Measurements with the SR620

Application Note #2

In order to realize the full potential of the SR620 Universal Time Interval and Frequency Counter, a brief look at its several modes of operation and some of their applications is appropriate. It is also important for a user to understand the performance specifications of the SR620, in order to draw reasonable conclusions from experimental data. How accurate is a particular measurement? What errors can be expected? This application note defines, in detail, the performance specifications and terminology for each mode of operation. This information will enable the user to fully understand the capabilities and limitations of the instrument.

The first section of this application note describes the type of measurements that the SR620 can perform and gives some application examples. It will give the reader an appreciation for the wide range of applications in which the SR620 Universal Time Interval and Frequency Counter can be used.

The second section (SR620 Specification Guide) explores the specifications of the SR620 in detail. A precise definition of measurement accuracy (resolution and error), along with explanations of technical terminology, is given for each mode of operation.

Applications of the SR620

The SR620 Universal Time Interval and Frequency Counter has been used to measure everything from the propagation delays of integrated circuits, to the distance to the moon. Its versatility and affordable price have made the SR620 an instant success in the engineering and scientific marketplaces. The SR620 can be used to measure time interval, frequency, period, pulse width, phase, rise and fall time, and will also do event counting. Statistical calculations including mean, standard deviation, Allan variance, minimum and maximum, are performed on up to one million samples in all modes of operation. In addition to displaying the statistical data on the 16-digit LED display, distribution graphs of the data, in histogram and strip chart format, can be displayed on an X-Y oscilloscope. Application examples of the SR620 are discussed below.

Time Measurement

The SR620 measures the time interval between two independent signals, A and B. An example using this mode of operation is measuring the electrical length of a cable. The cable can be configured as end-to-end or single-ended, with the remote end shorted to ground or left open. Using the built-in 1 kHz reference signal as a stimulus, the propagation delay from one end of the cable to the other, or between the incident and reflected rising edge of the pulse, can be measured. Knowing that electricity travels at approximately one foot per 1.5 nanoseconds, the cable length can easily be calculated.

Another time interval application is the measurement of propagation delays of integrated circuits. Again, the 1 kHz reference source can be used to excite the experiment, and the time delay from the input to the output of the integrated circuit can be measured.

Pulse Width Measurement

Magnetic and optical memory disk data is stored using different modulation schemes to minimize disk real-estate and maximize signal-to-noise ratio. For example, compact disk players use 3-11 modulation to obtain very high disk density. This scheme produces data patterns with nine different pulse widths (corresponding to 3, 4, 5, ...11 consecutive 0's). The SR620 can be used to measure these pulse widths and their variations, and display them graphically in histogram form on an X-Y oscilloscope.

Rise and Fall Time Measurement

When analyzing the transition time required for a least-significant-bit change in a DAC (digital to analog converter), the 10 % to 90 % rise time of that transition is of importance. Once the rise time has been established, the small-signal frequency response of the DAC can be calculated (bandwidth=0.35/rise time). The SR620 allows the user to set the start and stop voltage thresholds, in rise and fall time measurements, so that any part of a transition may be analyzed.

Frequency and Period Measurement

When measuring the quality of a reference frequency source, the jitter (standard deviation or Allan variance) is often of significance. The SR620 will analyze the source over a set gate time, and then display a distribution curve of the data showing the mean frequency, minimum and maximum frequencies, and the jitter, revealing the quality of the source. Frequency is measured as $N/(\Delta t)$ and Period is measured as $(\Delta t)/N$, where N is the number of cycles, and Δt is the elapsed time to complete N cycles.

Phase Measurement

When characterizing operational amplifiers, it is useful to know the phase verses frequency relationship. The SR620 can measure the difference in phase between the input and output at different frequencies so that a Bode plot can be constructed.

Event Counting

Used in conjunction with a discriminator, the SR620 can function as a photon counter that counts electrical pulses from a PMT (photomultiplier tube). It can count at a rate of up to 200 MHz. In another application, the SR620 has proven to be a cost effective way to count canned goods traveling on a conveyer belt as they pass a check point.

These examples represent only a few of many possible applications of the SR620. A full description of how to perform these, and other types of measurements, is given in the SR620's operation and service manual.

SR620 Specification Guide

This section provides an explanation of the specifications of the SR620 and their effect on the accuracy and resolution of a measurement.

Statistical Functions

The SR620 can display statistical information about the measurement of N samples. The SR620 computes and reports the mean, standard deviation or root Allan variance, minimum, and maximum values seen during the measurement. The equation for the statistical functions are given by:

$$\text{mean} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

$$\text{standard deviation} = \sqrt{\frac{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}{n(n-1)}}$$

$$\text{root Allan variance} = \sqrt{\frac{\sum_{i=1}^{n-1} (x_{i+1} - x_i)^2}{2(n-1)}}$$

Least Significant Digit (LSD)

The LSD is the smallest displayed increment in a measurement. The SR620 has a 4 ps single-shot LSD, and thus the smallest amount that two single-shot time interval measurements may differ by is 4 ps.

Resolution

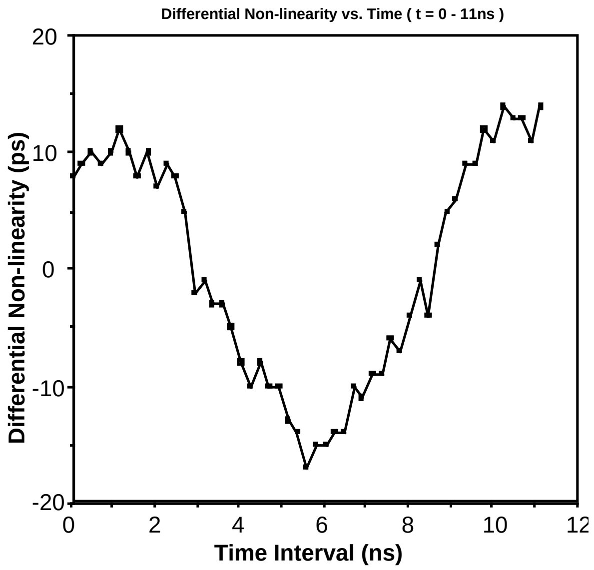
Resolution is the smallest difference in a measurement that the SR620 can discern. That is, the smallest statistically significant change which can be measured by the SR620. Resolution is of primary interest in comparing readings from the same instrument. The instrument resolution is limited by many things including short-term timebase stability, internal noise, trigger noise, etc. Because these processes are random in nature, resolution is specified as an rms value rather than a peak value. This rms value is the standard deviation of the measured value. The SR620's single-shot resolution is typically 25 ps rms. This number can be improved by averaging over many measurements, or in the case of frequency and period measurements, increasing the gate time. The single-shot LSD is always smaller than the single-shot resolution.

Error

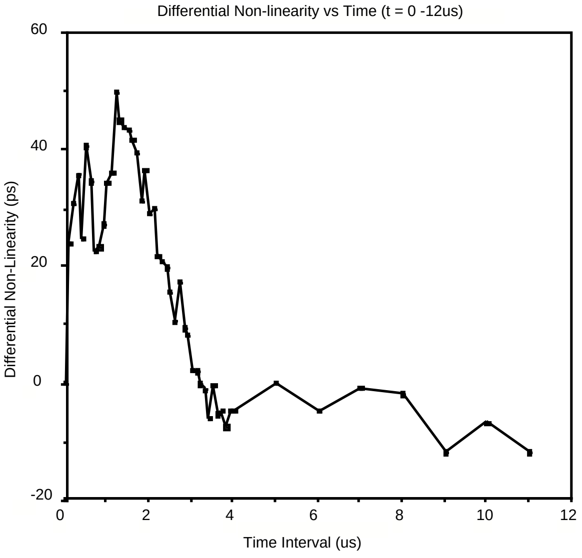
Error is defined as the difference between the measured value and actual value of the signal being measured. The error in a measurement is of primary concern when the absolute value of the parameter being measured is important. Error consists of the random factors mentioned above, and systematic uncertainties in the measurement. Systematic uncertainties include timebase aging, trigger level error, insertion delay, etc. Systematic errors may always be measured and subtracted from subsequent measurements to reduce the error. The SR620's absolute error is typically less than 0.5 ns for time interval measurements less than 1 ms.

Differential Non-Linearity

Absolute error is of interest in determining how far a value is from the actual value. Often only the relative accuracy (the difference between two measurements) is important. Differential non-linearity is a measurement of the relative accuracy of a measurement, and is specified as the maximum time error for any given relative measurement. The SR620's differential non-linearity is typically ±50 ps. That means if the time interval is changed by some amount, the SR620 will report that change correctly to within ±50 ps. Graphs 1 and 2 show the SR620's typical differential non-linearity as a function of time interval. Graph 1 shows the non-linearity over the time range of 0 to 11 ns. The deviations are due to the residual non-linearity of the time-to-amplitude converters used to interpolate a fraction of one 90 MHz clock tick. This curve repeats every 11.11 ns. Graph 2 shows the non-linearity over the time range of 0 to 11 ms. For times greater than 11 ms, the non-linearity is dominated by the timebase error.



Graph 1: Differential non-linearity for time differences of 0 to 11 ns. Graph reveals the residual non-linearity of the time-to-amplitude converters.



Graph 2: Differential non-linearity for time differences of 0 to 11 µs

Timebase Specifications

The specifications of the timebase affect both the resolution and error of measurements made with the SR620. A timebase may be specified by two parameters: its short-term stability and its long-term stability.

Short-Term Stability

The short-term stability of an oscillator is a measure of the changes in the output frequency of the oscillator on a short time scale (seconds or less). These changes in the frequency are usually random and are due to internal oscillator noise, output level modulation, etc. These random changes in frequency affect the resolution of the measurement, just as other internal noise does. The short-term stability of an oscillator is usually characterized by specifying either its Allan variance or its phase noise. The SR620's timebase short-term stability is specified by its Allan variance. Typical values for several gate times are:

	standard oscillator	**oven oscillator**
1.0 s gate	1.2×10^{-10}	2.3×10^{-11}
10 s gate	2.3×10^{-10}	1.0×10^{-11}
100 s gate	1.25×10^{-9}	4.2×10^{-11}
spec. limit at 1 s	2.0×10^{-10}	5.0×10^{-11}

The resolution of the SR620 is specified as:

resolution (rms) = $[(25\text{ ps})^2 + (\Delta t \times \text{short-term stability})^2]^{1/2}$

Where Δt is the time interval. For time intervals greater than 125 ms (standard oscillator) or 500 ms (oven oscillator), the short-term stability of the timebase will dominate the resolution limit of the SR620.

Long-Term Stability

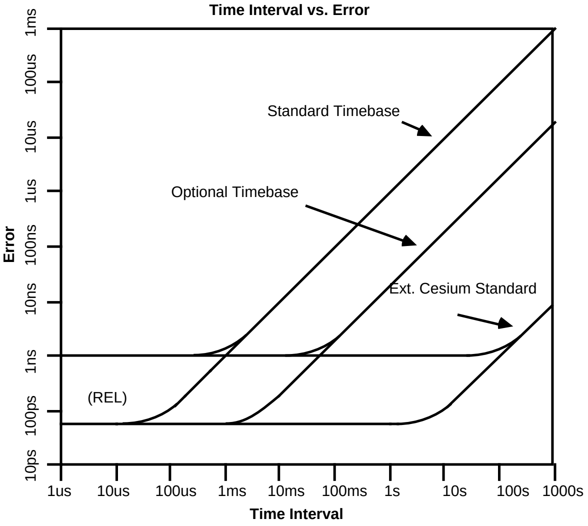
The long-term stability of an oscillator is a measure of its changes in frequency over long time intervals (hours, days, months or years). It is the long-term stability of the timebase that will ultimately limit the absolute accuracy of the SR620 and determines the calibration interval necessary to maintain a desired error limit. The long-term stability consists of two components: oscillator aging and oscillator temperature response. The aging of an oscillator is the change in frequency over time due to physical changes in the components (usually the crystal), and is usually specified as a fractional frequency change over some measurement period. Temperature response is due to changes in the oscillator characteristics as a function of ambient temperature, and is specified as a fractional frequency change over some temperature range. The timebase for the SR620 is specified as:

	standard oscillator	**oven oscillator**
Aging	1.0×10^{-6}/yr	5.0×10^{-10}/day
Temp. Response	1.0×10^{-6} (0 to 50 °C)	5.0×10^{-9} (0 to 50 °C)

For example, 30 days after calibration the oven oscillator may have drifted at most $30 \times (5 \times 10^{-10}) \times 10$ MHz = 0.15 Hz. Also, a worst case temperature variation must be assumed when evaluating the worst case error. The optional oscillator must be assumed to be at worst 5 ppb in error because the conditions when the SR620 was calibrated are unknown. This worst case error is not a good estimate of the actual oscillator drift under most conditions.

External Timebases

The SR620 has a rear-panel input that will accept either a 5 MHz or 10 MHz external timebase. The SR620 phase-locks its internal timebase to this reference. The phase-locked loop has a bandwidth of about 20 Hz, and thus, the characteristics the SR620's clock, for measurement times longer than 50 ms, become that of the external source. For shorter measurement times, the clock characteristics are not important compared to the internal jitter (25 ps rms) of the SR620. Thus, if the signal from a cesium clock is input into a SR620 with a standard TCXO oscillator, the short-term and long-term stability of the SR620 will become that of the cesium clock. This is illustrated in graph 3.



Graph 3: Error vs. time interval for various timebases

Trigger Input Specifications

There are two ways that the inputs can affect the resolution and accuracy of a measurement. The first is called trigger jitter and is due to random noise on the A and B input signals and the trigger input buffers. This random noise causes the input to trigger at a time different than it otherwise would in the absence of noise. Because this is a random process, it affects resolution just as the other random noise sources do. Trigger timing jitter can be minimized by careful grounding and shielding of the input, and by maximizing the input slew rate. Note, however, that the slew rate is limited by the SR620's 1 ns input rise time. The trigger timing jitter can be described by the equation:

$$\text{Trigger Timing Jitter} = \frac{\sqrt{\left(E_{\text{internal}}\right)^2 + \left(E_{\text{signal}}\right)^2}}{\text{Input Slew Rate}}$$

where

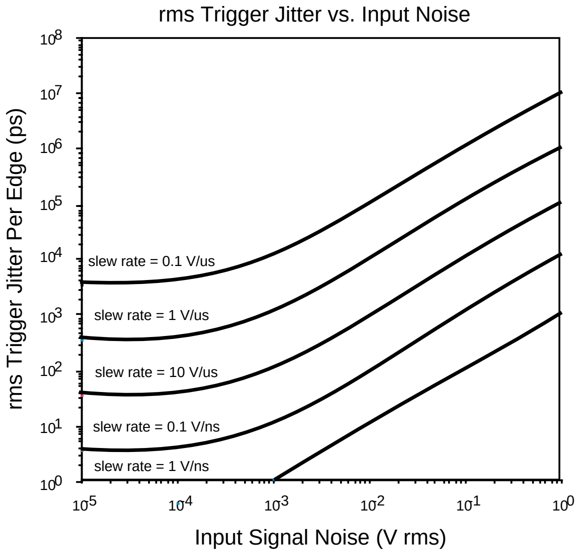
E_{internal} = internal input noise (350µ V rms typical)

E_{input} = input signal noise

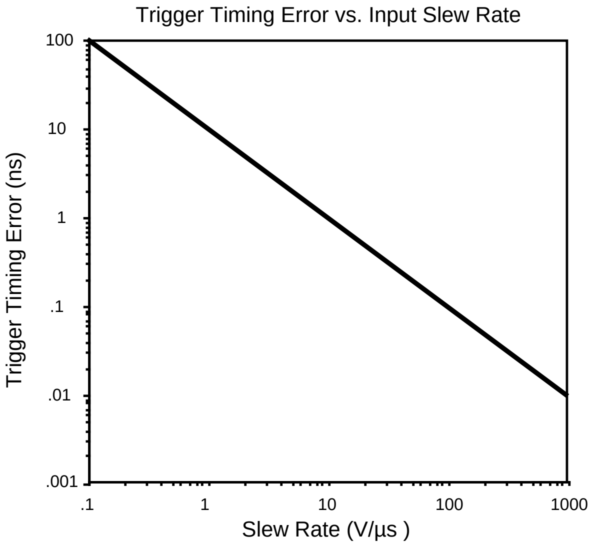
If the trigger level is set to a value other than the intended value, the time interval measured will be in error. This error (trigger level timing error) is a systematic error that affects only the error of the measurement and not its resolution. The SR620's trigger thresholds are set to an accuracy of 15 mV + 0.5 % of value. The effect this has on the measurement is given by:

$$\text{Trigger Level Timing Error} = \frac{15\,\text{mV} + 0.5\%\ \text{of setting}}{\text{Input Slew Rate}}$$

Graphs 4 and 5 show the effects of trigger timing jitter and trigger timing level error on resolution and error. These graphs are applicable to all measurements, not just time intervals.



Graph 4: Effect of input noise on measurement resolution showing reduced noise due to averaging



Graph 5: Effect of input slew rate on measurement error

Measurement Accuracy

The following equations allow one to calculate the SR620's resolution and error in the various measurement modes. The SR620's typical specifications are used in the following equations. For worst case bounds, simply replace the typical with the worst case numbers.

Note: The quantities added to calculate the SR620's resolution are independent rms quantities and must be added in quadrature as shown in the following equation:

$$\text{total} = \sqrt{x_1^2 + x_2^2 + \ldots}$$

Note: Timebase error refers to the sum of aging and temperature effects.

Time Interval, Width, Rise/Fall Time Modes

In the time measurement modes, the measurement resolution and error are given by:

$$\text{Resolution} = \pm\sqrt{\frac{(25\,\text{ps})^2 + (\text{time interval} \times \text{short term stability})^2 + (\text{start trigger jitter})^2 + (\text{stop trigger jitter})^2}{N}}$$

$$\text{Error} = \pm[\text{resolution} + (\text{timebase error} \times \text{time interval}) + \text{start trigger level error} + \text{stop trigger level error} + 0.5\,\text{ns}]$$

N = number of samples averaged

Frequency Mode

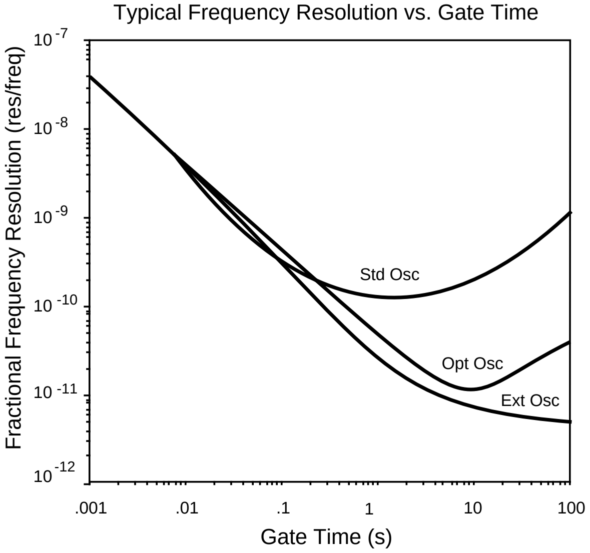
In frequency mode, the measurement resolution and error are given by:

$$\text{Resolution} = \pm\frac{\text{frequency}}{\text{gate time}}\sqrt{\frac{(25\,\text{ps})^2 + (\text{short term stability} \times \text{gate time})^2 + 2 \times (\text{trigger jitter})^2}{N}}$$

$$\text{Error} = \pm\left[\text{resolution} + (\text{timebase error} \times \text{frequency}) + \frac{100\,\text{ps}}{\text{gate time}} \times \text{frequency}\right]$$

N = number of samples averaged

The SR620's typical single-shot frequency resolution as a function of gate time is shown in Graph 6. The curves are for the standard oscillator, the optional oven oscillator, and an external high stability reference. The input signal noise is assumed to be negligible.



Graph 6: Frequency resolution as a function of gate time for the SR620's three oscillator options

Period Mode

In period mode, the measurement resolution and error are given by:

$$\text{Resolution} = \pm\frac{\text{period}}{\text{gate time}}\sqrt{\frac{(25\,\text{ps})^2 + (\text{short term stability} \times \text{gate time})^2 + 2 \times (\text{trigger jitter})^2}{N}}$$

$$\text{Error} = \pm\left[\text{resolution} + (\text{timebase error} \times \text{period}) + \frac{100\,\text{ps}}{\text{gate time}} \times \text{period}\right]$$

N = number of samples averaged

Phase Mode

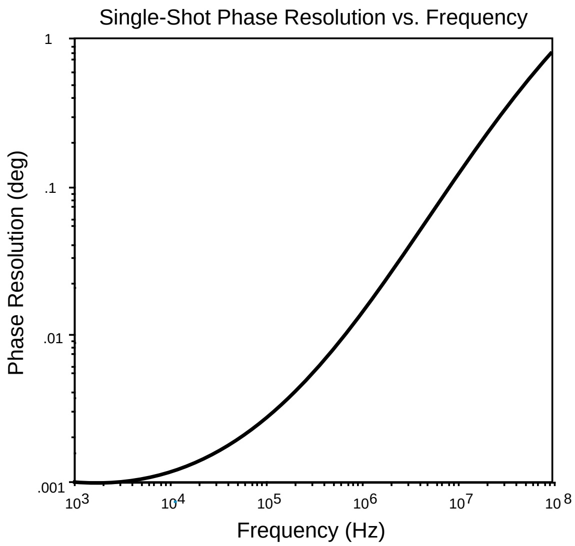
In phase mode, the measurement resolution and error are given by:

$$\text{Resolution} = \pm\left[0.001^\circ + 360\sqrt{\frac{(25\,\text{ps})^2 + (\text{gate time} \times \text{short term stability})^2 + 2 \times (\text{trigger jitter})^2}{\text{period}^2 \times N}\left(1 + \left(\frac{\text{phase} \times \text{period}}{360 \times \text{gate time}}\right)^2\right)}\right]$$

$$\text{Error} = \pm\left[\text{resolution} + \frac{(\text{timebase error} \times \text{time interval}) + \text{start trigger level error} + \text{stop trigger level error} + 0.5\,\text{ns}}{\text{timebase error} \times \text{period} + 1 \times 10^{-8} \times \text{period}} \times 360^\circ\right]$$

N = number of samples averaged and the gate time is 10 ms

Graph 7 shows the SR620's single-shot phase resolution as a function of frequency. The resolution may be increased by averaging.



Graph 7: Single-shot phase resolution vs. frequency

Count Mode

The resolution and error for count mode are:

Resolution = ±1 count

Error = ±1 count

Conclusion

The SR620 Universal Time Interval and Frequency Counter has many practical applications in engineering and science. It can be used to measure the propagation delays of integrated circuits, the quality of a reference frequency source, or any other time or frequency related quantity. Its ability to perform statistical calculations (mean, minimum, maximum, standard deviation and Allan variance) makes the SR620 applicable to almost any frequency or time related system.

Resolution, the smallest discernible difference in a measurement, is of primary interest when making comparative readings. Timebase stability, trigger noise, internal noise, etc. , all contribute to limiting the resolution. The SR620 provides the user with state-of-the-art performance with 4 ps single-shot least significant digit and 25 ps single-shot resolution. The ability to function with internal and external timebases provides the flexibility needed in many applications.

Error, the difference of a measured and actual value, is of interest when the absolute value of a measurement is important. Error consists of resolution, timebase aging, insertion delays, trigger level errors, etc. The SR620's absolute error is typically 500 ps.