest noise vertical systems available. To minimize sources of vertical noise outside the oscilloscope, be sure to follow good probing techniques such as making a secure connection and keeping the ground leads as short as possible. Try to control the test environment as much as possible by eliminating any stray interference that could inadvertently affect the design's signal quality. In digital oscilloscopes, maximizing the amplitude of a signal applied to the acquisition system will improve signal to noise and minimize vertical quantization error within the system.

Interleaving or Calibration Error

This is another of the big sources of errors affecting delta-time accuracy. Today's high-speed digital oscilloscopes use multiple digitizers, which are interleaved in a predetermined order to achieve high digitizing rates. Typically, these digitizers are interleaved in powers of two, with the predominant numbers being eight and sixteen. Interleaving errors result from mismatches in performance characteristics between these digitizers. All modern digitizers have calibration adjustments or self-calibrating routines. In order to get the optimum accuracy, you need to be sure that your instrument is properly calibrated (or self-calibrated) before beginning the measurement. Finally, digitizing errors will be different at different frequencies. We will use this fact to help in our evaluation (see Table 1 for a derivation of common points to compare digitizers and evaluate performance one-on-one).

Interpolation (Aliasing) Error

This source of error also poses a major threat to delta-time accuracy. Since sampling techniques used in digitizers sample the signal at a point in time determined by the system clock, the sample may not fall at the exact crossing level set for the measurement. To alleviate this problem, the system calculates where in time the signal crossed the set level between the digitized points using an interpolation algorithm. As a result, the accuracy of the measurement is dependent on the accuracy and consistency of this interpolation algorithm. Moreover, for the interpolation algorithm to be effective, there must be a sufficient number of sample points with respect to the frequency content of the signal and the bandwidth of the instrument to supply the necessary performance.

Note: Two of the most popular interpolation algorithms are sin(x)/x interpolation and linear interpolation. Sin(x)/x interpolation is the preferred method because it takes into account the bandwidth of the acquisition system. Sin(x)/x interpolation can be used effectively using a finite number of sample points, and is available on most oscilloscopes. The drawback of sin(x)/x interpolation is that it is computationally complex, and unless performed in hardware, requires long execution times. On the other hand, linear interpolation is one of the simplest interpolation algorithms. Linear interpolation is computationally simple and renders small interpolation errors when a sufficient number of sample points on each edge are acquired. At least 2.5 sample points should be acquired on each edge for linear interpolation to work without introducing too much error. To achieve the highest accuracy using linear interpolation, you should have 5 or more sample points on each edge. With Tektronix oscilloscopes, to increase the number of sample points per edge, simply increase the sample resolution. The oscilloscope accurately provides additional sin(x)/x interpolated points, with the sin(x)/x interpolation implemented in specialized firmware.

Assessing Digitizer Interleaving Performance

With all these different sources of error affecting the accuracy of the instrument – especially errors due to vertical noise, interleaving, and interpolation – there is no one way to specify simple delta-time accuracy for an arbitrary real-world signal. Instead, the only safe assumption is to determine the worst-case scenario for an actual signal. Even in those situations where the signal is thought to fit the best case, the worst should be assumed. This is because in the real world a signal could easily change due to jitter, for example, resulting in an erroneous measurement.

The most effective way to demonstrate the delta-time measurement accuracy of an instrument is to use what we refer to as the good, the bad, and the worst cases. Table 1, and Figures 1 and 2 show the characteristics of three different signals to illustrate the true performance of a digital oscilloscope under changing conditions, not just ideal conditions.

The best-case delta-time measurement accuracy of a digital oscilloscope can be characterized using a signal with its period determined by the following formula:

S_i * N * k

Where:

S_i = Sample interval (1/sample rate)
N = Number of interleaved digitizers
k = An arbitrary integer

For this example, the designer is using an oscilloscope with a sample rate of 20 GS/s and sixteen interleaved digitizers. To examine the best case delta-time measurement accuracy, the designer decides to make k = 1 because that will create a period of 800 ps or a frequency of 1.25 GHz. Such a signal is well within the range of today's high-performance designs and can be easily created by a stable signal source.

50 ps * 16 x 1 = 800 ps signal period

Waveform A (The Good) in Figure 1 and Figure 2A shows that for this particular digital oscilloscope, an input signal period of 800 ps results in optimal delta-time measurement accuracy. However, as Table 1 shows, if the signal period is the least bit different, then it very quickly becomes bad or even worst case. Now let's explain in detail what is meant by the good, the bad, and the worst case.

The Good

This is the best-case situation at which the input signal’s period coincides with the digital oscilloscope’s acquisition, canceling out any errors due to interleaving or interpolation. In this case, the two edges being measured are sampled by the same one of the “N” interleaved digitizers, therefore preventing interleaving error. Moreover, any interpolation error is canceled out because the period of the signal being measured coincides with the oscilloscope’s sample interval. The result is that the sample point always falls in the same place on the waveform (see waveform Figure 2A).

The Bad

This is the situation at which there is maximum error from digitizer interleaving but still minimal effect from aliasing. In this case, the input signal period has shifted by one sample interval, resulting in different digitizers acquiring the subsequent edges. This reveals any interleaving errors between the different digitizers. However, as interpolation is occurring at the same fractional distance from sample point to each edge, any aliasing errors will be canceled out just as they were in the “good” case (see waveform Figure 2B). But as Table 1 shows, the period does not have to change much for a signal to drift into these conditions.

The revised equation for this case would be:

S_i * ((N * k) ±1)

Or in our example:

50 ps * ((16 * 1) + 1) = 850 ps signal period

The Worst Case

This is the situation where the maximum error from both interleaving and aliasing occurs. Not only are different digitizers acquiring the two edges, but also the edges are occurring at different times within the sample interval, which reveals interpolation errors. This represents worst-case performance and should be considered representative of the real-world performance of the instrument (see waveform Figure 2C). This error can be minimized by using the sin(x)/x interpolation of the oscilloscope to acquire more points on each edge before using linear interpolation to find crossing times (see waveform Figure 2D).

Now our equation is:

S_i * ((N * k) ±1.5)

And therefore:

50 ps * ((16 * 1) + 1.5) = 875 ps signal period

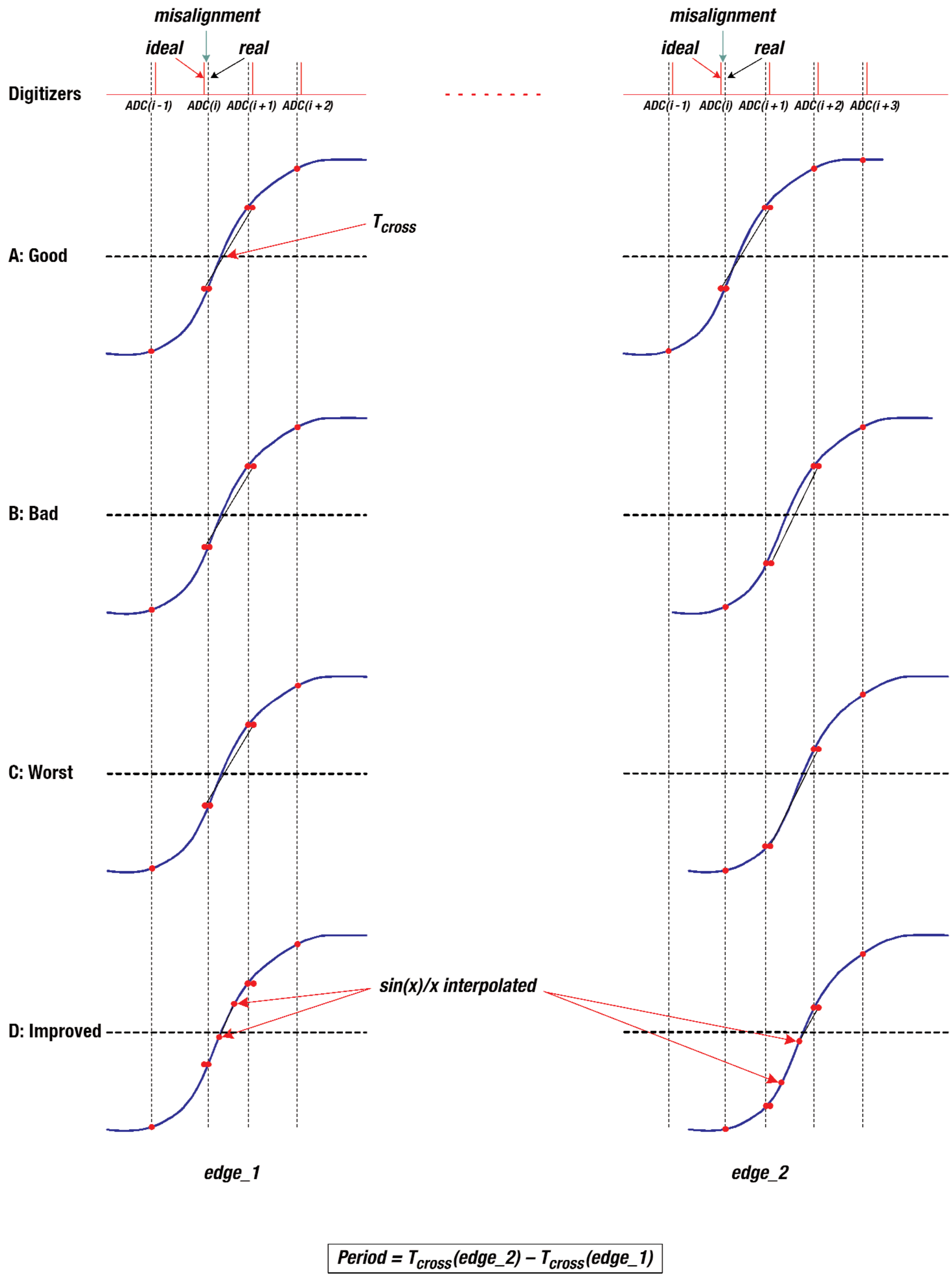
But why is an 800 ps signal period the best-case scenario? When the oscilloscope has small integer interleave ratios (such as two and four) along with sample rates in the small-integer Gigasample range, then many small-integer sample periods (such as 4 ns) falls into the “good” category. But remember, it doesn’t take much change in the signal period – usually only a few hundred picoseconds – to move it out of that ideal area.

Table 1. Deriving Common Points for Comparison of Digitizer Performance

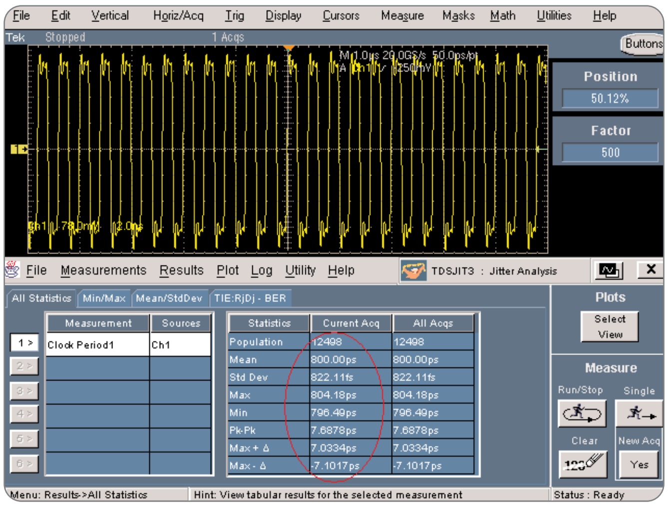
Ideal Points for Comparison

Results	Conditions	Æ Time Measurement	10 GS/s	20 GS/s
Good	No aliasing (interpolation error) No misalignment error	N * S_i * k	800 ps	800 ps
Bad	No aliasing (interpolation error) Misalignment error	S_i * ((N * k) ±1)	900 ps	850 ps
Worst Case	Aliasing (interpolation error) Misalignment error	S_i * ((N * k) ±1.5)	950 ps	875 ps

NOTES:
1. For N = 8 or 16.
2. k = arbitrary integer (in this case 1).
3. S_i = 1/10 GS/s or 1/20 GS/s.



▶ ***Figure 1.*** *Comparing digitizer interleaving and interpolation performance.*

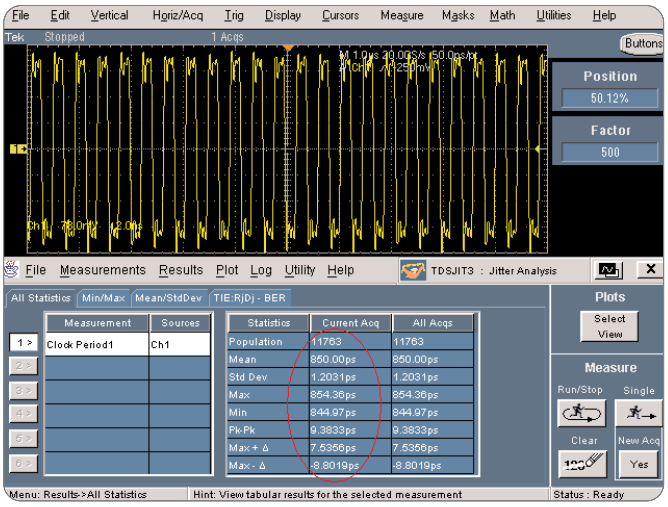


	Measurement	Sources
1 >	Clock Period1	Ch1

Statistics	Current Acq	All Acqs
Population	12498	12498
Mean	800.00ps	800.00ps
Std Dev	822.11fs	822.11fs
Max	804.18ps	804.18ps
Min	796.49ps	796.49ps
Pk-Pk	7.6878ps	7.6878ps
Max + Δ	7.0334ps	7.0334ps
Max - Δ	-7.1017ps	-7.1017ps

Menu: Results->All Statistics
Hint: View tabular results for the selected measurement
Status : Ready

▶ ***Figure 2A.*** *The Good – Waveform A benchmarks the overall system's ability to measure the standard deviation, equivalent to RMS jitter on a square wave with a period of 800 ps. This results in an impressive 822.11 fs delta-time measurement accuracy.*

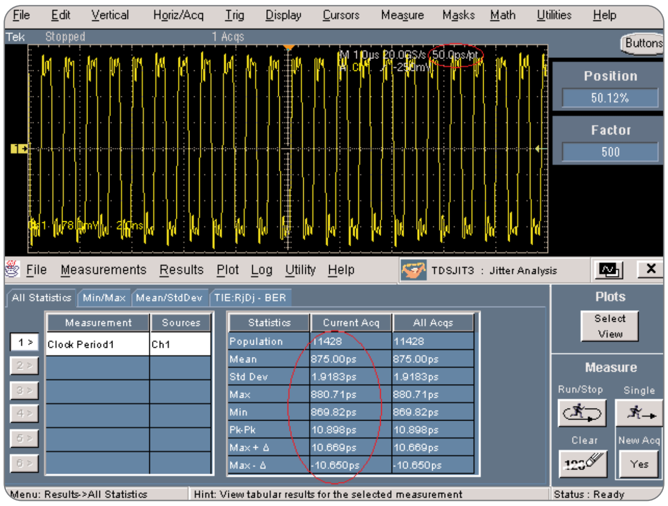


	Measurement	Sources
1 >	Clock Period1	Ch1

Statistics	Current Acq	All Acqs
Population	11763	11763
Mean	850.00ps	850.00ps
Std Dev	1.2031ps	1.2031ps
Max	854.36ps	854.36ps
Min	844.97ps	844.97ps
Pk-Pk	9.3833ps	9.3833ps
Max + Δ	7.5356ps	7.5356ps
Max - Δ	-8.8019ps	-8.8019ps

Menu: Results->All Statistics
Hint: View tabular results for the selected measurement
Status : Ready

▶ ***Figure 2B.*** *The Bad – Waveform B demonstrates the effect of accuracy when the error from digitizer interleaving is introduced by changing the input signal to a 850 ps period square wave. This results in RMS jitter of 1.2031 ps.*



	Measurement	Sources
1 >	Clock Period1	Ch1

Statistics	Current Acq	All Acqs
Population	11428	11428
Mean	875.00ps	875.00ps
Std Dev	1.9183ps	1.9183ps
Max	880.71ps	880.71ps
Min	869.82ps	869.82ps
Pk-Pk	10.898ps	10.898ps
Max + Δ	10.669ps	10.669ps
Max - Δ	-10.650ps	-10.650ps

Menu: Results->All Statistics
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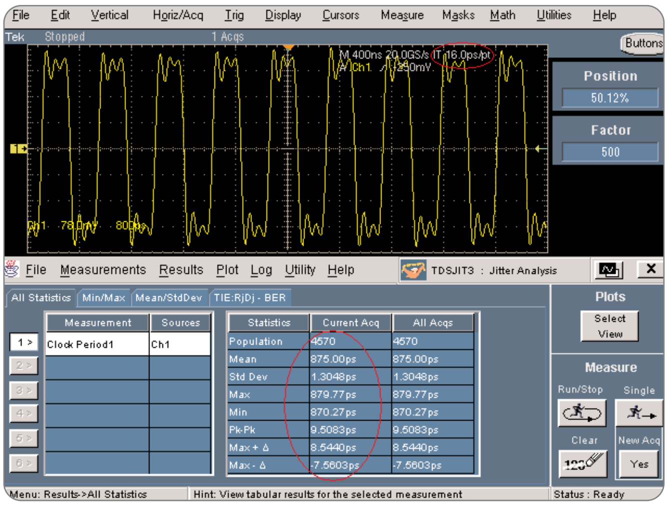
Status : Ready

▶ ***Figure 2C.*** *The Worst Case – Waveform C presents the worst-case scenario when the errors from both digitizer interleaving and interpolation occur at an input square wave signal with a period of 875 ps. With a risetime of 100 ps, there are only 2-3 sample points on each edge at sampling interval of 50 ps/pt. This results in RMS jitter of 1.9183 ps.*



	Measurement	Sources
1 >	Clock Period1	Ch1

Statistics	Current Acq	All Acqs
Population	4570	4570
Mean	875.00ps	875.00ps
Std Dev	1.3048ps	1.3048ps
Max	879.77ps	879.77ps
Min	870.27ps	870.27ps
Pk-Pk	9.5083ps	9.5083ps
Max + Δ	8.5440ps	8.5440ps
Max - Δ	-7.5603ps	-7.5603ps

Menu: Results->All Statistics
Hint: View tabular results for the selected measurement
Status : Ready

▶ ***Figure 2D.*** *The Improved Worst Case – Waveform D presents the improved worst-case scenario when the errors from both digitizer interleaving and interpolation occur at an input square wave signal with a period of 875 ps. However the total error is minimized by using the sin(x)/x interpolation feature of the oscilloscope. Using a sampling interval of 16 ps/pt in interpolation mode (IT), we have acquired 6 or more sample points on each edge. This results in RMS jitter of 1.3048 ps.*

These figures show that, in the real world, an engineer may have a signal that is designed to operate in the "good" category of the digital oscilloscope, say a 100 MHz clock signal. But real-world signals have jitter. If this signal has a peak jitter of 100 ps, it will operate in the bad or even worst-case category for some amount of time.

Therefore, even if the design engineer's input signal happens to nominally match the digital oscilloscope's best conditions with respect to delta-time accuracy, the worst-case measurement inaccuracy should be assumed.

The Fine Art of Picking the Optimum Measurement Equipment

The best way a design engineer can be assured that a digital oscilloscope will deliver the expected performance is to take the instrument for a "test drive." Submitting it to actual conditions is really the only way to find out how it will perform in a given situation. To compare different digital oscilloscopes, deliberately pick signals that will expose the worst-case conditions. The best approach is to deliberately compare the worst-case situations using the information in Table 1. One way to do this is to input a standard signal and then vary the frequency or the period to reveal the sources of the errors. Do this even if the signal in your application happens to fall within the best-case scenario category. Real-world signals are not perfect and a designer needs an oscilloscope that delivers exceptional delta timing measurement accuracy to handle all types of signal variations, whether they are good, bad, or worst case.

Be aware that performance parameters can change as settings change. For example, changing the channel count can affect the sampling interval and adjusting the volts per division setting can affect the vertical noise. So be sure to test the oscilloscope for its delta-time accuracy with the same set up that will be used to make the actual measurements.

Conclusion

Tektronix, Inc. follows a policy of full disclosure regarding specifications and the conditions under which they were taken. We specify performance at a level that you should reasonably expect to achieve under the same test conditions, rather than using a banner spec to grab your attention, only to disappoint you later under actual conditions. And if you'd like to see how any of our instruments operate with your signals, contact your local Tektronix representative for a hands-on demonstration.

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