Making More Accurate Jitter Measurements

A variety of new techniques are available to make more accurate timing measurements. Applications include analyzing the timing characteristics of a single signal (such as locating clock jitter anomalies) or characterizing the timing jitter between multiple signals (such as I and Q in wireless data transmissions). This paper will discuss the use of widebandwidth digital oscilloscopes incorporating histograms and trending plots in making precise timing measurements, their application to specific design problems, the use of statistical analysis to determine product specifications and sources of error in jitter measurements. Using advanced techniques, timing changes as small as one picosecond can be observed.

DIRECT READOUT OF JITTER USING HISTOGRAMS OR PARAMETERS

Jitter measurements are among the most common applications for digital oscilloscopes. With an extensive range of automatic measurement parameters, it is easy to measure the key timing parameters such as width, period, and duty cycle. Some digital oscilloscopes offer statistical analysis of these parameters over multiple acquisitions, providing direct readout of the mean, lowest and highest value, and standard deviation (sigma) of up to 5 measurement parameters as shown in Figure 1.

The standard deviation provides direct readout of the rms jitter for that parameter. The difference between the lowest and highest value is the peak-to-peak jitter. For example, in Figure 1, the width has an rms jitter of 38 ns and a peak to peak jitter of 130 ns.

Some digital oscilloscopes offer the ability to read out the maximum and minimum values of parameters but only use data from the first pulse captured each time the scope triggers. This can cause the loss of important data and even lead to incorrect conclusions. Oscilloscopes with sufficient processing capability can measure an unlimited number of values of a parameter on each single-shot trigger. Parameter measurement statistics provide direct reading jitter characterization. A parameter analysis package extends this capability, providing histogramming, trending and statistical parameters to automatically interpret the histogram data. Histograms provide a visual display of the statistical distribution of the measured parameters. The trending function draws a line graph that shows the time evolution of parameter values. Using the four traces available in a DSO, it is possible to display up to 4 histograms or trend lines.

Knowledge of the distribution of random processes like jitter is often of critical importance in understanding the source. An example is shown in Figure 2 where the width jitter of a waveform is histogrammed.

Note that in addition to the histogram display, the sigma and range of the distribution are being readout as parameters. In this case, the jitter is uniformly distrib-
uted (i.e. any of the width deviations within the range are equally probable). Figure 3 shows the analysis of width jitter in which the jitter has a Gaussian distribution.

The uniform distribution is often associated with synchronization operations. The input waveform to a synchronizer selects the next available internal clock pulse. If the input and internal clocks are independent, then the delay between the input and the clock is distributed uniformly over a clock period.

The Gaussian distribution is associated with random noise which, in Figure 3, is associated with the phase noise in a reference oscillator.

When making a precision jitter measurement, it is useful to know the sources of jitter inherent in the oscilloscope. These include trigger jitter, timebase stability, and delay jitter. In high-performance digital oscilloscopes, jitter due to the DSO (or other measuring instrument) is generally uncorrelated with the device under test, the instrument jitter can be subtracted from the total jitter using quadrature subtraction:

\[
t_{\text{DUT}} = \sqrt{(t_{\text{meas}} - t_{\text{instr}})^2}
\]

Where:
- \(t_{\text{DUT}}\) - jitter of device under test
- \(t_{\text{meas}}\) - total measured jitter
- \(t_{\text{instr}}\) - jitter due to instrument

The jitter due to instrumentation should be measured under the specific conditions of the test being performed. This will be discussed in the next section.
SETUP - VERIFYING THE ACCURACY OF TIMING JITTER TESTS

DEMONSTRATING THE ACCURACY OF TIME PARAMETER HISTOGRAMS

Oscilloscopes equipped with parameter analysis capabilities can characterize time interval measurements with picosecond resolution in histogram displays. This usually brings up questions concerning the accuracy of these measurements. The following experiment demonstrates the inherent accuracy of measuring short (<1 us) time intervals using the random interleaved sampling (RIS) acquisition mode. It also serves as a model to setup real world measurements.

In this demonstration, the propagation delay of a length of coaxial cable is measured using a fast (32 ps) edge as the driving source. The oscilloscope is triggered externally using the trigger output of the edge generator. The cable delay, for a 2-meter RG 58C/U cable, is approximately 9 ns. The oscilloscope is set to a sweep speed of 5 ns/div with a RIS sampling rate of 10 GS/s. The time delay between the Channel 1 and Channel 2 waveforms was measured using the delta delay (Ddelay) (1,2) parameter. The cable delay is constant and any variation in the delay is due to the oscilloscope. This experiment allows testing of the accuracy of the measurement system. In a real example, two signals of interest would be connected to the inputs of the DSO, and the timing jitter between them could then be analyzed.

In RIS mode, many acquisitions are made, and the time between the trigger and the first sample is measured using a time-to-digital converter (TDC) which has a 10 ps resolution. Since the trigger and sampling clock are generally not synchronous, there is a random distribution of time offsets. The oscilloscope places selected samples into appropriate 100 ps wide bins to achieve the 10 GS/s effective sampling rate (20 times the single-shot rate of 500 MS/s). The accuracy of this process is dominated by the TDC interpolator accuracy. Other error sources, such as slew rate error in the delay measurement, are minimized by using a signal with a fast transition time. Similarly, the acquisitions are triggered simultaneously using the common, external trigger source to eliminate trigger jitter as an error source. And finally, the timebase accuracy, 10 ppm, has little or no effect contributing much less than 1 ps of error.

![Figure 4](http://www.lecroy.com/tutorials)

Figure 4. A test setup for measuring propagation delay through a coaxial cable. Since the delay of the passive cable is fixed, the variations in measured values are primarily due to the oscilloscope.
Figure 5 shows the result of the measurement. The upper trace shows the input to Channel 2; the middle trace shows the delayed signal as seen in Channel 3; and the lower trace contains the histogram of over 10,000 acquisitions and delay measurements.

The basic delay parameter and three additional statistical parameters appear in the table below the trace display. The statistical parameters read the mean (average), standard deviation (sigma), and range of the histogrammed delay measurements. Note that the standard deviation, which corresponds to the rms error, is 11.5 ps. This is less than the specification limit of the interpolator (TDC) rms accuracy of 20 ps. Keep in mind that this is the accuracy of any single measurement made with this oscilloscope. If multiple measurements are made and averaged, then the accuracy improves by \( \sqrt{n} \), which is why measurement parameter readouts are better than 1 ps resolution.

Using this method an oscilloscope, with parameter analysis capabilities can provide timing accuracy of 11.5 ps for each individual measurement of the time between two signal edges. However use of statistical analysis allows a change in average timing between the two signals to be measured to 1 ps or better.

**Locating Clock Jitter Anomalies Using Histogram and Trend Plots in a Single Signal to Locate Period and Width Violations**

Trend graphs plot a series of up to 20,000 measured parameter values and display them on the oscilloscope screen. When combined with the local (cycle-to-cycle) parameters, these plots are ideal for locating timing anomalies in large blocks of acquired clock signals.

The upper trace in Figure 6 contains 10,000 cycles of a 10 MHz clock waveform. Trend graphs of local period (lper) and local time over threshold (ltot) are shown in Trace A and Trace B. Trace A, the third trace from the top, shows a histogram of local period shows the distribution of cycle-by-cycle period measurements.

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flat trend with the exception of several spikes. Each spike represents a variation in the period of a single cycle of the clock waveform. The deviation can be read using the vertical axis scaling of 1 ns/div. The horizontal (event) axis of the trend plot has a one-to-one correspondence with each cycle in the acquired trace. By using a zoom expansion of the acquired trace centered around the region corresponding to a spike in the trend plot, we can view the period anomaly. This is shown in Trace C where the long period (102.5 ns instead of the nominal 100 ns) is marked by the relative time cursors arrows.

Similarly, the bottom trace (Trace B) shows the location of each cycle which has a width which differs from the nominal value.

In Figure 7, Trace C has been redefined as the histogram of local period. The histogram displays the distribution of up to 2,000,000,000 measured parameter values. In this example, it is showing the distribution of cycle-to-cycle period. The vertical scale is a logarithmic display of the number of measurements of each value. The center of the horizontal axis represents a period of 100 ns. The horizontal scaling is 1 ns/div. The small distribution to the right occurs about 102.5 ns.

The histogram and the trend displays are complementary. The histogram shows the number and distribution of parameter values, while the trend shows its location in the acquired data.

The interpretation of waveforms and histograms is aided by the use of measurement parameters. In Figure 8, the parameter readouts show the average, low, high, and standard deviation of the local period and local time over thresh-

Figure 8. Parameter statistics and statistical parameters completely characterize waveforms and histograms.
old measurements. This is an example of parameter statistics. The lower three parameters read the average, range, and standard deviation of the histogram of local time over threshold (width). These values correspond to the mean width, the peak-to-peak width jitter, and the rms width jitter in the acquired waveform. Figure 9 shows the same type of analysis applied to the local period measurement. Trends and histogramming analysis of any of the 40 standard or 60+ application-specific measurement parameters are available in high-performance oscilloscopes.

**Relative Jitter Measurements**

Using histograms to characterize relative timing jitter between multiple signals such as clock and data

Relative timing jitter between multiple signals, such as clock and data waveforms, has traditionally been measured using “Eye” diagrams. These persistence displays provide good qualitative information about both timing and signal-to-noise ratio.

High-performance oscilloscopes augment the eye diagram with statistical analysis of waveform parameters. Histogramming delay, Δ delay, or Δ time @ level provide a quantitative analysis of relative timing between two waveforms. In Figure 10, the leading edge jitter of the data waveform (Trace 2), shown in a traditional eye diagram, is measured relative to the clock (Trace 1) using the Δ time parameter.

**Figure 10.** Histogram of relative timing jitter between clock and data waveforms. Data waveform is shown in traditional “Eye” diagram format. The histogram shows the distribution of jitter across the leading edge of the eye.

**Figure 11.** Measuring the trailing edge jitter. After acquiring the histogram, use the parameter cursors to limit analysis to the trailing edge.
time @ level parameter. This parameter provides independent settings of the threshold level, shown as dashed horizontal lines, for each waveform as well as user selection of the desired edge slope. The top line of the parameter readout field shows the average, low, high, and sigma of this parameter for 3045 sweeps.

The lower trace is a histogram of the time @ level parameter. The horizontal range has been selected to match the Time/Div setting for the data waveform. This allows a visual analysis of the number of occurrences of each edge delay value. Additional statistical parameters, including average, sigma, range, and mode, provide a quantitative readout of the distribution of the delay values shown in the histogram. Note that parameter cursors (the dashed vertical lines in Figure 10) select the region being analyzed in all displays. In this example, the analysis is confined to the leading edge of the eye diagram. Since the histogram parameters are also being computed, the histogram must also be within the parameter cursors.

The trailing edge of the data waveform can also be analyzed in a similar manner, as shown in Figure 11. In Figure 11, the histogram was generated using the entire width of the “eye.” The acquisition was stopped, and the parameter cursors used to select only the trailing edge. The statistical parameters analyze only the region within the cursor limits, providing a detailed analysis of the trailing edge.

Histograms accept up to 2,000,000,000 measured values with a resolution of up to 2000 bins. There are a total 18 statistical parameters available to help analyze histograms. In this example, the standard deviation of the histogram yields the rms jitter, while the range provides the peak-to-peak jitter. Average value and mode (most commonly occurring value) are also displayed.

Figure 12. Histogram of the width and period of a clock waveform show different distributions of time jitter.

Figure 13. The Gaussian distribution found in the amplitude values of a random noise generator.
USING STATISTICAL ANALYSIS TO CHARACTERIZE RANDOM EVENTS

Electronic measurements produce data that contains both systematic and random variations. For example, the width and period of a clock pulse can be viewed as having a nominal value accompanied by a random variation which we call jitter. Statistical analysis allows engineers to study and characterize these random processes thereby gaining insight as to their causes. A parameter analysis option in a digital oscilloscope offers engineers an ideal tool for visualizing and quantifying random processes as shown in Figure 12. The histogram display shows the shape of the distribution of parameter values and statistical parameters provide accurate and concise measurements of that distribution.

The distribution of measurement values is related to the underlying process which generates the distribution. Figure 13 is an example of a random process that produces a Gaussian or normal distribution of amplitude values. The Gaussian distribution is a good indication that a random process is shaping variations in the measurement.

Consider what happens when a Gaussian distributed noise signal is applied to an envelope detector as shown in Figure 14. Here the process involves half-wave rectification and filtering (simulated in the scope using waveform math), and the distribution of amplitude values changes to a Rayleigh distribution. The amplitude values are no longer symmetric about the mean value (the effect of rectification). Knowledge of these effects allows calculation of expected noise power related to the input noise levels. Conversely, if the process were unknown, measurement of the input and output distributions would help identify it.

Let’s look at another distribution. The uniform distribution of delay shown in Figure 15 is characteristic of normal operation in a timing synchronizer. This circuit synehron-
nizes a random trigger event with an internal 400 MHz clock (2.5 ns period). If the input signal is independent of the system clock then there is an equal probability of having any value of delay between the input and output over the range of 1 clock period. In this example, observe that the primary distribution of the measured delay varies uniformly over a range of 2.5 ns as expected, but occasionally a longer delay occurs. This highlights an advantage of the statistical study of measured data in that it quantifies rarely occurring events which might be otherwise missed.

The upper trace (A) in Figure 17 is the clock. The middle trace (D) is the Q output, and the lower trace (B) is the histogram of the delay between positive going edges of the clock and the Q output. The histogram shows the distribution of over 1100 individual measurements. The statistical parameters average (avg[C]) and range (range[C]), listed in the parameter readout field below the display, provide a quantitative measure of the histogram. This data can now be stored into memory M1 for later comparison and the experiment repeated at 0°C.

The results of the next set of measurements is shown in Figure 18. Trace C, to the right in the lower trace, contains the data taken previously at 25°C which was stored in memory M1. Trace B, overlaid on Trace C and to the left in the lower trace, shows that the propagation delay has shifted to a lower value. The average value (mean) has shifted from 41.448 ns to 40.417 ns as indicated in the statistical parameter readings. In addition, the shape of the distribution has narrowed indicating a reduction in the spread of the measurements as shown in the

Figure 16: The propagation delay of a flip-flop is a typical specification that can be characterized by statistical analysis.

Figure 17: A histogram showing the distribution of over 1100 measurements of the propagation delay of a 74HC74 at 25°C.

**USING STATISTICAL ANALYSIS TO DETERMINE PRODUCT SPECIFICATIONS**

Oscilloscopes are ideal instruments for measuring the electrical characteristics, such as risetimes, setup/hold time, and propagation delay of electronic devices. Oscilloscopes with a parameter analysis option can perform statistical analysis on up to 2,000,000,000 measurements and display this data as a histogram.

Statistical parameters, extend the analysis capability, offering accurate readouts of up to 18 key statistical measurements such as mean, standard deviation, range, and many others.

http://www.lecroy.com/tutorials
range parameter change from 460 ns to 400 ns. These represent only two of the possible choices for analysis parameter readout. The complete list of available statistical parameters is shown in the accompanying table below.

This is a simple example of how histograms can be used to characterize component or unit specifications under selected conditions. It is extremely useful in applications where the manufacturer has not characterized the device in exactly the way required by your application. Note also the ability to display and compare data taken at different times and under different conditions. This total integration of measurement, display, and analysis is a hallmark of LeCroy oscilloscopes.

### STATISTICAL ANALYSIS AS A DIAGNOSTIC TOOL

Diagnosing circuit problems requires a fair amount of skill and good measurement tools. In most cases, the more ways you can look at a problem, the easier it is to solve. Parameter analysis provides an alternative view of the data and gives the diagnostician additional perspective. Consider the problem of detecting and diagnosing crossover distortion in a push-pull amplifier stage shown in Figure 19.

Distortion, especially at low levels, is difficult to see in a conventional oscilloscope time display. Figure 20 is an example of a waveform with crossover distortion. The distortion, although significant, is barely visible and could easily be missed.

Modern oscilloscopes offer additional processing such as the Fast Fourier Transform (FFT) to help detect problems like distortion. The FFT is a great asset in determining the existence of distortion, as shown in Figure 21, but it cannot differentiate between the various sources of distortion.
Clipping, asymmetries, limiting, and crossover all produce similar frequency domain spectra. The high harmonic content, in this case approximately -40 dB below the fundamental, is the key indication of the distortion that is present in the waveform.

The histogram of the amplitude data values, added to the waveform and FFT in Figure 22, provides the missing information about the nature of the distortion. The histogram is calculated by dividing the amplitude range of the oscilloscope into from 20 to 2000 bins (100 bins are used in this example). The number of samples which fall into each of these bins is plotted on the vertical axis against the nominal voltage value of the bin on the horizontal axis. The histogram of data values shows the number of samples in the waveform within each small voltage range. Note that instead of the usual "saddle shaped" histogram of a sine wave, we observe a higher than normal population of sample values at the center which represents zero volts. The waveform is hesitating at the zero crossing, a sure sign of crossover distortion. Clipping and limiting would be manifested as a higher population at the maximum and/or minimum peaks. Distortion due to asymmetry would be visible as an asymmetric histogram.

The ability to view the signal in three different domains (time, frequency, and statistical) provides a powerful tool for anyone having to diagnose complex circuit problems.

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Oscilloscopes with advanced memory management make such recovery possible due to the high level of functional integration designed into them.

Consider the histogram of delay measurements shown in the bottom trace of Figure 23. This histogram shows the uniform distribution of the delay between the two source waveforms shown in the Traces 2 and 3. These waveforms are from a trigger circuit which synchronizes an external event (Trace 3) with an internal 400 MHz clock to produce a synchronous pulse output (Trace 2).

The expected delay between the input and output is uniformly distributed over a range of 2.5 ns. Note, however, that a small number of output pulses are delayed by an additional 2.5 ns clock period. This behavior was not expected. Of the 1000 waveforms that were used to create the histogram, only the last one is still available in the scope.

We can take advantage of the long memories and the memory segmentation (sequence mode) available in some digital oscilloscopes to retain from 20 up to 2000 measured waveforms in the scope’s acquisition memory. The maximum number of segments varies with the total amount of memory available in any given model. Each of the segments has an individual time stamp which provides a real-time readout with 1/10 second precision and a relative time stamp with 1 ns resolution.

Memory segments pose no problem for the analysis, because the analysis functions operate correctly on data in the segmented memory.

Another advantage of oscilloscopes with advanced memory management is that the segmented traces can be displayed individually while retaining exact horizontal synchronization. This allows both the input and output waveforms for any selected seg-

Figure 22: The histogram of data amplitude shows a higher than normal number of sample values at the zero crossing at the center of the distribution. This indicates that the high harmonic levels are due to crossover distortion.

Figure 23: A histogram of delay between traces 3 and 2 with an unknown event occurring 2.5 ns outside the expected range.
ment to be displayed individually. Not only can they be displayed but parametric measurements of the delay for each segment can be displayed to help identify the data we’re looking for.

Figure 24 shows the same histogram setup using sequence mode with 1000 memory segments. Sequence is an acquisition mode controlled using the time-base menu. Note that the histogram data appears the same and can be confirmed by comparing the parameter readouts. The individual traces are viewed by expanding the upper traces using zoom mode. The oscilloscope is setup to lock the horizontal axes of both traces together using multi-zoom. The result is shown in Figure 25. Using multi-zoom, we can quickly scan through all the segments until the desired measurements are found. Note that the bottom line of the parameter readout is reading the delay for only the segment currently being viewed. In Figure 25, segment 228 is being displayed. Note that the delay measurement for this segment is 55.8 ns, making it one of the three measurements of interest.

This is a great example of how LeCroy oscilloscopes allow users to combine functions easily and seamlessly to solve tough measurement problems. In this example, statistical analysis, sequence mode, automatic parameter measurements, and multi-zoom were combined to acquire, store, analyze, and document the desired waveforms.

Figure 24 - Histogram of 1000 measurements acquired and stored in sequence (segmented memory) mode.

Figure 25 - Using Zoom to review individual waveform segments reveals one of the 3 long delays, 55.8 ns in segment 228