MtronPTI'S Oscillator Jitter Basics

WHAT IS JITTER?
HOW IS JITTER MEASURED?

SECTION 1
JITTER DEFINITION

An ideal clock signal at 155.52 MHz will have a period of 6430 pico-seconds for one complete cycle. Successive cycles of a "noise free" waveform will measure exactly 6430 pico-seconds. The noise elements that will cause the clock period to vary from 6430 pS are known as jitter. Jitter is composed of both deterministic (from specific causes like power supply noise), and random content. The random portion of Jitter can be characterized using Gaussian distribution statistics. For example, three hundred successive measurements of the period of a 155.52 MHz clock oscillator that contains only Random Jitter elements would appear as a Gaussian distribution (with one peak). Plus or minus one standard deviation would contain 68.26% of all period measurement data points:

+/- 2 sigma would contain 95.4 % of all measurements taken.
+/- 3 sigma would contain 99.73%.
+/- 4 sigma would contain 99.99366%
+/- 7 sigma would contain (100- 1exp-12)% of all measurements taken.

A Gaussian distribution with a larger standard deviation would have wider tails, more period measurements further from the mean (both smaller and larger). The distance from the smallest period measurement to the largest period measurement is known as the Peak-to-Peak Jitter level in pico-seconds. The peak-peak value is dependent on the sample size. Larger sample measurements of the same unit under test will yield larger peak-peak values. The use of Standard Deviation (1-sigma) is only valid in pure Gaussian distributions. If any Deterministic Jitter (has specific causes as outlined below) exists in the distribution, the use of 1-sigma based on the entire Jitter histogram for the estimation of probability of occurrence is invalid. If Deterministic Jitter exists in the signal, than the histogram of period measurements will comprise multiple peaks. It is likely that a dominant contributor to Jitter such as power supply ripple is modulating the clock to bring about multiple peaks. Or, the oscillator signal could contain lots of sub-harmonic power. Total Jitter is a combination of Random Jitter interacting with Deterministic Jitter.

SECTION 2
SOURCES OF JITTER

Random Jitter comes from many sources. Thermal vibrations of semiconductor crystal structure cause mobility to vary depending upon the instantaneous temperature of the material. Another source of Random Jitter comes from the imperfections due to semiconductor process variation such as non-uniform doping density. Multiple Random Jitter sources add in an RMS fashion, but a peak-to-peak value is needed when adding Random Jitter to Deterministic Jitter to obtain Total Jitter, peak to peak.

Deterministic Jitter is created by identifiable interference signals. It is always bounded in amplitude and has specific causes (not random). Deterministic Jitter can be generated by cross talk between adjacent signal traces. This happens when incremental inductance from one conductor converts induced magnetic field from an adjacent signal line into induced current. This induced current increases or decreases the voltage, thus causing Jitter.

EMI Radiation can cause deterministic Jitter. A sensitive signal path can be affected by the magnetic field from an EMI source. EMI sources include power supplies, AC power lines, and RF-signal sources. Like cross talk a noise current is induced on the timing signal path, which thereby modulates the timing signal voltage level.

Deterministic Jitter can be generated by noise in power layers of a multi-layer substrate. This noise can change threshold voltages in logic gates. Or, a change in ground reference at the threshold voltage will result in changing the required voltage to switch the gate.

Deterministic Jitter can appear when multiple gates switch to the same logic state simultaneously. Current spikes can be induced on power and ground planes, creating another opportunity for threshold voltage level shifting.

SECTION 3
HOW MTRONPTI MEASURES JITTER

MtronPTI uses time measurement systems from Wavecrest, phase noise systems, and digital scopes to measure both time-domain and frequency-domain Jitter. While measurement technique will be briefly discussed in this tutorial, Wavecrest has written a number of application notes on the fundamentals of Jitter measurements using their equipment. Their website is located at www.wavecrest.com. Two particular application notes to start with include:

DTS MEASUREMENT TECHNIQUE (Getting Started)
JITTER ANALYSIS (Getting Started).

The DTS measures the time between two events. Internally many time measurements (samples) are compiled into a histogram (Figure 1 directly below). Basic statistics such as sample size, mean, peak-to-peak, and 1-sigma can be viewed on the front panel. This data on the oscillator output signal can be delivered over GPIB to Wavecrest Virtual Instruments software, API software or to users' custom software. Data from hundreds or thousands of histograms can be compiled into plots, which highlight more information about output signal quality. Specific values of Jitter accumulation such as Jitter frequency and power, and magnitude of Deterministic and Random Jitter can be displayed in these plots.
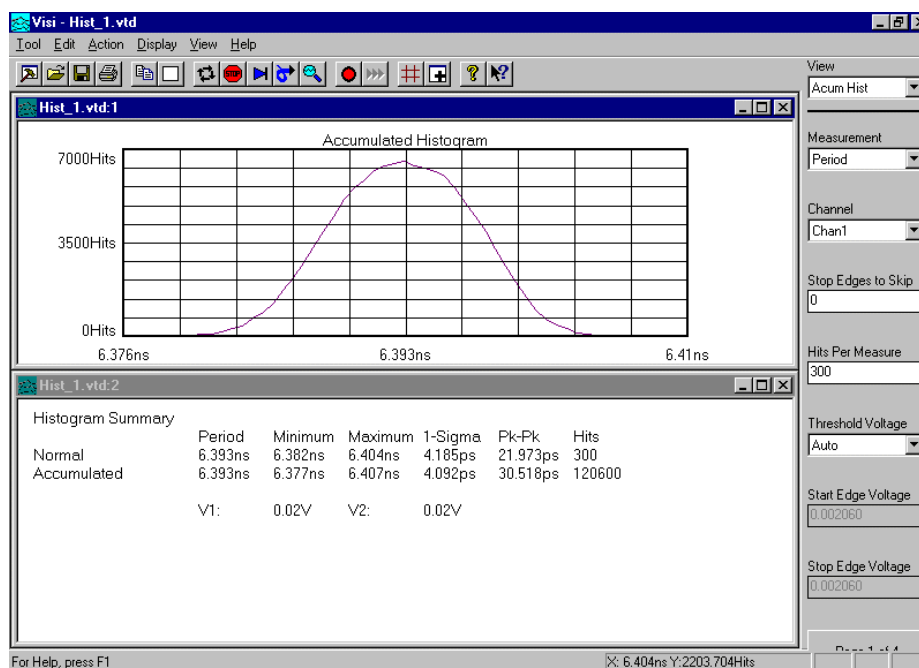

FIGURE 1

The DTS measures time between two events, which are threshold crossings. A digital sampling oscilloscope measures the voltages with respect to time relative to a trigger. Event based measurements allow the DTS to determine actual edge placement to within 800 femto-seconds (hardware resolution of DTS). Sampling scopes interpolate data between sampled points to determine the time of the threshold crossing. Because scopes depend upon the use of a trigger signal, any Jitter on this waveform could potentially mask out a jitter contributor. One particular digital scope from an industry-leading supplier listed 1.5 pS as the rms Jitter error for their measurement set-up. The DTS uses asynchronous random sampling of events to establish a valid statistical distribution of event times. It gathers samples every 21uS to 25uS independent of the DUT operating frequency. By randomizing the acquisition time, there is no chance of masking out a Jitter signal that could match a sampling rate.

1 Sigma Cycle to Cycle jitter data from 4 Oscillator IC's
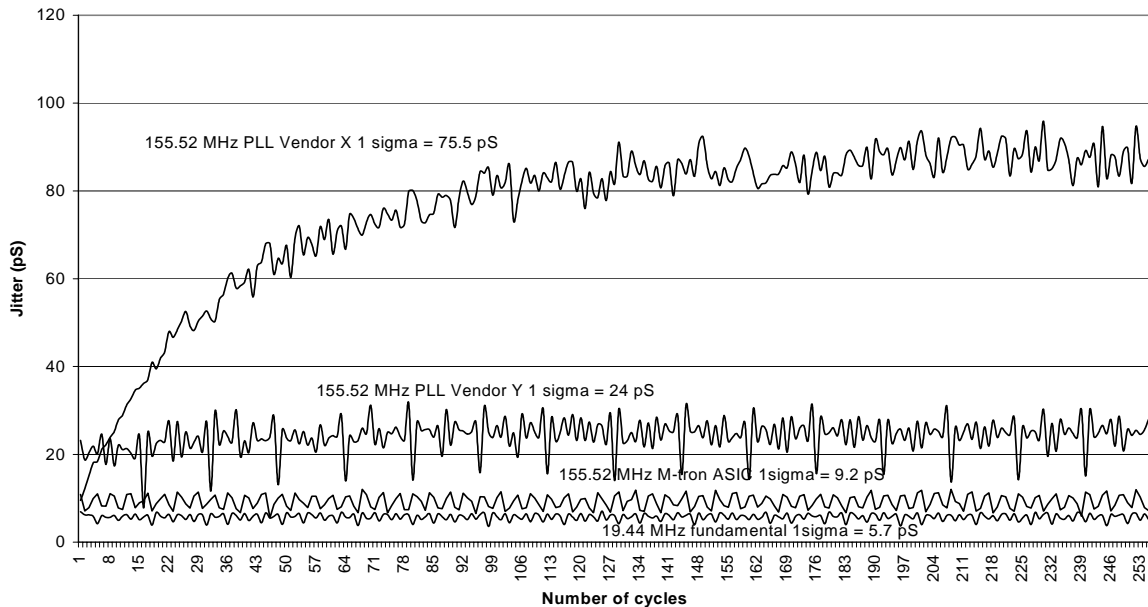**Measured using Wavecrest DTS-2075**

FIGURE 2

The DTS measurement system includes many software tools to enhance one's understanding of waveform characteristics. The Jitter analysis tool allows the user to view Jitter modulation. For example, the user can measure hundreds or thousands of histograms each consisting of 300 sample measurements of a waveform's period. The standard deviation from all of these sample groups can be plotted to show accumulated Jitter over a designated time period (Figure 2 depicted directly above). Other critical waveform parameters such as rise time, fall time, propagation delays, and frequency can be examined in this fashion.

The time domain data can be connected to the frequency domain by using an FFT to determine the frequency and amplitude of the Jitter components. Advanced software tools beyond the scope of this discussion are also available from Wavecrest. The Tail-fit[TM] algorithm enables the user to analyze multimodal distributions (more than one peak). In non-Gaussian distributions, Gaussian assumptions apply to the tails (furthest left and right regions) when it is possible to calculate the equivalent 1-sigma of these tail regions. In this way Tail-fit[TM] allows for the calculation of probabilistic occurrence of outlying measurements for non-Gaussian distributions.

Thus, a prediction of peak-to-peak Jitter for a given waveform can be approximated (with very high confidence) a billion cycles after power-up without waiting for one billion signal periods to complete.

Another advanced software feature involves the calculation of integrated jitter when the user specifies a frequency bandwidth such as the SONET range of 12KHz to 20 MHz. Depending upon the number of sample measurements specified in the set-up, the integrated jitter test would take between 0.5 and 1.5 minutes per unit.

SECTION 4
TYPES OF JITTER SPECIFIED FOR OSCILLATORS:

Measurements in the time domain

Cycle to cycle Jitter measures the difference in period between adjacent cycles. Peak to peak cycle Jitter is the width of the distribution of period measurements from smallest value to largest value. Peak-to-peak is obtained from a histogram of successive edge measurements. The more sample measurements that are taken, the larger the difference between the smallest and the largest period data points. The distribution of sample period measurements has an RMS or standard deviation (1-sigma) associated with it.

The 1-sigma level of a distribution of period measurements can be used to calculate bit-error rate. The expected BER is defined as the probability of causing a bit error when the Total Jitter (Random plus Deterministic), peak to peak, exceeds the Jitter budget.

Listed below is a table of Random Jitter (pk-to-pk) versus BER:

PROBABILITY OF DATA ERROR	PEAK TO PEAK = N*RMS
10^{-10}	Pk-Pk = 12.7*RMS
10^{-11}	Pk-Pk = 13.4*RMS
10^{-12}	Pk-Pk = 14.1*RMS (+/- 7 sigma)
10^{-13}	Pk-Pk = 14.7*RMS
10^{-14}	Pk-Pk = 15.3*RMS

Measurements in the frequency domain

Integrated Jitter over a specified bandwidth can be obtained from MtronPTI's DTS time measurement system. For example, SONET standards require jitter performance within the frequency band of 12 KHz to 20 MHz offset from the carrier frequency. Depending upon the number of samples measured, the Wavecrest system will calculate this value in 30 to 90 seconds per unit.

Integrated Jitter can also be obtained from a phase noise measurement system over a given bandwidth. Depending upon the number of averages within each frequency offset band, the measurement could take as long as four minutes per unit. Each measurement technique has its' advantages and disadvantages. Supplemental discussions with MtronPTI technical support can review these measurement technique differences in more detail.

On a particular 155.52 MHz, PECL oscillator product, the Integrated Jitter was 1.08 pS in the frequency band of 12KHz to 20 MHz. This same DUT had a cycle-to-cycle 1-sigma level of 5.99 pS as measured in the time-domain. The peak to peak in the time domain was 45.8 pS.

Even though the Integrated Phase Jitter looks better because it is a smaller number, the time domain measurements communicate the same information about the oscillator waveform noise signature.

SECTION 5
CONVERSION OF PHASE NOISE DATA TO INTEGRATED PHASE JITTER:

There are many papers that describe how to derive equations to express RMS Jitter in terms of Phase Noise. What we will show you is a practical application that was developed for a Microsoft Excel spreadsheet. This is a tool that can be used by any engineer interested in analyzing Phase Noise data. We start out with the well-established equation to calculate RMS Jitter in seconds from phase noise.

$$J_{rms} = \frac{1}{(2 \cdot \pi \cdot fo)} \cdot \sqrt{\int_{f_1}^{f_2} S\phi(f) \, df} \quad \text{Eq.1)} \qquad S\phi(f) = f \cdot \phi \quad \text{Eq.2)} \qquad \phi = 2 \cdot \left[10^{\left[\frac{dBc}{10}\right]} \right] \quad \text{Eq.3)}$$

fo = The carrier frequency in Hz
f_1, f_2 = The offset frequency range of interest in Hz
Φ = Phase noise in radians^2 / Hz
dBc = Phase noise power relative to the carrier
$S_\Phi(f)$ = Spectral Density at a particular offset frequency f in Hz, (see Eq.2.)

Φ is related to phase noise power by Eq.3. Substituting Φ in Eq.2 we arrive at our final definition for $S_\Phi(f)$ in Eq.4.

$$S\phi(f) = f \cdot 2 \cdot \left[10^{\left[\frac{dBc}{10}\right]} \right] \quad \text{Eq.4)}$$

To approximate the integral we use the summation of trapezoids Eq.5.

$$\int_{f_1}^{f_2} S\phi(f) \, df \approx \sum_{j=1}^{n} m_j = \left[\frac{S\phi(f_1) + S\phi(f_2)}{2} \right] \cdot (f_2 - f_1) \quad \text{Eq.5)}$$

Phase Noise test systems plot frequency along a logarithmic scale, at least 3 points should be picked in each decade. For example to get evenly spaced points we chose to use a 10, 20, 50, 100, 200 ... etc. method. More points equals better correlation.

All that is left is to take the square root of the summation and then divide by (2*PI*Fo). We have described all the pieces necessary to make this a simple task to implement into a spreadsheet or code this into a BASIC or C program.

Here are results listed below comparing this method with the Aeroflex PN9000 Phase Noise Test Set using n = 16 points from 10 Hz to 1 MHz.

46.720 MHz VCXO

Range:	rms noise (ps)	Meas	% Diff.
10Hz-1MHz	2.93	3.14	-6.8%
100Hz-1MHz	0.59	0.57	3.6%
1KHz-1MHz	0.22	0.22	-2.0%
10KHz-1MHz	0.20	0.20	-1.2%

161.000 MHz clock multiplier

Range:	rms noise (ps)	Meas	% Diff.
10Hz-1MHz	15.16	15.10	0.4%
100Hz-1MHz	12.65	12.73	-0.6%
1KHz-1MHz	12.53	12.45	0.6%
10KHz-1MHz	12.52	12.45	0.6%

SECTION 6
CORRELATION OF OSCILLATOR JITTER FROM SUPPLIER TO CUSTOMER

Regardless of what type of Jitter is specified, the maximum oscillator Jitter level that would cause the end product to fail its' system requirements should be determined. In most cases the oscillator Jitter contribution to overall system Jitter is 25% or less. To help oscillator companies simulate operation in the customers' board, information about noise-ripple into the oscillator supply should be given to the supplier. Then, the Jitter measurements can be performed with and without supply-line noise injection so that the customer better understands how the device performs with some "on-board" signal interference.

MtronPTI recommends to its' customer base that:

1). Time-domain 1-sigma Jitter and peak-to-peak levels be specified using 50000 period cycles.

2). Integrated Phase Jitter over the SONET bandwidth (12 KHz to 20 MHz) should be specified as well.

3). Phase Noise performance at different frequency offsets should be specified to give oscillator suppliers a complete picture of the oscillator signal noise profile.