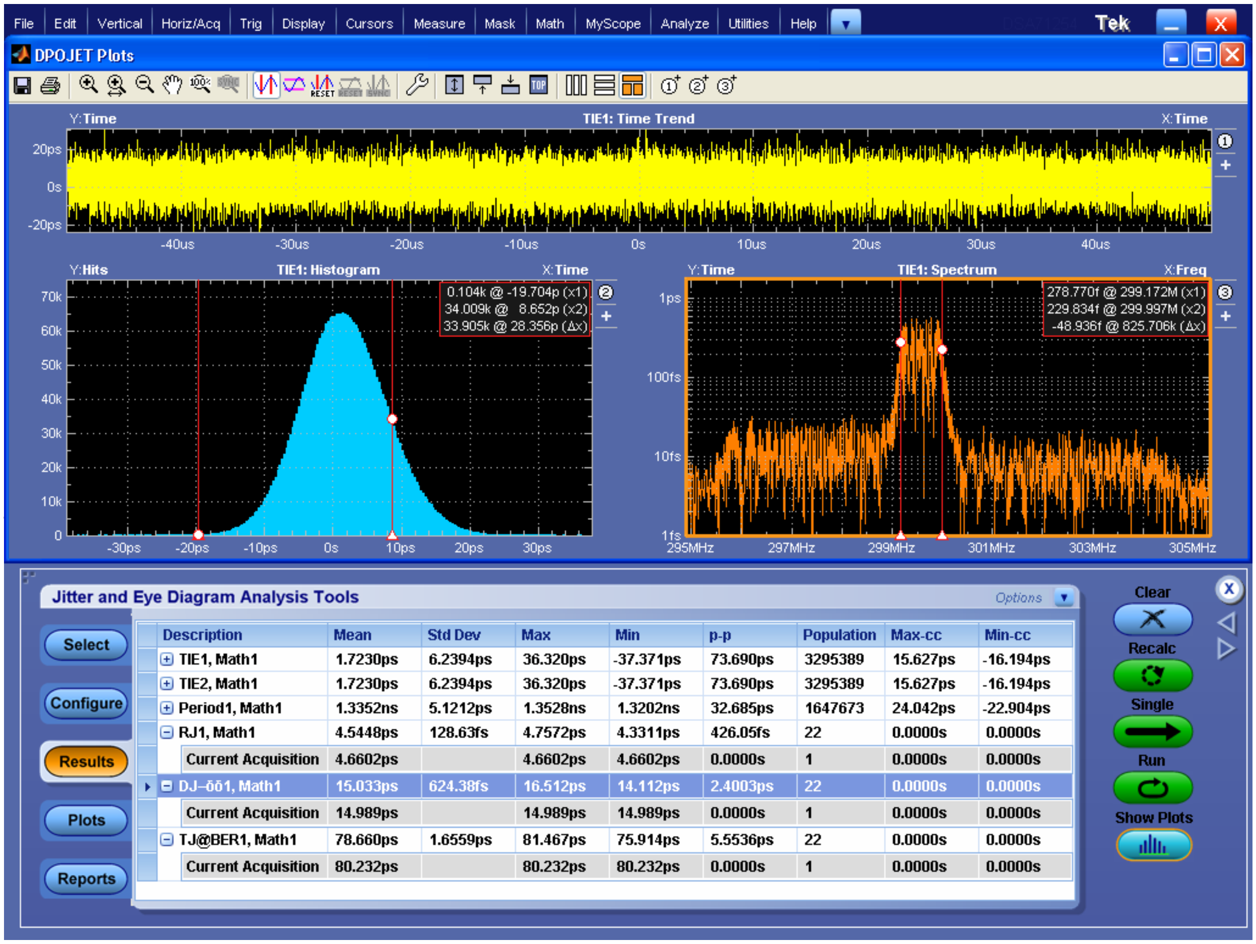
Jitter Analysis:

Accuracy ▸ Delta Time Accuracy ▸ Resolution ▸ Jitter Noise Floor



Accuracy

Parametric measurements require known accuracy to ensure adequate tolerance and testing margin. Jitter measurements are not excluded. Tektronix specifies accuracy and states typical values for jitter measurement ability. Accuracy and jitter measurements are affected by several factors: among theses are major contributors like instrument timing stability, sampling noise, amplitude instrument noise floor; and signal interpolation error.

Interpolation error is an error due to linearly interpolating between real voltage samples. This error is shown to be less than 0.3 ps RMS when measuring signals with with 100 ps t_r and detecting at the 50% threshold at 20 GSa/s. This error can be minimized and in many cases improved using SIN(X)/X interpolation and methods such as maximizing signal amplitude to input full scale. In most cases this error is swamped by other sources of error – but it can be easily mitigated using non-linear interpolation, like Sin(X)/X or Sinc interpolation.

The next source of timing error is vertical or amplitude noise. Instrument amplitude noise is a result of amplitude noise intrinsic to the input attenuators, preamplifiers, track and hold amplifiers, and analog to digital converter circuitry. This noise will change based on attenuator settings, bandwidth limits, and even room temperature.

How stable the timing elements in a sampling system are directly affects timing measurement accuracy. If the timebase has errors, so the measurements taken relative to the timebase will have equal or larger errors. Timebase stability in an oscilloscope starts with a reference clock, any frequency multipliers, counters, and associated circuitry that gates or triggers when the voltage samples that are taken.

Two more sources of error are ADC aperture uncertainty and quantization error. These can manifest as both amplitude and timing noise – depending on how the sample data is used. It is difficult to distinguish the actual source of an error because of how analog to digital conversion takes. Because any sampler has a finite amount of time it gates the sample, ADC aperture uncertainty, any sample taken may include both temporal and amplitude errors. Combined with the resolution of the ADC and related quantization error, sample time and voltage placement has a finite error.

Finally, amplitude noise is another important factor in timing measurement accuracy. With fast edges, the amplitude will have little effect, but as edge rates slow, amplitude noise can become dominant. This is because when edge rates are slow relative to the system bandwidth, amplitude noise changes the timing of the threshold crossing - thus amplitude noise converts into timing measurement error.

So how does one deal with all these noise sources and remain confident results are accurate? Tektronix uses the term Delta Time Accuracy to specify the accuracy of time measurements. The specification is very important because it includes errors from the effects that affect timing accuracy, including the ones described above.

Delta Time Accuracy

For the DPO72004, the Delta Time Accuracy (DTA) specification is similar to:

$$DTA_{pk-pk} = 5 \times \sqrt{2 \times \left[\left[\frac{N}{A} \times t_{rm} \right]^2 + t_j^{\,2} \right]} + TBA \times duration$$

Where: *A* = input signal amplitude (volts)

t_{rm} = 10-90% measured risetime (sec)

N = input-referred noise (volts rms)

t_j = short/medium term aperture uncertainty (sec rms)

TBA = timebase accuracy (2 ppm)

duration = delta-time measurement (sec)

assumes edge shape that results from Gaussian filter response

The details of a particular instrument's specified Delta Time Accuracy can be found in the appropriate instrument manual. Generally, the specification means that for any edge to edge timing measurement, you can determine the accuracy of the result, guaranteed and traceable to the NIST.

The equation above includes scale and signal amplitude, input noise, and other influencing factors. The full topic of DTA is too complex too cover in a short paper, so we'll limit the discussion to a few components we can control. To do that, we will look at the DTA specification for the TDS6000 Series oscilloscopes, which uses a constant to account for worst case influences.

$$DTA = \pm 0.3 \times SI + 2.0\, ppm \times MI$$

Where: SI is the sample interval in seconds.

MI is the measurement interval in seconds.

± 0.3 is the fixed constant to factor in the oscilloscope acquisition system.

2.0 ppm is the DPO70000 timebase accuracy specification

Why the formula? Different factors affect the accuracy differently. Timebase accuracy - how well the 10.0 MHz reference is calibrated and has drift occurred - affects long term measurements. E.g., when measuring a 1.0 ms pulse, sub-picosecond effects like an interpolation error, are very small compared to the error caused by a 0.4 ppm calibration offset. 1.0ms * 0.4 ppm results in a 400 ps error. Sampler error, vertical gain accuracy, interpolation accuracy and noise are contained in the first term, and affect short term measurements. E.g., when measuring a 3 GB/s data signal, timebase error is insignificant, and sampling error becomes dominant. A 10% error in sampler timing is 2 ps. But 2 ppm of 333 ps is only 667 as.

Looking at two examples of measurements made with a DPO72004, one short period clock, and one long pulse width, allows visualization of the predominate errors. In a fast 1.0GHz clock, the period is being measured using real-time sampling at 50GS/s, or 20 ps per point. Using the DTA equation we find:

$$DTA = \pm 0.3 \times 20\,ps + 2.0\,ppm \times 1ns = \pm 6.002\,ps \;\; peak$$

This will be the maximum peak measurement error in any one measurement made in a single shot or real time acquisition. Over a significant sample size, about 1000 measurements, the standard deviation of the error is typically 0.06xSI+3.5ppmxMI. In this example, it amounts to about 1.2 ps RMS.

In a longer period measurement, the short term effects dictated by the constant 0.3 are overwhelmed by timebase calibration and stability:

$$DTA = \pm 0.3 \times 20\,ps + 2.0\,ppm \times 10us = \pm 21.200\,ps \;\; peak$$

In this case we see that when measuring a 100 kHz clock the measurement error can be as large as 21 ps peak. The rms result will be similarly affected since timebase errors are deterministic.

It is worth noting the accuracy specification for Tektronix oscilloscopes, like the DSA72004, is for the specified calibration period and includes the environmental range. That means that over the specified temperature and humidity range and for a period of one year after calibration, the largest measurement error will be equal to or less than the Delta-Time-Accuracy specification. For typical serial data rates, that error is less than 6 ps peak, and less than 1.2 ps RMS. Typical accuracy is much better as seen in the accompanying images.

Resolution

Measurement resolution defines the ability to reliably detect a measurement change. It should not be confused with measurement accuracy or even measurement repeatability. With timing measurements, resolution is the ability to discern small changes in a signal’s timing, whether the change is intentional or a result of noise. Items as substantial as a hardware counter bit width, or even the counter’s electrical bandwidth can limit timing resolution. Or things as obscure as the software that performs the mathematical averaging can limit timing resolution.

In hardware timers, like the typical Time Interval Analyzer (TIA, SIA), timing resolution is limited in hardware to hundreds of femto-seconds. If a hardware counter or it’s equivalent circuit is clocked at 5 GHz, it can’t detect a change any smaller than 0.2 ps. This is a physical limitation of the device and easily understood.

In real-time oscilloscopes, timing resolution is limited by sample rate, interpolation accuracy and software based math libraries. Using sample rates of 50 GS/s and SIN(X)/X interpolation, resolution of tens of femto-seconds is possible. Since the resolution in this case is based on math libraries, the real resolving power is sub-femto-seconds (0.0001 ps).

Resolution implies the ability to measure a very small change in timing. But this may not always be true. What happens when the change is smaller that the intrinsic measurement noise within the instrument? Thus the overall system noise floor must be considered when measuring small amplitudes of noise or jitter. Simply knowing the system resolution is not at all helpful in understanding the true limit of resolution, accuracy, or overall capability.

Jitter Noise Floor

What is the Jitter Noise Floor? Jitter noise floor (JNF) is the intrinsic instrument noise portion of a jitter measurement. JNF sets the lower limit on detectable jitter. Jitter amplitudes near the JNF become objectively unobservable. While some may claim you can resolve jitter amplitudes that are less than the JNF, the ability to do so has no parametric value due to other systematic errors.

One method of verifying JNF is to measure a noise free perfectly timed signal. While perfect signals are rare, suitably good sources do exist that can be used to demonstrate jitter noise floors. Common instruments recommended for this testing are high precision RF generators with low phase noise, like an Anritsu 3690A. Other methods include using a shorted transmission line such that the reflect pulse is unchanging, and the reflected pulse width is measured.

The JNF equation for a DSA72004 oscilloscope is:

$$JNF = \sqrt{\left[\frac{N}{FS \times A} \times trm\right]^2 + tj^2} \quad \text{(sec rms)}$$

Where: A = input signal amplitude (volts)

t_{rm} = 10-90% measured risetime (sec)

N = input-referred noise (volts rms)

FS_j = full scale range of input

t_j = short/medium term aperture uncertainty (sec rms)

assumes edge shape that results from Gaussian filter response

Tektronix uses time interval error to measure JNF. TIE is optimum because includes any phase error in the signal – whether the error is high frequency or low frequency in nature, single event or and accumulated error. Further, with real-time instruments the reference for the TIE method can be a calculated perfect clock. *[1]

One other factor affects JNF. That is the frequency band of jitter noise you want to include in the results. All noise, including jitter, can have frequency components with wavelengths from kilometers to angstroms. When measuring JNF – limits on the included frequency range should also be stated. At Tektronix, our typical numbers are representative of JNF for the longest record length and maximum sample rate. And we specify with equation like the one above.

When we want to show a JNF value comparable to our competitor's products we will often use shorter record lengths comparable to the target. For example, the DSA72004 delivers up to 200 Mpt record lengths at 50 GSa/s, giving it the ability to measure jitter down to 250 Hz. For comparative purposes, an Agilent DSO81304B has only 2 Mpt record lengths at 40 GSa/s, thus the Agilent can only measures jitter down to 20,000 Hz.

Understanding most noise is a 1/f phenomenon, the six octave range between 250 Hz and 20 kHz is critical, and is equivalent to the frequency offset from carrier in phase noise measurements. To properly compare these two instruments, it's important the DSA72004 record length and vertical FS settings be set comparable to the compare target.

When making a comparison in this range of frequencies, the DSA72004 has a JNF of 400 fs compared to the Agilent DSO81304B JNF*[2] of 650 fs.

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*[1] Worth noting only real-time instruments can measure jitter from near DC to up to instrument bandwidth while maintaining the various phase and harmonic relationships, thus capture subtle phase and harmonic noise relative to a perfect reference (non-realtime methods use internal hardware clock recovery circuits as phase references that filter lower frequency noise out of the results – similar to the PLL TIE measurement mentioned above).

*2 Agilent has used JNF and JMF (jitter measurement floor) interchangeably.

Summary

Combined with DTA, JNF helps to define what a particular instrument can measure, effectively and accurately, within the temporal or timing domain.

The screen captures on the following pages demonstrate the typical performance of the DSA72004 oscilloscope measuring a signal from a stable source, like a BERT or RF generator.

The first image, Figure 1, shows a relatively short record, ten nanoseconds. TIE is 328 fs RMS. This would be similar to how our competitors reflect jitter measurement floor.

The next image, Figure 2, shows a more reasonable and longer record capture of ten microseconds. In this case the DSA72004 TIE has increased only slightly to 374fs. Note that this record length is near the limit of competing oscilloscopes.

The third image, Figure 3, shows a TIE measurement of a stable clock signal made over a 1ms record of 40Mpts at 40GSa/s – twenty times longer than the longest record of competing instruments. An acquisition of 1ms included noise sources from 1kHz up to the bandwidth of the oscilloscope, in this case, 15GHz.

The TIE is now about 1.0ps RMS, but more important is the peak-to-peak value of the maximum timing error. Over the 1ms acquisition, peak timing error measurements are less than ±7ps, and cycle-to-cycle is about ±4ps peak. If one considers how instruments are typically used today and look at PLL based TIE measurements, the errors fall to under ±3ps peak, and to under 500fs RMS across the 40 mega-point 1ms record shown.

The actual instrument JNF is less than the value displayed since the source also has noise.

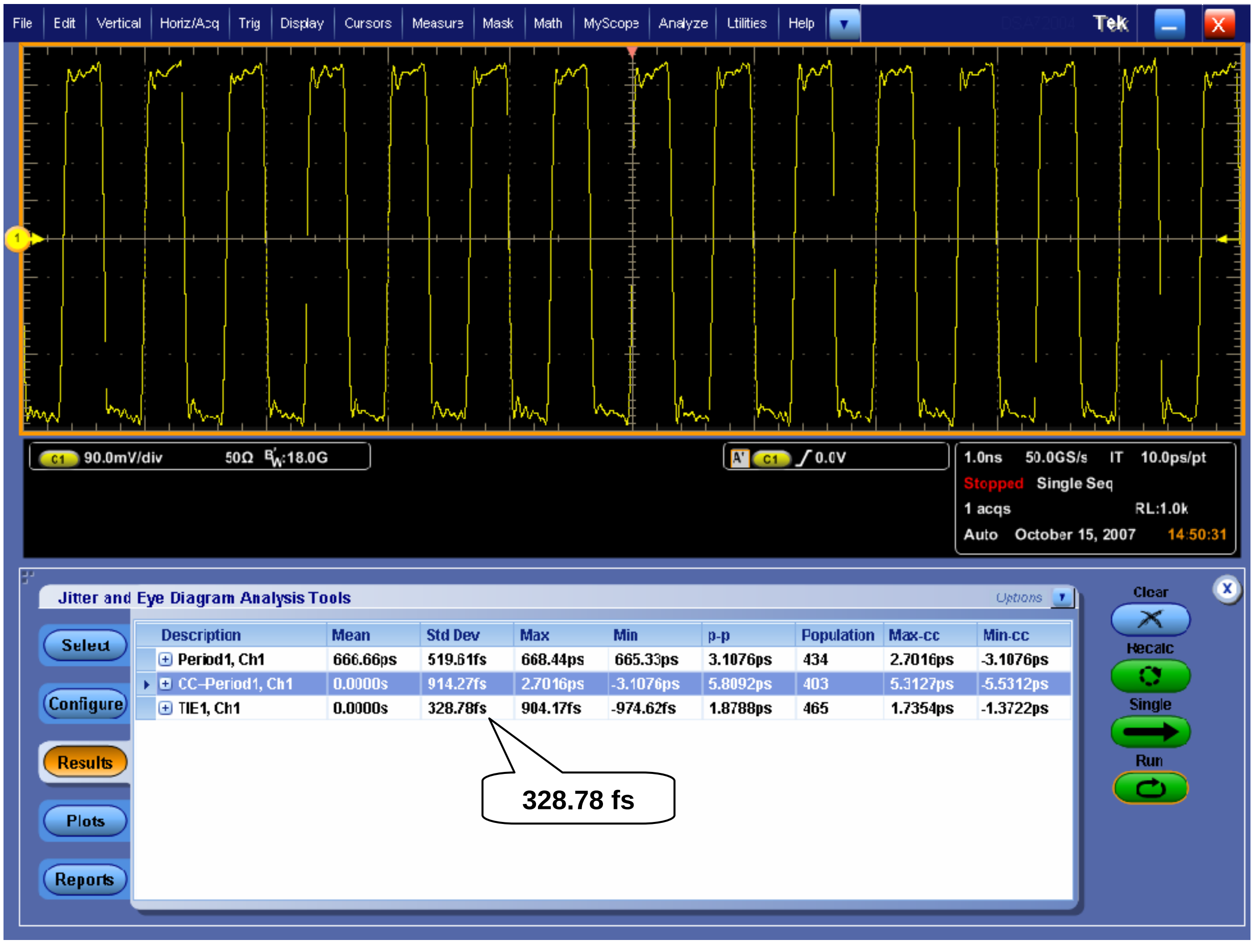

Figure 1 – 10 ns Acquisition

Figure 1 shows a measurement technique similar to how competitors determine Jitter Measurement Floor. This timebase setting only includes noise frequencies down to about 200MHz. Not a realistic test case for most standards testing where the measurement requirements extend to 1.5 MHz, and below.

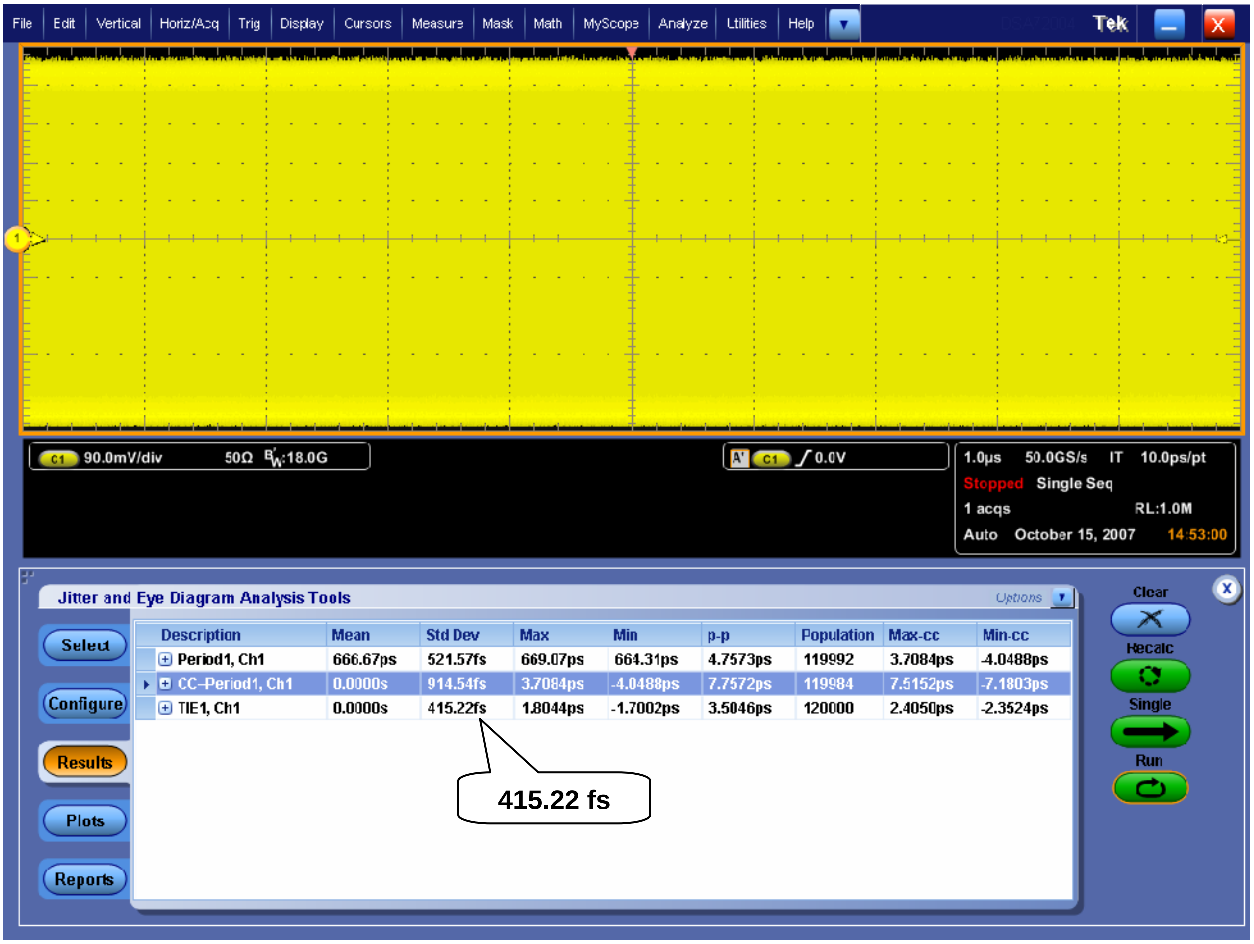

Figure 2 – 10 us Acquisition

Figure 2 – 10 us Acquisition is showing jitter noise floor over a longer acquisition interval. This includes low frequency noise down to about 100kHz. This provides a more complete view of noise on the signal, one comparable to the maximum record length of the DSO81304B instrument, but still doesn't realistically represent how real-time oscilloscopes are used today.

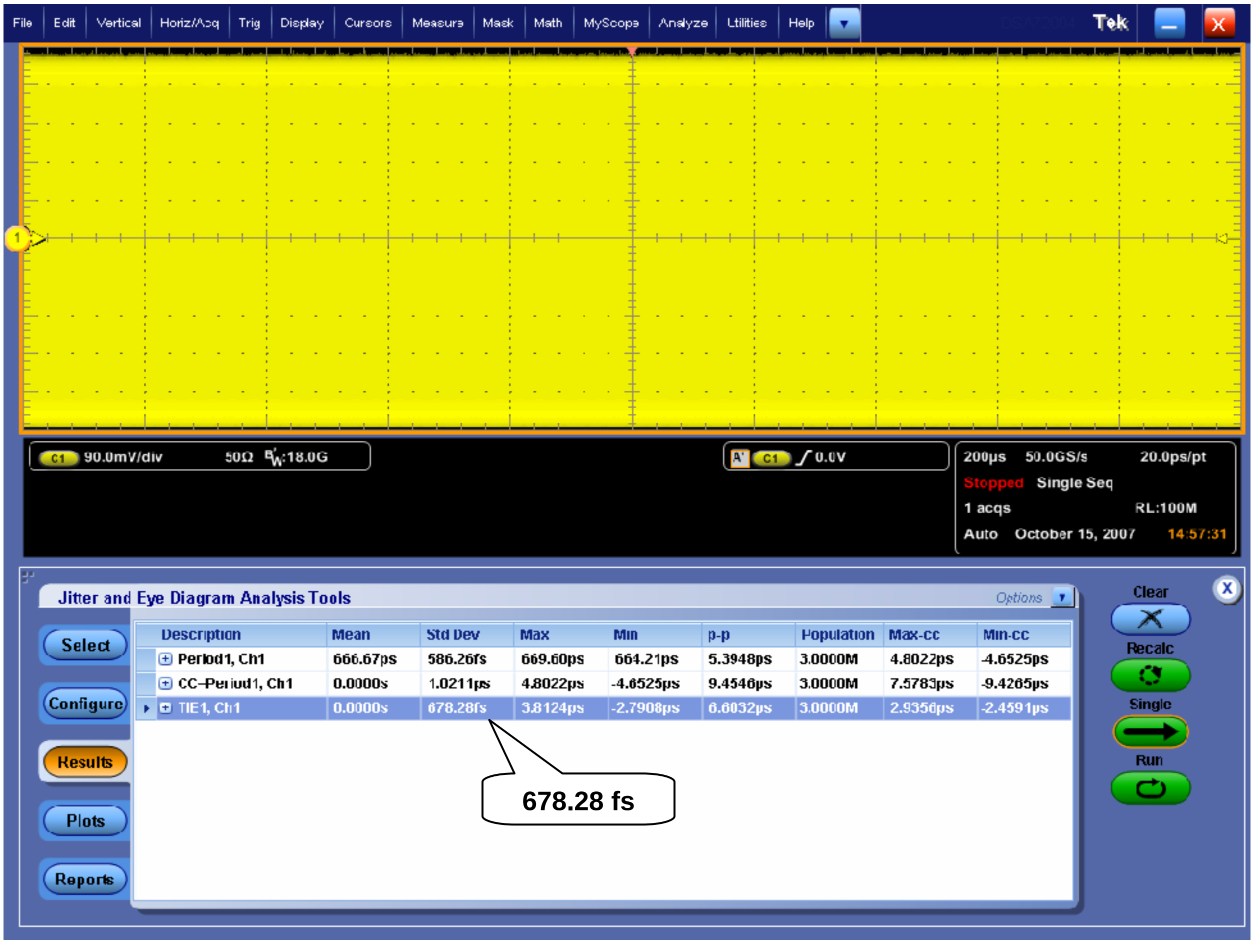

Figure 3 – 2 ms Acquisition

In Figure 3, a 2 ms acquisition allows direct viewing of jitter and modulation effects down to 500 Hz. Yet the DSA72004 maintains a sub-picosecond JNF: an amazing 678 femto-seconds RMS.

In today's standards, like FBD, PCI-Express, DDR2, the long record length acquisitions are acquired and processed to show cycle-to-cycle dependencies, validate modulation profiles of reference clocks and validate PLL and clock recovery performance. In this view we see the DSA72004 has extremely fine long term performance over this 50GSa/s 100 Mpt record.

Jitter is a DC to light phenomena. When trying to discover where jitter is coming from, you need to ability to look across the entire jitter spectrum, from sub-kiloHertz power supply frequencies up to multi-gigaHertz adjacent clock and data frequencies. The Tektronix DSA70000 Series oscilloscopes provide you with this ability.

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