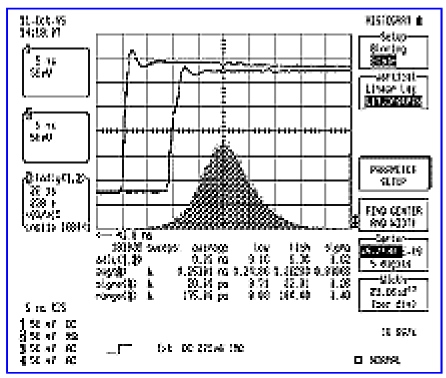
Accuracy in Time Jitter Measurements with LeCroy Oscilloscopes

Introduction

Accurate characterization of jitter errors requires a good understanding of signal digitizing and measurement methods. This Application Note describes how to make accurate time jitter measurements.



Measurement Methodology

A digital oscilloscope can be represented by the diagram in Figure 1. An understanding of each stage (or link in the measurement chain) is essential in order to ensure optimal measurement accuracy.

The stages shown in the diagram represent hardware (Stages 1 and 2) and software (Stages 3, 4 and 5):

Stage 1:
The external analog signal is input to the analog amplifier of the oscilloscope which is adjusted with the gain and offset controls.
Stage 2:
The ADC digitizes the analog signal. Numeric data are then sent to the internal memories.
Stage 3:
Internal calculations on numeric data.

Stages 4 and 5:
Statistical capabilities of the internal software can be used to build histograms and perform calculations on histograms.

Sample Rate

In order to make accurate time measurements between two signal edges, it is essential to perform a precise measurement of the edges. Adequate amplifier risetime and sufficient sample rate are the principal requisites for adequately representing signal edges.

Time measurements performed between two features on a signal are determined by finding the elapsed time between the amplitude levels corresponding to those features. For example, the time of a rising edge crossing a particular amplitude level can be deduced from the linear interpolation of the two nearest samples (see Figure 2).

Ideally, the 20-80% risetime of the waveform, or any other measurement of a signal edge, will be more accurate if the sample rate of the DSO is sufficient for capturing a minimum of two samples on the edge. For example, a 20-80% risetime of 2 ns can be characterized using a 1GS/s sample rate. If the risetime of the input signal is less than 2 ns, a 1 GS/s sample rate will be insufficient for maintaining good measurement accuracy, i.e. the signal will be undersampled.

Comparing the sigma values (standard deviation) in Figures 3 and 4, below, it can be clearly seen that a greater error occurs in cases where the risetime is calculated with fewer points.

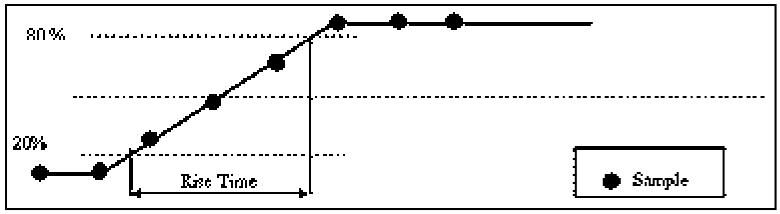
In Figure 3, sigma is 0.1 ns because the risetime calculation is based on more than three points. The fast sample rate, 2 GS/s, provides a high time resolution and hence a precise value of the rise time.

To digitize the same signal as in Figure 3, the sample rate selected in Figure 4 is reduced to 200 MS/s. Now, less than two points are used to perform the risetime measurement. The sigma value shows a higher deviation, demonstrating the reduced accuracy of the time measurements.

Amplifier Risetime Effects on Timing Measurements

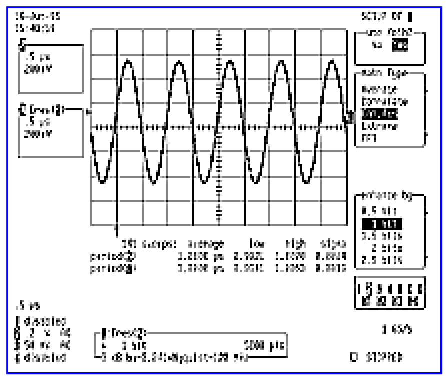
The intrinsic risetime of the input amplifier can affect the measurement of signal rise times. The measured risetime of a signal is a function of the instrument's risetime and the actual signal risetime. It can be expressed in the following formula:

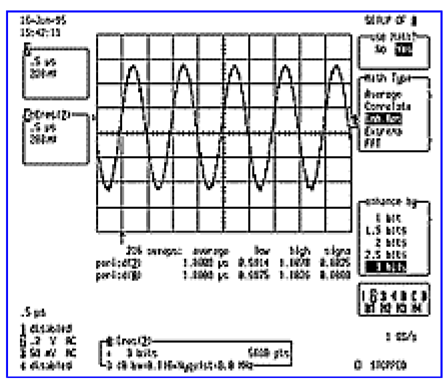
where: tsig is the signal rise time, tmeas the measured rise time, and tinstr the instrument risetime.



Bandwidth and Filtering Effects on Jitter Measurements

A jitter analysis is based on repeated measurement of the time between two signal edges. Absolute amplitude measurements are not required, and it is thus possible to bandwidth limit the input signal. If both of the edges have equal risetime, this frequency limitation increases the risetime but does not cause any instability in the relative time of the two signal edges. The filtering ensures that the edge is sampled adequately with more samples, without degrading the cyclic time measurement.





In fact, bandwidth limiting can improve the measurement by reducing noise on the waveform and by allowing the scope to capture more points on a fast signal edge. Note that by applying a 200 MHz filter to the signal edge in Figure 5, the scope can now capture more than two samples on the edge. The 20% to 80% risetime has been slowed to 1.8 ns but the position of this edge relative to another signal feature can now be measured more accurately.

The oscilloscope's intrinsic risetime is generally determined by the following equation:

(Risetime in ns) (Bandwidth in MHz)=0.35

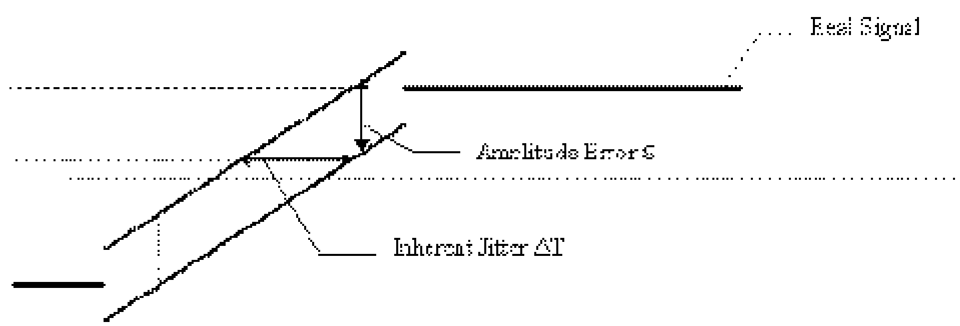
For example, LeCroy's LC 534 DSO has an internal low-pass analog filter of 200 MHz, which has an equivalent risetime of 0.35/200e6 = 1.75 ns. If the signal edge is oversampled, and depending on by how much, the ERES (Enhanced RESolution) function of LeCroy oscilloscopes can be applied to improve measurement accuracy. The ERES digital filter is a selection of six gaussian filters available with the Advanced Math package (WP01). The main benefit of applying this digital filter is noise reduction. For example, for an ERES enhancement of 0.5 bits, the noise is reduced by a factor of 1/÷2 in amplitude, assuming non-systematic noise. Reducing noise improves timing measurement accuracy.

In Figure 6, period measurement with statistics is performed directly on a 1 MHz sinewave (CH 2) and a 1 MHz sinewave that has been filtered (Trace A). The filter used is a 1-bit ERES filter providing a 120 MHz low-pass filter (as shown in the equation at the bottom of the screen). As already described, the sigma value is reduced for the filtered waveform due to reduced noise.

This observation is even stronger for a lower low-pass filter, with 3 bits of enhanced resolution, as shown in Figure 7. In this case the Nyquist frequency is 8 MHz and the sigma has a very small value representing a very accurate time measurement.

Measurement Accuracy and Resolution

In order to understand the resolution and accuracy of the time jitter measurement, knowledge of the sources of measurement error is required. This section describes the major components of error and how best to minimize their effect.



The major components of error are:

Amplitude Error

Aperture Uncertainty
Trigger Jitter
Interpolation Error.

Amplitude Error

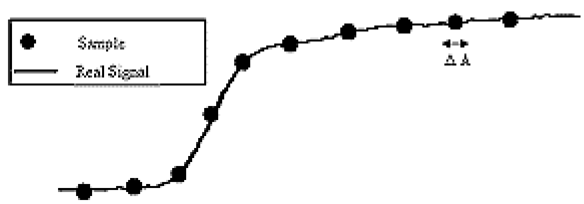
The diagram above shows a greatly accentuated vertical scale that demonstrates the effect of amplitude error.

This diagram illustrates that an amplitude error causes a time error, Inherent Jitter. The thick, dark line represents the real value of the signal, while the lines above and below it represent the values measured by the oscilloscope with an amplitude error. This diagram demonstrates that an amplitude error implies a time error.

Amplitude errors that can vary on a shot-to-shot basis and thereby simulate jitter are caused by :

Noise
ADC Quantization
Gain or timing mismatch in interleaved channels acquisition.

There are other sources of amplitude error (DC gain, offset), but they will not affect jitter because they are constant in time.



From Figure 8: assuming 200 mV and 32 quantization levels per division (based on 8-bit digitizer = 255 levels over eight divisions), the quantization error is estimated to 1 LSB:

Quantization error
200 mV/32 = 6 mV.

Measurement error due to an inherent jitter DT is given from:

where e is the Amplitude Error Range and DT is Inherent Jitter, so that For a signal risetime of 20-80% in 2 ns (based on 1GS/s sampling) and a signal amplitude of 1V:

This theoretical limit demonstrates the inherent jitter due to quantization effects only.

his inherent jitter specification. However, with high-fidelity oscilloscopes and the use of bandwidth-limiting filters, the effects of noise can be minimized, as discussed above.

Aperture Uncertainty:

The Aperture Uncertainty in a sample-hold or ADC is the total uncertainty in the time of the sample (or convert) command pulse and the time the input signal is actually sampled. This jitter's usual causes include noise, signal-amplitude-dependent delay variation (as in a flash ADC), and temperature. Aperture uncertainty is often used interchangeably with aperture jitter but aperture uncertainty is the more inclusive term.
The aperture uncertainty D A represents the range of time during which the sampling circuit has sampled the signal somewhere within the range. This voltage sample is then converted to a number by the ADC and stored into memory.

The aperture uncertainty in a LeCroy oscilloscope is measured as ± 10 ps. This is the timing jitter due to aperture uncertainty in any single measurement. When performing multiple measurements of the time between two signal features, this factor will add to the width of a histogram but will have little affect on the absolute time measured as the average time between the two signal edges.

Trigger Jitter

In the trigger system, the trigger jitter is the total uncertainty in the time measured as trigger time by the oscilloscope compared to the real-time trigger point occurs in the signal.

This jitter in a LeCroy oscilloscope is measured as ±10 ps.
The trigger jitter contributes to the complete jitter value only in the case of the Delay parameter, which is a measure of the time between the trigger point and a feature on the signal.

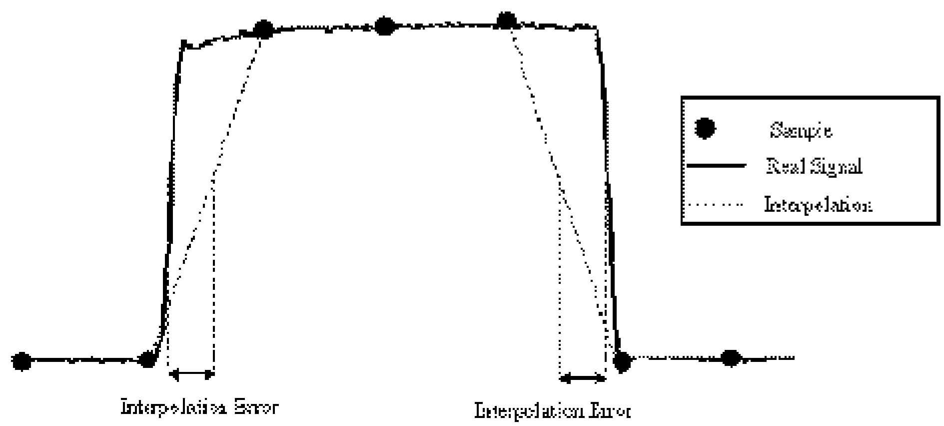
Interpolation Error

The two most common types of interpolation algorithms used in digital scopes are "linear" and sin(x)/x. Both modes are available as standard in all LeCroy DSOs.

Interpolation reconstruction error is important when the sampling rate is insufficient (as discussed at the beginning of this application note). Figure 10 shows the theoretical maximum error to be less than one sample period. The real value of the interpolation error is not only dependent on the ratio Sampling Rate/Time Interval to be measured but also on whether or not the samples are on the edges. For example, the error will be maximized if there are no samples on the edges and minimized if the time interval measured is an integer multiple of the sampling period.

Parameters for Jitter Measurement

The LeCroy parameter system offers a variety of parameters that allow characterization of time specifications such as the jitter of the signal acquired. The following parameters are standard in all LeCroy oscilloscopes.



Width: Duration between the leading and trailing edges of a pulse waveform as measured between the 50% point on both edges.
Period: Duration of a full cycle at 50% crossing (1.0/Freq).
Duty cycle: Percent of time data above 50% (100%* width / period).
Delta t@level: Transition time between levels able to be selected for one or two signal sources. Signal levels can be defined in percent or as voltages.
Delta delay: Time between the 50% transitions of two sources.
Delta c2d+: Delta Clock to Data Positive: time from clock-threshold crossing to next data edge (hold time).
Delta c2d-: Delta Clock to Data Negative: time from clock-threshold crossing to previous data edge (setup time).
Frequency: Repetition rate of full cycles for a periodic waveform (through 50%).
Delay: Time from the trigger (or t=0) to the first 50% transition.

Each parameter described above, except Delay, is multi-valued. For each acquisition, the parameter is determined whenever possible - up to 50 different values for one acquisition.

Depending on the nature of the acquisition performed, the different error sources must be considered. The following table shows the different cases:

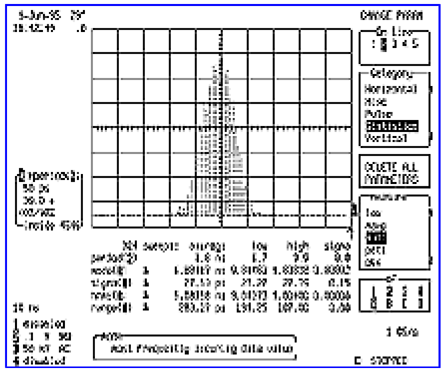
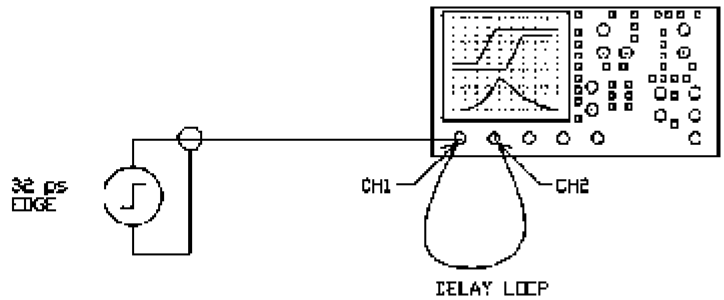


Figure 11 shows the histogram of the period of a 102 MHz sinewave (period equal to 9.804 ns) delivered by a very stable sinewave source. The standard deviation of the period measured shows that the measurement of the period has an RMS repeatability of 27.53 ps. The worst case difference between the smallest measured period and the largest ("range" of the jitter histogram) is 203 ps, representing 2% of the total period value.

The histogram is gaussian in shape, showing that the jitter is not due to a dominant external influence or systematic noise (which would appear in other peaks in the distribution).

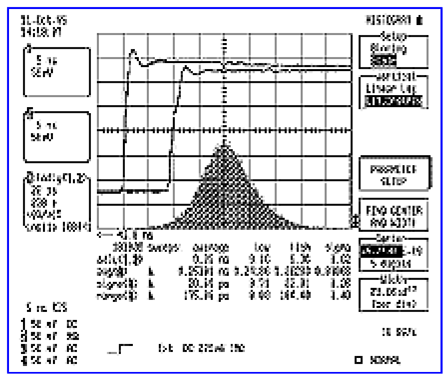
The following example (Figure 12) shows the setup for measurement of the propagation delay of a length of coaxial cable using a fast edge as the driving source.

The time delay between the Channel 1 and 2 waveforms was measured using the delta delay (1, 2) parameter. The cable delay is constant (approximately 9 ns), and any variation in the delay is due to the oscilloscope. Figure 13 shows the result of the measurement. The upper trace shows the input to Channel 1, the middle trace the delayed signal as seen in Channel 2, and the lower contains the histogram of over 100,000 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.
The repeatability of the delay measurement of this 9.25 ns cable is 20.69 ps. For each individual measurement of the delay. But if the length of the cable were to be adjusted by 10 ps, it would be very easy to see from a new histogram that the median had changed by half a division on the screen. The accuracy of the "range" and the "sigma" are much more accurate than 20 ps. If an adjustment is made to a circuit, it is easy to see when a timing change of 5 ps has occurred or the range of jitter or sigma has decreased by a few picoseconds.



Conclusion

The accurate measurement of jitter and other timing specifications used in high-frequency circuit design requires a firm understanding of signal acquisition and measurement methods.



The principal actions for achieving accurate time measurements are: Select the right system bandwidth, minimizing noise but maintaining signal timing fidelity.

Maximize the sample rate and always ensure at least two samples on any edge to be characterized.

Use bandwidth limiting filters - digital or analog - to reduce noise effects. Get to understand the measurement method being used and locate the measurement reference points on the waveform.

Use parameter distribution histogram analysis in order to ensure good measurement technique.

Ensure use of the maximum dynamic range of the amplifier and digitizing system.

With the adoption of the above methods, it is quite possible to make timing measurements with an accuracy of three picoseconds and a resolution of a fraction of a picosecond using LeCroy High Performance DSOs (9350, 9370, 9384 & LC Series). Oscilloscopes which do not have a histogram feature from other vendors typically achieve 10 to 30 picosecond accuracy.