Isolating Frequency Measurement Error and Sourcing Frequency Error near the Reference Frequency Harmonics

White Paper

Abstract—*Instruments, which source or measure frequencies are susceptible to interaction between the instrument's reference frequency and its measured/ sourced frequency when the two frequencies are close to each other. Before analyzing instruments (counters) and sourcing instruments (sources and clock generators) can be evaluated, a methodology to separate the analyzing error from the sourcing error is described. The error in counters is discussed with the implications to many typical measurements.*

Speaker/Author: Robert Leiby
Agilent Technologies
900 South Taft, Loveland, CO 80537
Phone: 970-679-2866
E-mail: rob_leiby@agilent.com

Introduction

Measurement of many fundamental quantities is made by comparing the Device Under Test (DUT) to a known reference. It is assumed that the reference quantity and the quantity being measured do not interact at a level that will compromise the measurement. However measurements that involve temporal quantities, such as frequency, do have an interaction at a level that is measureable. When two frequencies in a system are very close to each other, 10.000,000 MHz and 10.000,001 MHz for example, edges will become synchronous with each other at a rate proportional to the difference of the two frequencies. Edges of the frequency of interest going in and out of alignment result in measurement errors in these systems. For 10.000,000 MHz and 10.000,001 MHz, the rate at which the edges go in and out of alignment is 1 Hz. The difference of the two frequencies is known as the beat frequency. Minimizing the beat frequency effecting a measurement presents a design challenge to the design of frequency sources and frequency analyzers (counters).

Today's counters have accuracies that allow these errors to be cleanly observed. A survey of three popular counter models has shown that this error will manifest its self as a variation of the reading. This error could be a periodic manifestation or a perceived as increase in the random noise. The magnitude of the error has been observed from a dozen pico (10^{-12}) parts to hundreds of pico parts.

Customers that use counters to analyze their 10 MHz products and are aware of this problem have their counters evaluated for this error which can have a significant impact. The impact of the beat frequency error is greatest when evaluating crystals or oscillators whose frequencies are close to a harmonic of the reference frequency. The irony of this error is that the more accurate these oscillators are, the more likely they will be incorrectly rejected for noise issues.

Agilent Technologies

2. Method to evaluate counters and sources for reference interference.

Both sources and analyzers (counters) have the problem of beat frequencies near their primary reference clocks and its derivatives. To isolate the two from each other, the analog time references of the source and the analyzer need to be offset from each other. (This procedure will not work with mathematically compensated time bases.) A counter's input reference is set 4 ppm away from the sources reference by using a high quality clock generator. The clock generator and source also have a problem sourcing frequencies near their reference frequency, but the 4 ppm difference between the source and counters references was selected to keep the 10 MHz beat effect of the clock generator away from the frequencies used to characterize the counters' beat error. The rms noise of the measurement is composed of the Root Sum Squared (RSS) of the instruments used to create the setup: the RSS of the clock generator noise at 4 ppm off the 10 MHz, the counter noise, the reference distribution amp noise and the source. Therefore do not use these graphs to estimate the counters or sources random noise.

Figure 1 show two of the possible setups of the instruments for using a source and clock generator for the 4 ppm reference shift. Depending on the extent of the external reference swing of the counter or source, different setups may be required. A source or counter with a good Oven Controlled Crystal Oscillator (OCXO) may only accept references with less than 2 ppm shift, so the frequency shift and test setup will be governed by the equipments capability. Good cabling, power distribution, and safety ground routing should always be practiced.

Figure 1 can be helpful in determining the correct approach to solving this issue. The diagram on the left is used when the counter can use a reference that is 40 MHz from the true 10 MHz. The output of the source "A", referenced to a true 10 MHz, is set to 40 Hz above (or below) the 10 MHz reference and used to drive the references of the counters. A second source "B" is referenced from the true 10 MHz reference, and its output is varied around 40 Hz above (or below) the 10 MHz reference.

If the source "B" can be locked 4 ppm from a true 10 MHz then the diagram on the right is used. "A" is used to provide a true 10 MHz to the counters reference, while its output is used to generate the reference for "B" 40 Hz above (or below) a true 10 MHz. The output of "B" is then varied 40 Hz below (or above) a true 10 MHz.
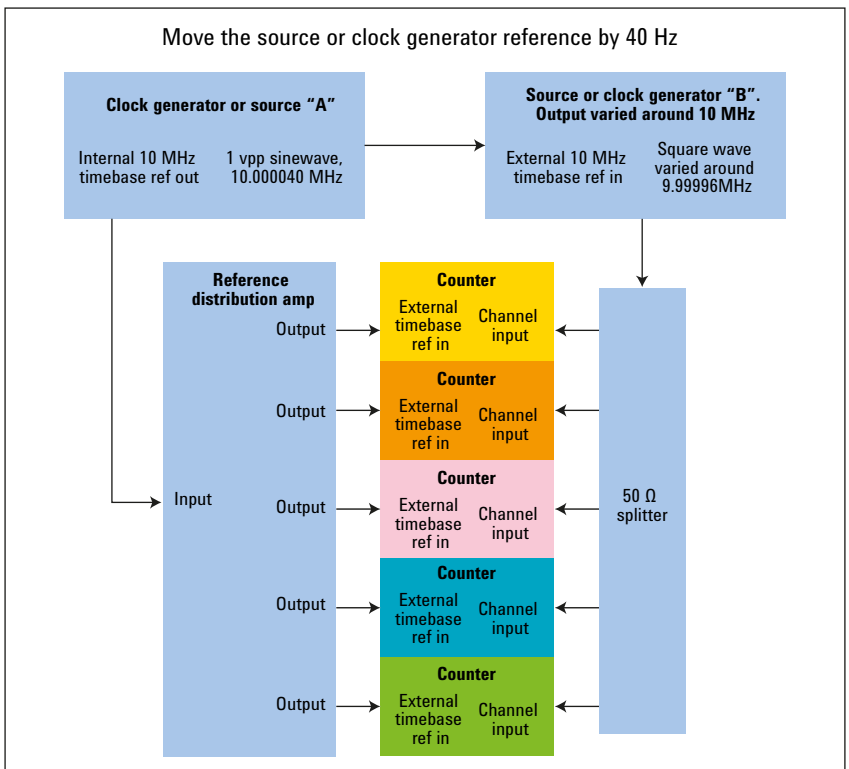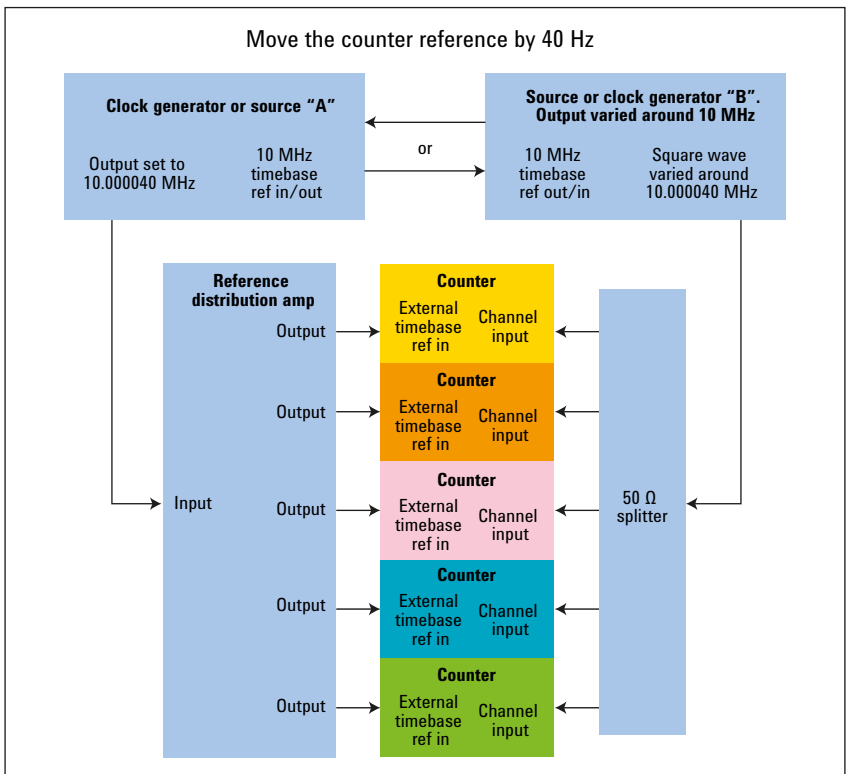
Move the counter reference by 40 Hz

Clock generator or source "A"

Output set to 10.000040 MHz | 10 MHz timebase ref in/out

or

Source or clock generator "B". Output varied around 10 MHz

10 MHz timebase ref out/in | Square wave varied around 10.000040 MHz

Reference distribution amp

Input

Output

Counter
External timebase ref in | Channel input

Counter
External timebase ref in | Channel input

Counter
External timebase ref in | Channel input

Counter
External timebase ref in | Channel input

Counter
External timebase ref in | Channel input

50 Ω splitter

Move the source or clock generator reference by 40 Hz

Clock generator or source "A"

Internal 10 MHz timebase ref out | 1 vpp sinewave, 10.000040 MHz

Source or clock generator "B". Output varied around 10 MHz

External 10 MHz timebase ref in | Square wave varied around 9.99996MHz

Reference distribution amp

Input

Output

Counter
External timebase ref in | Channel input

Counter
External timebase ref in | Channel input

Counter
External timebase ref in | Channel input

Counter
External timebase ref in | Channel input

Counter
External timebase ref in | Channel input

50 Ω splitter

Figure 1. Possible test setups for shifting references by 4 ppm.

The error that is the result of two frequencies beating against each other is deterministic and not stochastic. Quantifying the error is therefore limited to the quantification of deterministic signals. Two measurements were used to quantify the error. The rms of the error and peak to peak error were chosen.

Figure 2 is a wide span of frequencies showing the source and counter errors on one graph. The horizontal axis is the output frequency of the source. The thin vertical line at 10 MHz is the source error while the rest of the graph, centered at 10.000040 MHz is the counters beat error.
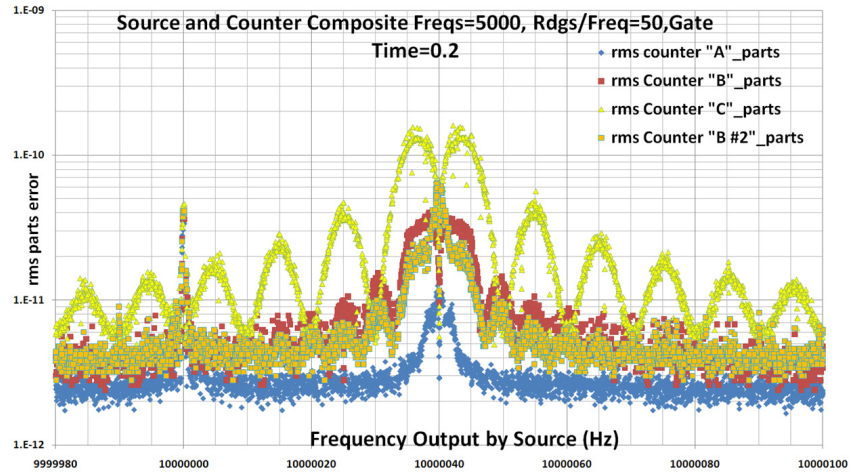
Figure 2. Composite graph of source and counter errors.

3. Source Beat Frequency Error

For completeness, Figure 3 and Figure 4 are the source beat errors of two very accurate sources used for the analysis. Even at only 2 Hz from of their reference frequency the error is only 2E- 12 rms (gate time adjusted).
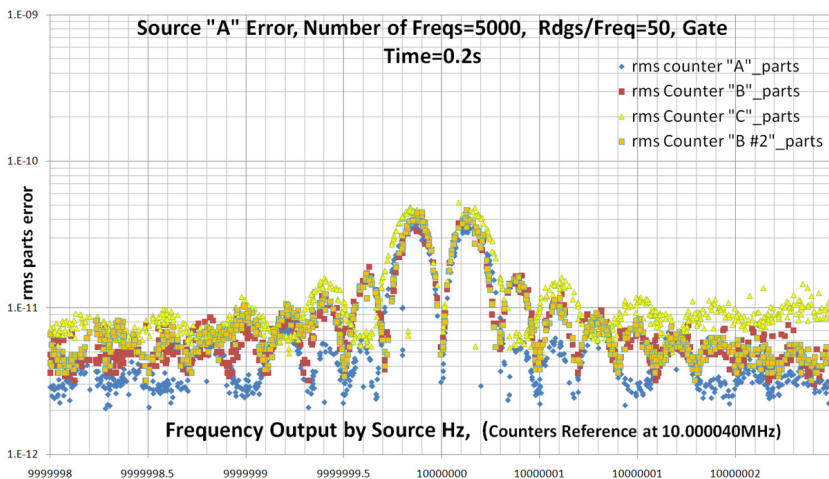
Figure 3. Source A error signature.
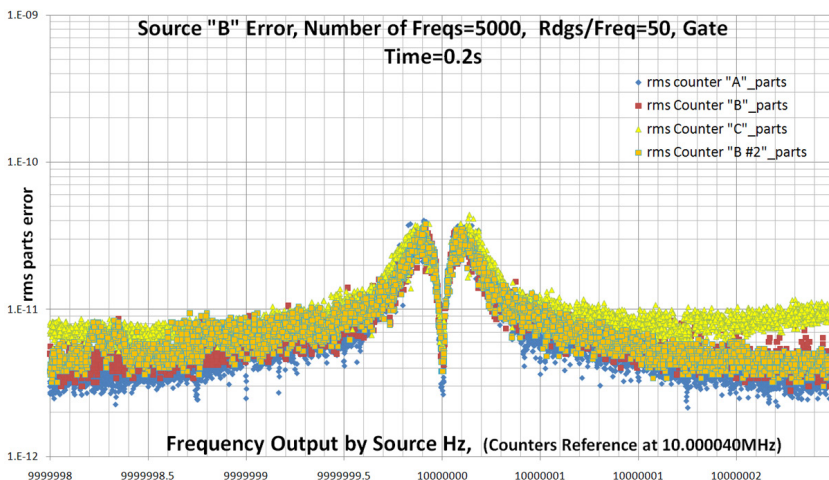
Figure 4. Source B error signature.

4. Counters Beat Frequency Error

Counters will have an error of some type when the input frequency (or input frequency harmonic) is near the harmonics of the counters reference clock frequency. Usually this is at the harmonics of the 10 MHz reference clock. The magnitude of the error for a counter model is governed by the architecture, data reduction algorithms, layout, gate time and dead time. Gate time plus dead time is the time between consecutive measurements. When the input frequency is very slightly offset from the time base frequency (or harmonics), the time base and the input signal pull each other's edges as the two waveforms edges slide by each other. This "*beating*" of the two frequencies results in a measured time error with a periodicity related to the differences of the two frequencies, and the processing algorithm. If the data processed (gate time) encapsulates integer multiple periods of the beat frequency then the error could be averaged to zero over the gate time, however other gate times will yield varying results. Measuring the error at just one frequency will not indicate the best counter. A 100 ppb change in the difference in the signal frequency to time base frequency may drastically change the conclusions from the test. The nulls in the error curves are not the same between counter models.

Measuring the standard deviation of 100 consecutive measurements will provide the rms of the measurement of the beat frequency error for the gate time used. If the rms for 100 consecutive measurements is plotted for a variety of frequencies, then the shape of the error curve is uncovered. The shape of the curve or "*signature*" is unique to each counter model and its setup. In addition to the rms, the internal statistics package in the counters also provides the maximum and minimum reading for the 100 measurements, which is close to the peak to peak of the error waveform. Figures 5 through Figure 7 are the rms error in parts for three gate times: 0.1 second, 0.3 second and 1 second for two of product "*A*", two of product "*B*", one product "*C*" using the source with a external reference 40 Hz offset from the counters reference using the clock generator, therefore eliminating the sources 10 MHz beat frequency error. The span of the "*signature*" plot of frequency verses rms error drops inversely with the gate time; however the basic shape will be the same. The magnitude of the error is normalized by the gate time used.

Note that since there is over 10x difference in minimizing the beat effect, the graphs of the error are presented in logarithmic scale.

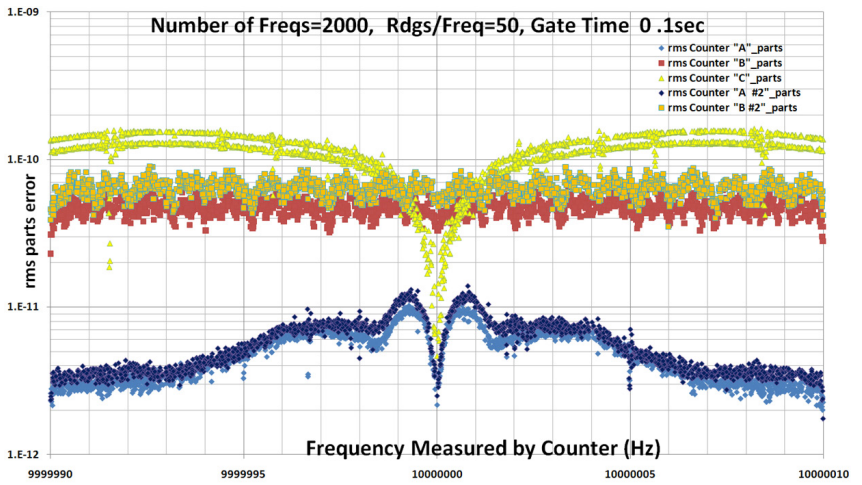*Figure 5. Counter errors at 100 ms gate time.*

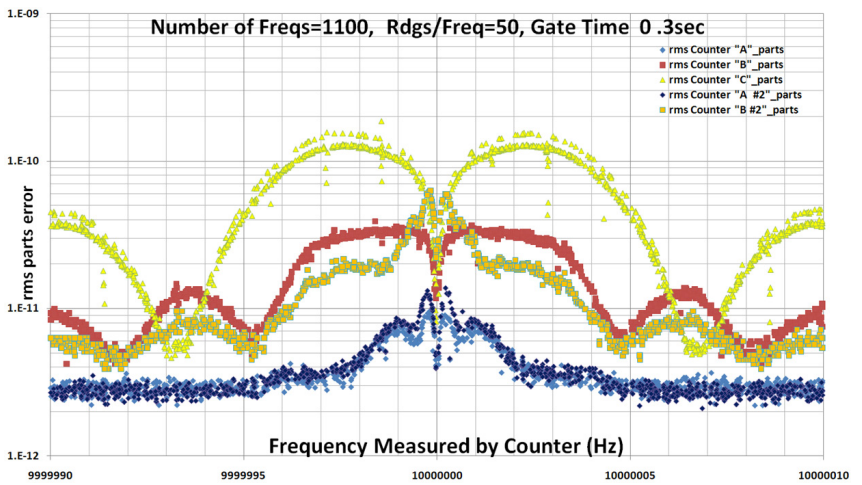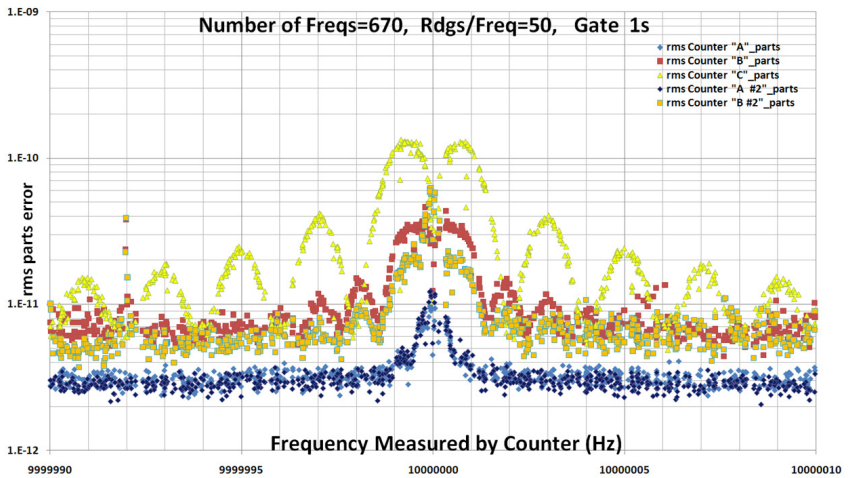*Figure 6. Counter error at 300 ms gate time.*

Figure 7. Counter error for 1 second gate time.

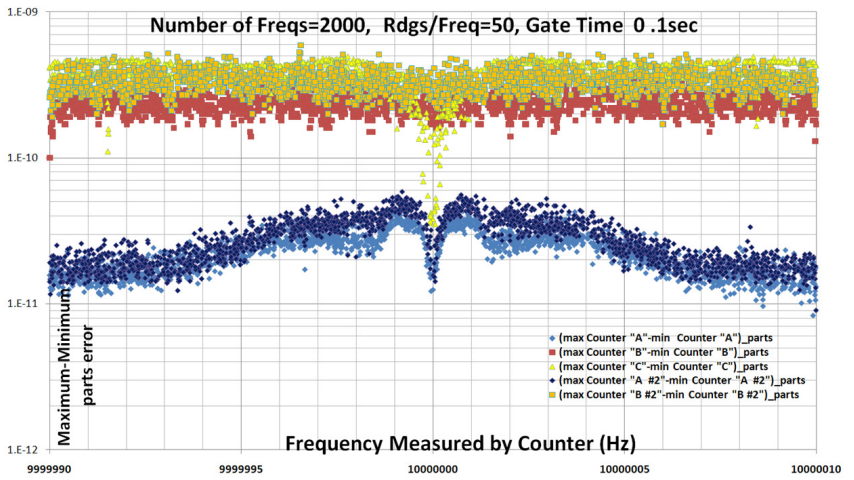The peak to peak error is show in Figure 8 through Figure 10.

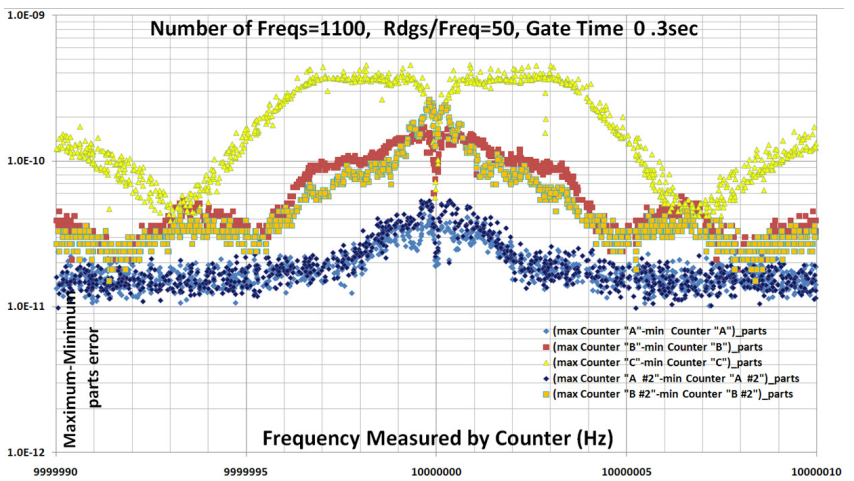*Figure 8. Peak to peak counter error for 100 ms.*
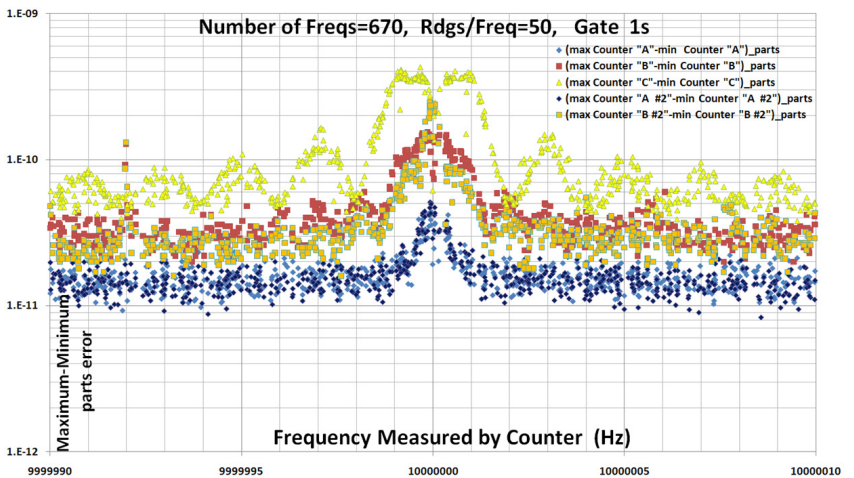

Figure 9. Peak to peak counter error for 300 ms.

Figure 10. Peak to peak counter error for 1 second.

A well aged double insulated disciplined OCXO is present in most calibration labs. One of the usages of this reference is characterizing the time stability of DUTs time base by measuring the various variances. Variance measurements assume no deterministic error, just random forms of error and movement. Many times the raw data from measuring the variance of a 10 MHz DUT is plotted and a periodic movement in the readings is observed. As seen in the preceding graphs the magnitude of the error is related to the frequency difference between the DUT and the reference clock, gate time of the counter and model of counter. In a few scenarios, fortunately, the measurement frequency a null of the error plot, other times it is the worst case error. Usually the variance measurement equipment has a fixed frequency and the DUT has a fixed frequency. There is no possibility of analyzing the problem in the frequency domain. When an error is only observable in the time domain, identifying the source of the measurement error and its avoidance is not possible.

Figure 11 is a time plot of counters "A", "B", and "D" measuring a source a few fractions of a ppm (0.04 ppm) difference between the source frequency and the reference. Figure 11 is the time domain data for 1 second gate. Notice that the error may appear as a periodic waveform or just a low level random noise of the DUT and instrumentation. Change of difference between reference frequency to frequency measured, gate time or even dead time between measurements would give a significantly different plot.
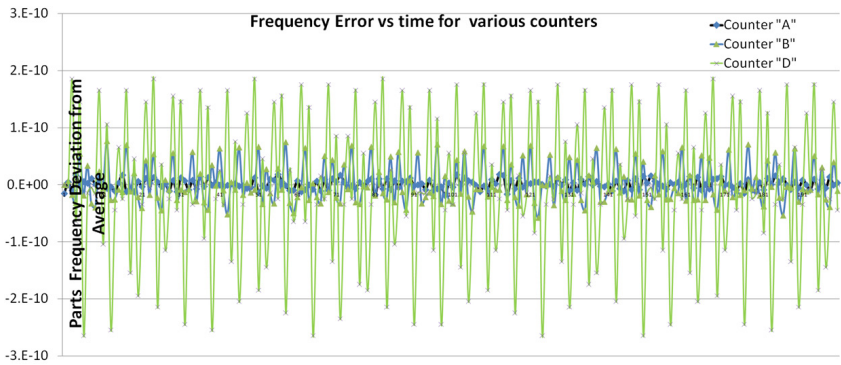
Figure 11. Time plot of counter's error.

Summary:
- Sources and frequency analyzers are susceptible to error when the frequency being sourced or measured is close to their reference clock.

- Changes in vendor, model, gate time, or frequency will significantly affect the measured error. Counters should be evaluated to determine the magnitude of error.

- A source's error needs to be evaluated at the same time the counter is being evaluated.

- Knowledge of the source's error used to evaluate the counter is very important.

- A simple and effective method is used to measure the sources and counters error separately by offsetting the references of source and counter.

- Errors cannot be evaluated at just one frequency or gate time, but must be evaluated across a continuum of frequencies surrounding the reference frequencies and their harmonics.

- Evaluation of 10 MHz sources (crystals, oscillators) is a common encounter with this type of error.