Secrets of oscilloscope time measurements

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Oscilloscopes utilize both hardware and software tools to enhance the resolution of time measurements. Happily, most of the processing is transparent.

The primary display from an oscilloscope is amplitude versus time. Most of the focus when using oscilloscopes is on the vertical axis, including amplitude resolution, analog bandwidth, and vertical accuracy. The time axis does not seem to get equal billing. That's because oscilloscope time bases are very good.

Timebase accuracy

The oscilloscope's timebase generates the sampling clock, which samples the input signal at uniform time intervals at the sampling rate. The sampling rate and the length of the acquisition memory determine the horizontal scale factor. The timebase clock of an oscilloscope has a frequency accuracy generally specified in parts per million (ppm) or parts per billion (ppb).

For example, an instrument with a timebase specified as accurate to within ± 0.1 ppm (100 ppb). This means that any time interval, T, being measured is accurate to within ± $0.1/10^6$ of the value of T. If the measured interval is one second, the uncertainty of the measurement is $\pm1\times10^{-7}$ seconds or ±0.1 microseconds (ms).

Clock oscillators are subject to frequency drift over time. This timing uncertainty is cumulative and increases as the oscillator operates over longer periods. That drift, called aging, is usually specified as an additive uncertainty in frequency, expressed in parts per million per year (ppm/yr). A typical clock timebase accuracy specification might be ±0.1 ppm + 0.05 ppm/year. The time is measured from the instrument's last calibration.

If the oscilloscope's internal timebase is not as accurate as desired or if the oscilloscope's operation must be synchronized with other instruments, many oscilloscopes include an external clock reference input. The external reference is usually generated from a very stable signal source at either 10 or 100 Megahertz (MHz), which is used to synchronize the internal timebase to the reference input to improve its accuracy.

Improving time resolution

The time resolution of a digitizing instrument, based only on the sampling clock frequency, would be the reciprocal of the sampling rate. An oscilloscope that samples at 40 gigasamples per second (GS/s) would have a time resolution of 25 picoseconds.

Oscilloscopes enhance hardware time resolution by using a specialized frequency counter called a time-to-digital converter (TDC). In real-time acquisition mode, the time-to-digital converter measures the time between the trigger event and the next sample.

In general, the trigger event and the sample clock are not synchronous. The time delay between these two events is uniformly distributed over the sampling period. The uniform distribution means that any time delay between zero and the sampling period is equally possible. The time delay for each acquisition is called the horizontal offset and is a characteristic of the acquired waveform. **Figure 1** shows a horizontal offset measurement.

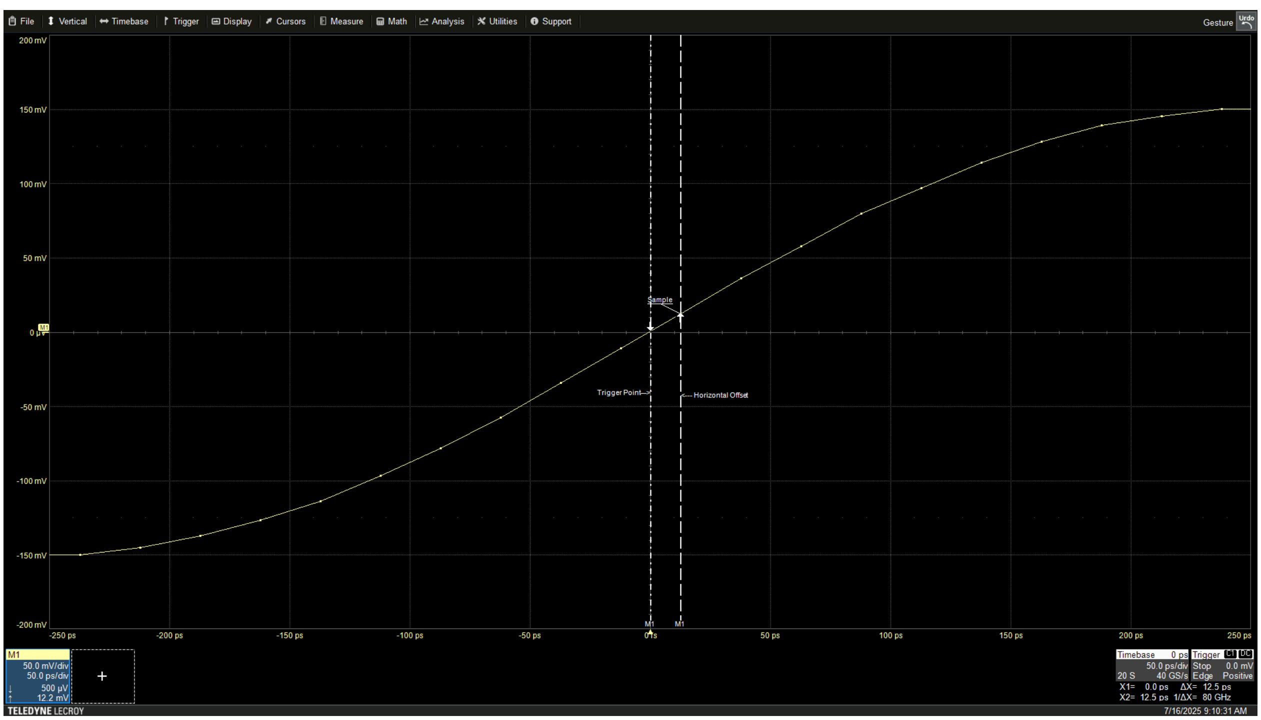

Figure 1 A typical measurement of the horizontal offset of an acquisition measuring time between the trigger point and the next sample point.

The figure shows an acquired waveform. The bright dots on the waveform indicate the real samples.

Horizontal relative cursors provide a visual measurement of the time between the trigger point and the next following sample and display the Δx value of 12.5 ps in the cursor readout field in the lower right corner. The TDC output provides an exact digital readout internally.

The time resolution of the TDC is much finer than the sample rate. In this specific example, it is five ps. The horizontal offset is used to align waveform samples for display and measurements. It is also used to combine multiple acquisitions of a periodic waveform into a random interleaved sampling acquisition.

Random interleaved sampling

Random interleaved sampling (RIS) is an acquisition mode that enhances the instrument's time resolution when measuring multiple periodic waveforms with a stable trigger point. The oscilloscope acquires multiple waveforms, each with the same shape (**Figure 2**).

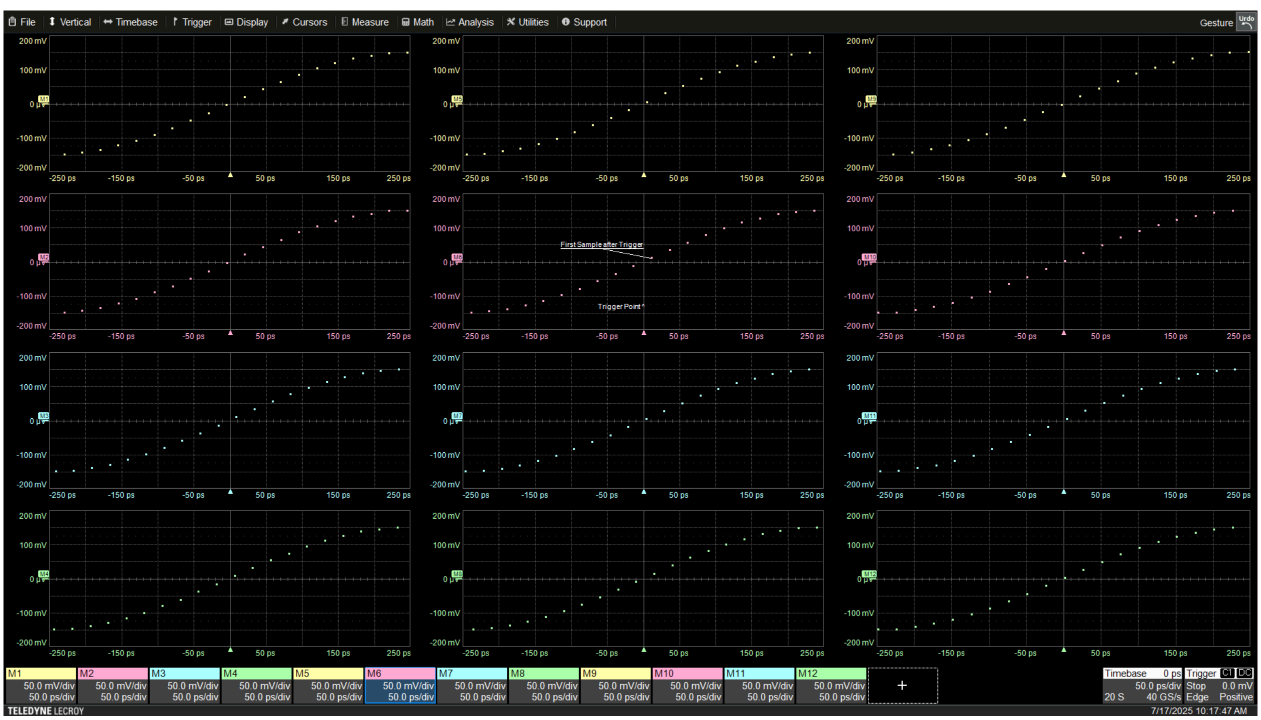

Figure 2 The horizontal offset, time delay between the trigger and the next sample, is uniformly distributed over the sampling period; multiple acquisitions show this variation.

Each acquired waveform has a horizontal offset uniformly distributed over the sampling period. Multiple acquired waveforms will each have a different horizontal offset. Examining the time difference between the trigger point and the first sample that follows in the figure illustrates this variation. Overlaying the twelve waveforms shows how they synthesize a waveform with an effectively higher sample rate (**Figure 3**).

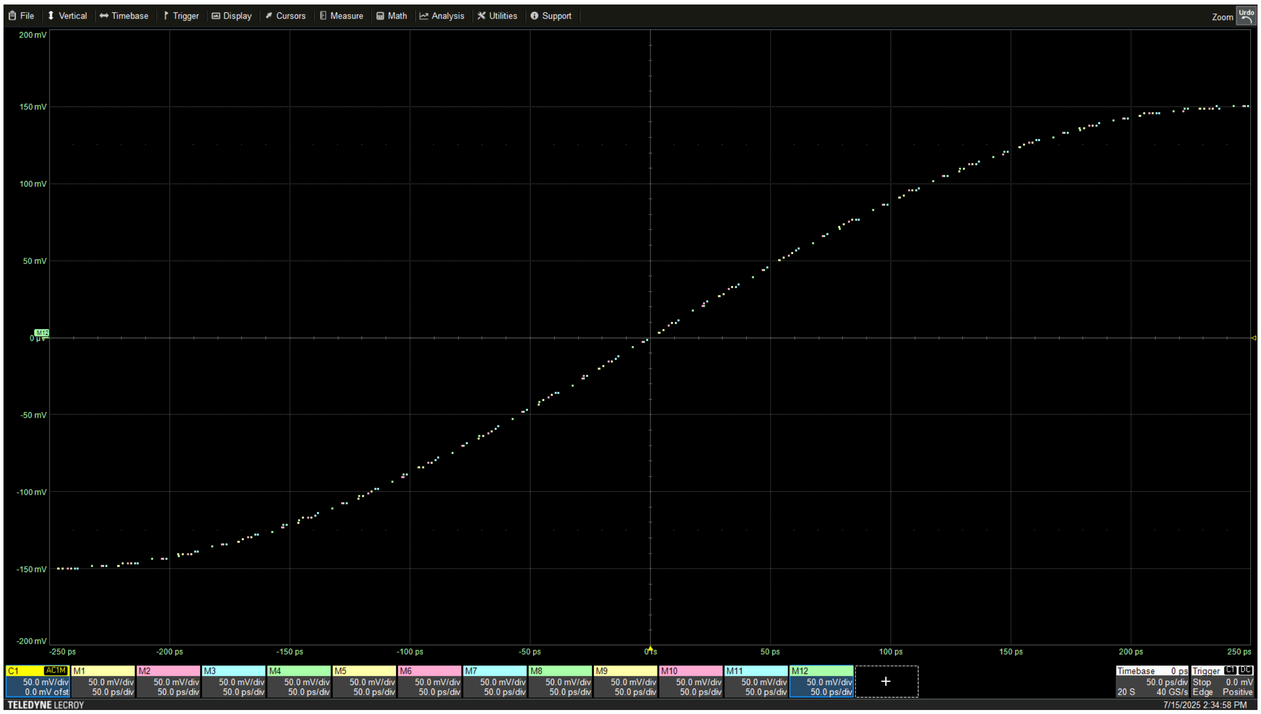

Figure 3 Creating a composite waveform from multiple acquisition results in a higher effective sample rate.

The oscilloscope measures the horizontal offset of each waveform and categorizes them to select those whose values are multiples of the desired effective sampling rate. These selected waveforms are combined to form the RIS waveform (**Figure 4**).

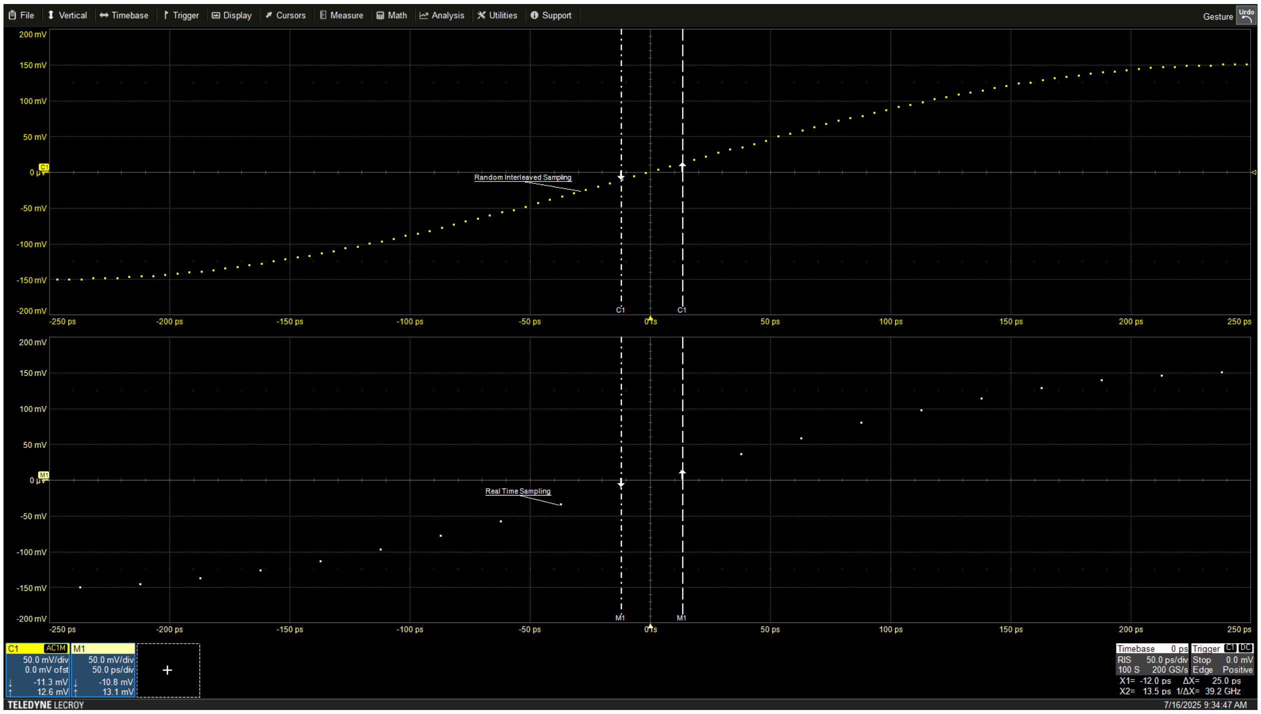

Figure 4 This graph compares a real-time and RIS waveform.

The lower waveform in the figure is the real-time acquisition. Cursors mark a 25 ps sampling period of the real-time waveform. The upper trace is the RIS acquisition. Note that there are five effective sample periods between the cursors; the effective sample rate is five times the 40 GS/s sample rate, or 200 GS/s. Remember that the RIS acquisition mode requires multiple repetitive acquisitions with the identical waveform using a stable trigger point.

Sequence mode

Sequence mode is another acquisition mode that uses the TDC. This mode is used to minimize the dead time between adjacent acquisitions. It is also applied to reduce the time between acquisitions. Sequence mode breaks the acquisition memory into a user-defined number of segments. Each segment holds a single acquisition. Since the oscilloscope does not need to display the trace between segments, the dead time between acquisitions is minimized.

The downside of this mode is that the time between segments is indeterminate as the instrument waits for the next acquisition trigger. To counter this, the oscilloscope marks the location, in time, of each segment in two ways.

First, it labels the start of each segment using the oscilloscope's real-time clock to label each trigger time. The real-time clock has a resolution of one second, which is not practical for fast acquisitions. It also uses the TDC to measure the time delay of each trigger from the first trigger in the acquisition (**Figure 5**).

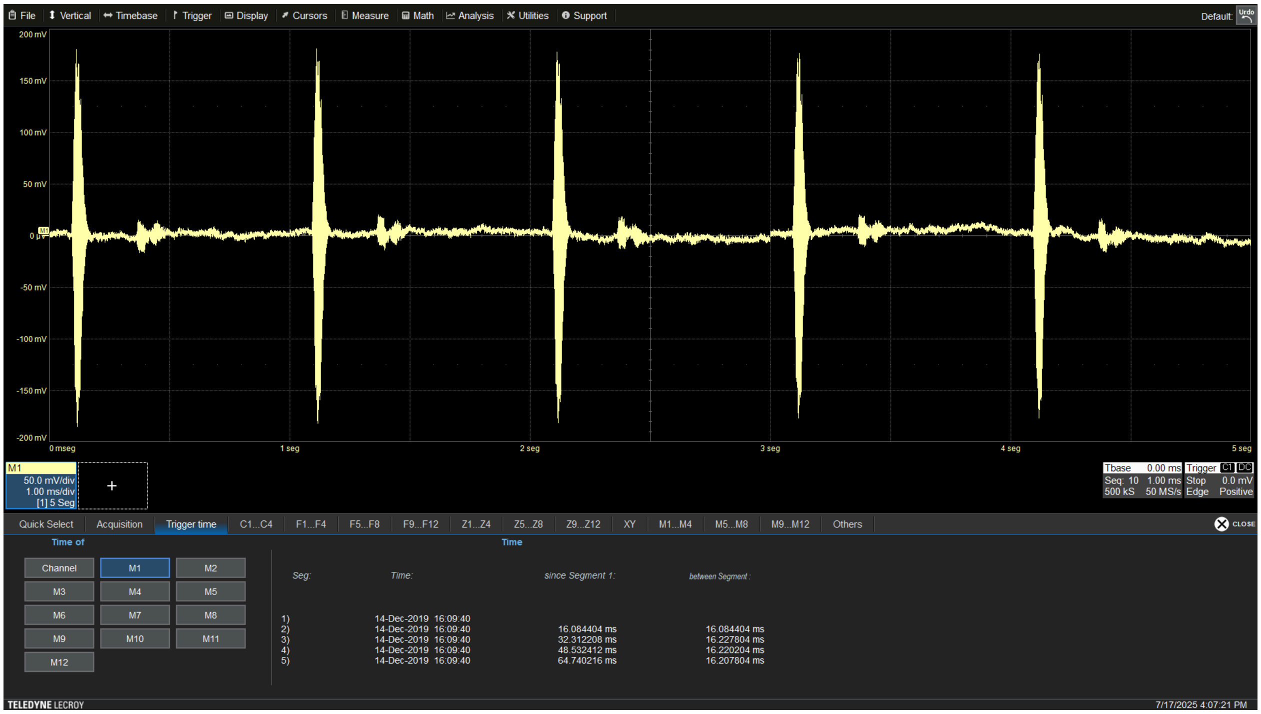

Figure 5 A sequence mode acquisition of five ultrasound pulsed bursts showing the sequence mode time stamps.

The figure shows a sequence-mode acquisition of five ultrasonic pulse bursts, each in its own segment. The sequence mode time stamps appear under the graphic display, including the absolute time from the oscilloscope’s real-time clock in the column labeled time. Additionally, it lists the time from the start of the first segment and the time between segments. These TDC-measured times are displayed with a resolution of one nanosecond.

The time stamps indicate the timing of the trigger events. It basically places each segment at a specific time. If each trigger event is an anomaly, then the time stamps provide the frequency of the anomalies, a bit of diagnostic information that often proves useful.

Interpolation

If the TDC is the hardware tool for precise time measurements, then interpolation is the software tool. Interpolation is a mathematical technique for increasing the effective sample rate of an acquired signal. Interpolation calculates intermediate sample values between the real-time samples. Interpolation is usually applied to the displayed data, but in many cases, it is incorporated into application-specific measurements.

Interpolation is also available as a math function and can be used to increase the time resolution of acquired waveforms. The oscilloscope used in this article offers sin x/x, linear, or cubic interpolation with sampling rate improvement from two to fifty calculated points per real-time sample. Interpolation increases instrument processing time proportional to the number of interpolated samples.

On the positive side, interpolation can be applied to single-shot acquisitions. On the downside, interpolation requires that the data meet the Nyquist criteria and have a sample rate greater than twice the signal's bandwidth. Failure to satisfy Nyquist can result in significant errors. From a data integrity perspective, it is essential to note that RIS data comprises all real samples, whereas interpolated data is a combination of real and calculated sample values.

Jitter measurements

Jitter is a short-term variation in the timing of a digital signal from its nominal value. Any timing parameter can be the subject of jitter analysis, and the main timing parameters considered are variations in width, period, and time-interval error (**Figure 6**).

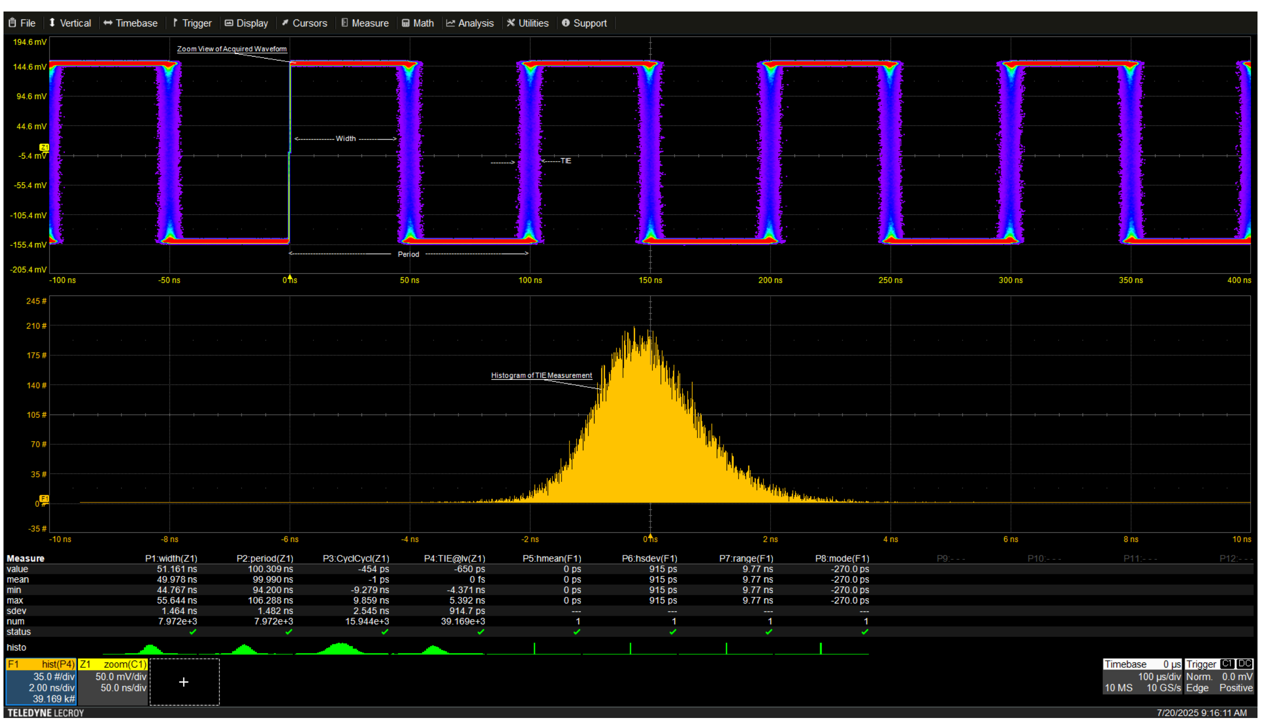

Figure 6 This graphic gives examples of timing uncertainty in width, period, and time

interval error jitter, including jitter measurements along with the histogram of time interval error.

Width or period jitter can be measured using the width and period measurement parameters, respectively. The jitter is evident in the statistical readouts for minimum (min), maximum (max), and standard deviation (sdev). The difference between the maximum and minimum is the range or peak-to-peak jitter. The standard deviation is the root-mean-square (RMS) jitter.

Time interval error (TIE) measures the difference between each actual waveform edge and the ideal location of that edge. The ideal edge locations are computed from the waveform's mean frequency. TIE can be thought of as the instantaneous phase of the signal.

The time parameters period, width, and TIE are measured by determining the time between edges. For a period, it is the time between adjacent edges with the same slope. For the width measurement, it is the time between adjacent edges with different slopes. TIE measures the time between an acquired edge and an ideal edge. The measurement uses interpolation to achieve the highest possible time resolution (**Figure 7**).

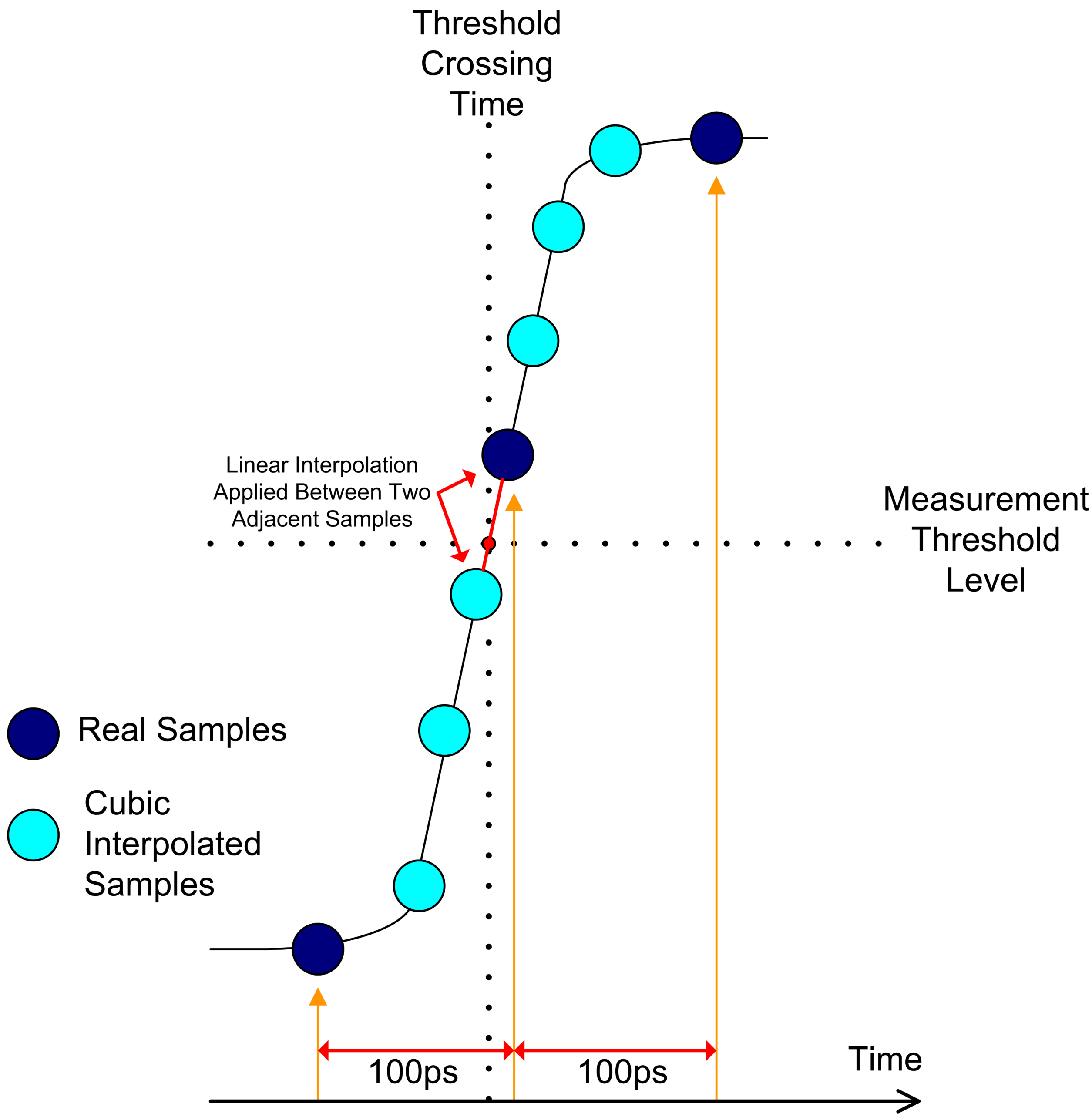

Figure 7 A dual interpolator finds use in obtaining a more precise measurement time resolution.

The figure shows an edge defined by three real-time samples taken with a 10 GS/s sampling rate. The interpolator uses a cubic interpolation to fit several interpolated samples between each real-time sample. Then, the two samples that bracket the measurement threshold are used to perform linear interpolation to determine the time at which the measurement threshold is crossed. The resulting measurements in this example have a resolution better than 1 picosecond.

Jitter has both random and deterministic components. Random jitter is associated with stochastic processes, such as noise, and is unbounded, meaning it increases with increasing observation time. Deterministic jitter is bounded, and its amplitude is limited with increasing observation time. The random components of jitter are studied using statistical tools, such as histograms.

Figure 6 shows the histogram of the TIE parameter. There are parameters intended to interpret histograms themselves. The histogram mean (hmean), mode (hmode), standard deviation (hsdev), and range (hrange) are examples of histogram-specific parameters.

Conclusion

Oscilloscopes utilize both hardware and software tools to enhance the resolution of time measurements. Improved time resolution is used both in displaying the data and in measurements. Happily, most of the processing is transparent and requires little user interaction to achieve good results.

Arthur Pini is a technical support specialist and electrical engineer with over 50 years of experience in electronics test and measurement.

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