Jitter and Signal Noise in Frequency Sources

Objective

Define and analyze different jitter types in frequency sources along with corresponding test set-ups and consequent analysis methods.

Definition

“Jitter consists of short-term variations of the significant instants of a digital signal from their ideal positions in time. “(ITU-T)
Rising and falling edges in a digital data stream never occur at exact desired timing. Defining and measuring accurate timing of such edges concerns and affect performance of synchronous communication systems.

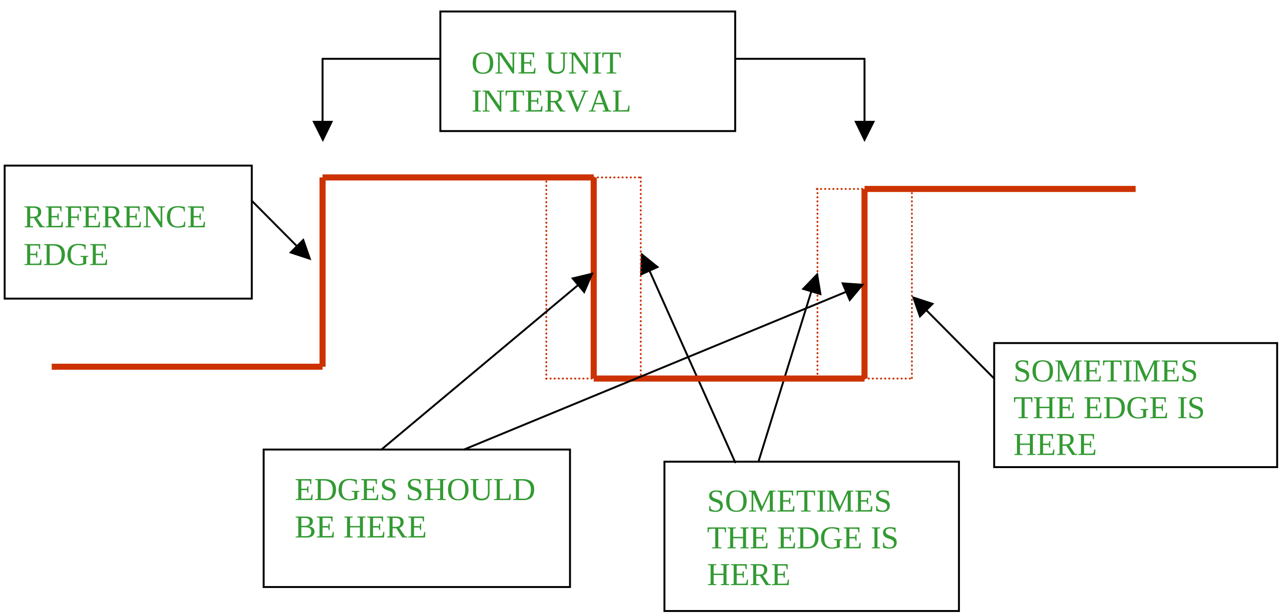

Figure 1

The edges displacement, of a given signal, are a result noise with both spectral and power contents.. These edges may vary randomly with respect to time as a result of non-uniform noise over the frequency domain. (hence; jitter caused by a noise at 10KHz offset could be greater or smaller than that of a noise at 100KHz offset). Spectral content of a clock jitter may differ greatly based on the different measurement techniques or bandwidth evaluated.

RALTRON ELECTRONICS CORP. ▪ 10651 N.W. 19th St ▪ Miami, Florida 33172 ▪ U.S.A.
phone: +001(305) 593-6033 ▪ fax: +001(305)594-3973 ▪ e-mail: sales@raltron.com ▪ internet: http://www.raltron.com

System Disruptions caused by Jitter

Clock recovery mechanisms, in network elements, are used to sample the digital signal using the recovered bit clock. If the digital signal and the clock have identical jitter, the constant jitter error will not affect the sampling instant and therefore no bit errors will arise. (Such case will be applied to low frequency jitter in which the recovery clock mechanism can follow the digital signal phase variations; at higher frequency jitter variations, >0.5UI, will result with inaccurate sampling and loss of valuable data.).

Measuring Jitter

There are three types of instruments being used to measure jitter: 1) BER (bit-error-rate), 2) Jitter Analyzers and 3) Oscilloscopes. The type of instrument used to measure jitter will depend on the application, electrical/optical, datacom or telecom, and the bit rate (see figure below). A mix of these instruments may be needed to accurately track down a problem related to jitter. The most common method is to start with a BER tester. To further isolate the problem, additional testing is done using a jitter analyzer or an oscilloscope. In addition to quantify jitter, measurements should assist designers to investigate the root cause and source(s) of the problem to effectively eliminate jitter.

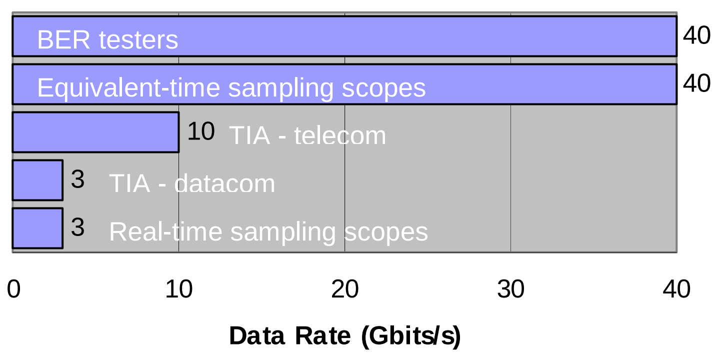

Figure 2

Prior to jitter measurment, we must first understand the types of jitters, and its sources. Jitter is divided into two general categories: **Deterministic jitter** (Dj) and **Random jitter** (Rj). Furthermore, Dj is divided into **Periodic jitter** (Pj) and **Data Dependent jitter** (DDj) whih is composed of **Duty Cycle Distortion** (DCD) and **Inter-Symbol Interference** (ISI). The integration of all individual jitter components result in the **total jitter** (Tj). It includes contribution from all deterministic and random components (see figure below).

RALTRON ELECTRONICS CORP. ▪ 10651 N.W. 19th St ▪ Miami, Florida 33172 ▪ U.S.A.
phone: +001(305) 593-6033 ▪ fax: +001(305)594-3973 ▪ e-mail: sales@raltron.com ▪ internet: http://www.raltron.com

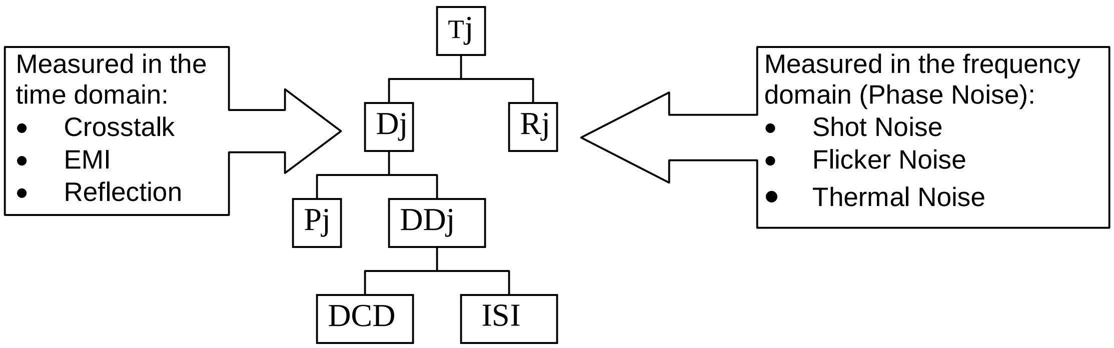

Figure 3

Deterministic jitter (Dj) has specific causes, and it is predicable and consistent. It has a non-Gaussian amplitude distribution that is always bounded which can be characterized by its peak-to-peak value. It comes from system sources such as **crosstalk**, **inter-symbol interference – ISI - (reflections)** and **power supply** feed through **(EMI)**.

Periodic jitter is cyclical resulting from a cross-coupling or EMI (AC power lines, RF signal sources, etc.) from a switching power supply. The latter is known as uncorrelated periodic jitter which couples into the data or system clock signal. A correlated periodic jitter is the coupling of an adjacent data signal from a clock of the same frequency. It is designated by a frequency and magnitude measured as a peak to peak number.

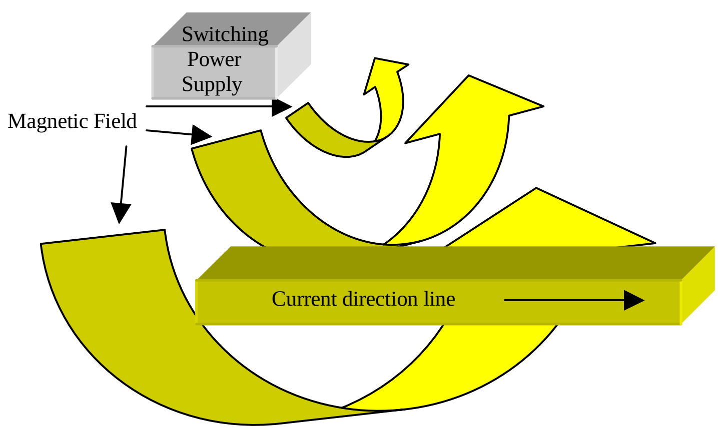

Figure 4

RALTRON ELECTRONICS CORP. ▪ 10651 N.W. 19th St ▪ Miami, Florida 33172 ▪ U.S.A.
phone: +001(305) 593-6033 ▪ fax: +001(305)594-3973 ▪ e-mail: sales@raltron.com ▪ internet: http://www.raltron.com

Pj can be quantified using an **oscilloscope**. Activated on the rising edge of a clock and move across the display until another rising edge of a clock is displayed. The Pj is the band of the rising edge exhibited on the scope.

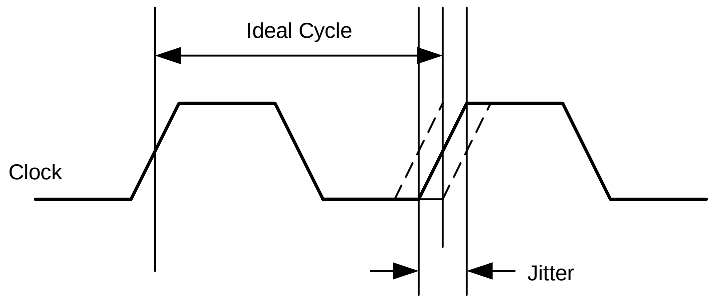

Figure 5

Periodic Jitter

Data Dependent jitter (DDj) is divided into **Duty Cycle Distortion** (DCD) and **Inter-Symbol Interference** (ISI).

DCD is the deviation in propagation delay between high to low and low to high times. In other words, it is the deviation in the mean pulse with of the positive pulses compared to the negative pulses in a clock-like bit sequence. Amplitude offset errors, turn on delays and saturation maybe some of the causes of DCD.

ISI is sometimes referred to as data dependent jitter. It is usually the result of bandwidth limitation in the transmitter or physical media; therefore, creating varying amplitudes of data bits due to limited rise and fall times of the signal. It occurs when the frequency component of the data (symbol) is propagated at different rates by the transmission medium.

Random jitter (Rj) is considered not bounded and can be described by a Gaussian probability distribution. It affects long-term device stability characterized by its standard deviation (rms) value. It is generated from physical sources like: thermal noise, white noise and scattering in optical media.

Common sources of Deterministic Jitter

Electromagnetic Interface (EMI) results from conducted radiated emissions undesirably radiated from local devices or systems. Common sources are switching type power supplies which radiate strong, high frequency magnetic and electric fields conducting a large amount of electrical noise into a system lacking of adequate shielding and output filtering. EMI alters the biasing of electrical signals coupling or inducing noise currents in a conductor.

RALTRON ELECTRONICS CORP. ▪ 10651 N.W. 19th St ▪ Miami, Florida 33172 ▪ U.S.A.
phone: +001(305) 593-6033 ▪ fax: +001(305)594-3973 ▪ e-mail: sales@raltron.com ▪ internet: http://www.raltron.com

Crosstalk arises by accidental coupling of a magnetic and/or electric field to an adjacent conductor carrying a signal. The unwanted signal components are added to the original signal altering its bias determined by the amount of the interference signal.

Reflection is caused by the interfering of the signal with itself occurring when impedance mismatches exist in the channel. Optimal signal power transfer in cooper technology happens when the medium has the same characteristic impedance in the transmitting and receiving ends. A portion of the energy is reflected back to the transmitter if an impedance mismatch exists at the receiver coming from uncontrolled stubbing and incorrect terminations. Likewise, if the mismatch is at the transmission end, it ingests part of the reflected energy, and the receiver gets reflected the remainder. Ultimately, the receiver gets the delayed signal out of phase with the original one which is algebraically added with the first arriving signal.

Common sources of Random Jitter

Shot noise also known as broadband "white noise" is created by the movement of electrons and holes in a semiconductor whose amplitude is a function of the average current flow generated by fluctuations about its average value. In a semiconductor, it will depend in the randomness of the density of electrons and holes. It is a contributor of Rj in a signal channel.

Flicker noise also known as pink noise is proportional to the reciprocal of the frequency, 1/f. It is only of concern in low frequency measurements. It is normally found in resistors, diodes, switches and transistors, among other components. Typically, it must be measured empirically.

Thermal noise is the noise generated by thermal agitation of electrons moving freely within a conductor.

BER tester, Jitter Analyzers (also known as Time Interval Analyzers -TIA), Oscilloscopes

BERTs allow engineers to obtain an accurate measured bit error rate of a device under test . They are designed to sample every single bit received in a data stream comparing it against a predetermined pseudorandom bit sequence (PRBS) pattern. In most cases jitter analyzer or oscilloscopes cannot achieve such accuracy.

Jitter Analyzers (TIA) measure the interval from a reference clock to a signal edge or between threshold crossings; using histograms and collecting a large number of data points. Devices in high speed data-com buses like Fiber Channel, Serial ATA, Infini-band and Rapid IO which contain rates up-to 3.125 Gbits/s per channel benefit from using TIA for testing. TIA's are found in production lines testing because they can predict BER in a few seconds.

RALTRON ELECTRONICS CORP. ▪ 10651 N.W. 19th St ▪ Miami, Florida 33172 ▪ U.S.A.
phone: +001(305) 593-6033 ▪ fax: +001(305)594-3973 ▪ e-mail: sales@raltron.com ▪ internet: http://www.raltron.com

Oscilloscopes use an external trigger event and a sampling clock to build the eye diagram sampling over time a repetitive signal. The threshold crossing time of a signal is formed by a histogram allowing to measure jitter. An approximation of the jitter's probability density function (PDF) is derived from the histogram that can be examined to characterize jitter.

Real time sampling oscilloscopes are useful in testing subsystems, cables, devices or systems communicating at high speeds (i.e. 3.125 Gbits/s, the current highest possible speed for transmitting data over copper). These type of scopes measure jitter on any clock signal, not only the ones used in communications.

To measure jitter at high bit rates in today's world, sampling oscilloscopes are the best choice due to their high bandwidth sampling. They require PRBS signals which are repetitive due to their low sampling rate (150 ksamples/s or less) to generate eye diagrams in order to build jitter diagrams.

Oscilloscopes

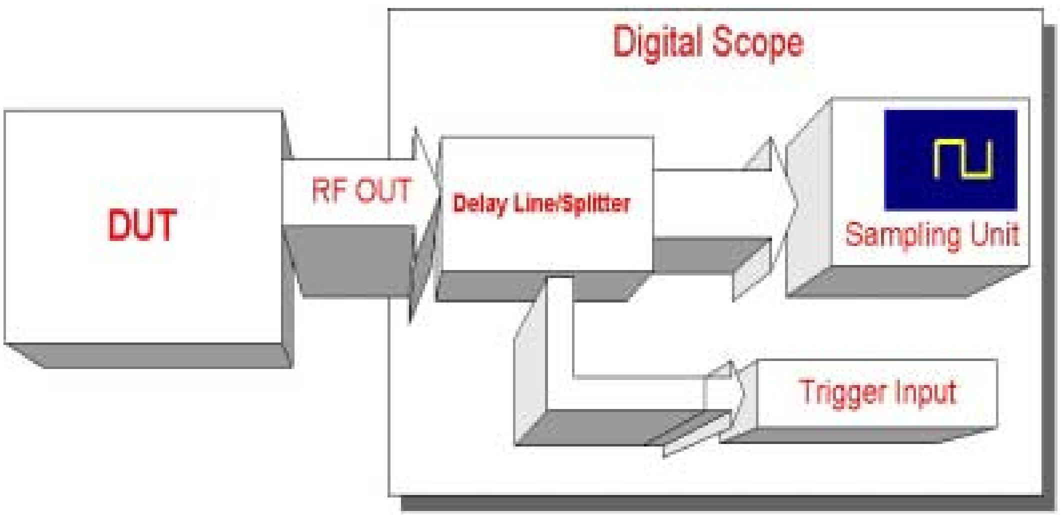

Figure 6

Phase Noise

Phase noise is the frequency domain view of the noise spectrum around an oscillator signal. It is a rapid, short-term, random fluctuation in the phase of a wave, caused by time domain instabilities.

A sine wave can be represented by:

$V(t) = V_p \sin(2\pi f_0 t)$

Where:
Vp is peak amplitude
f_0 is the nominal frequency
t is time

The sinusoidal wave form, in Figure 7, has a $Vp = 2.5V$ with a nominal frequency of *1MHz; resulting in* $V(t)=2.5\sin(2\pi 1\times10^6 t)$

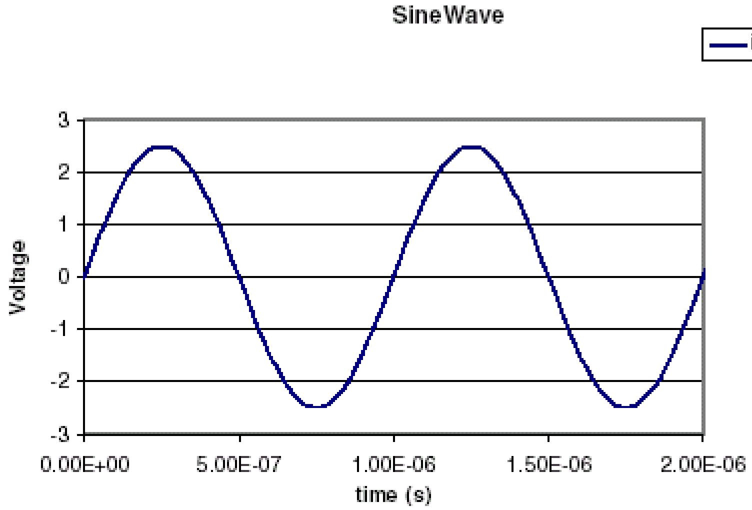

Figure 7

Figure 8 shows the same sinusoidal signal as above with the addition of phase noise, $\varphi(t)=2\pi\sin(1.5\pi f_0 t)/15$ which is the predominant source of noise. And for digital and telecom application the one of most concern.

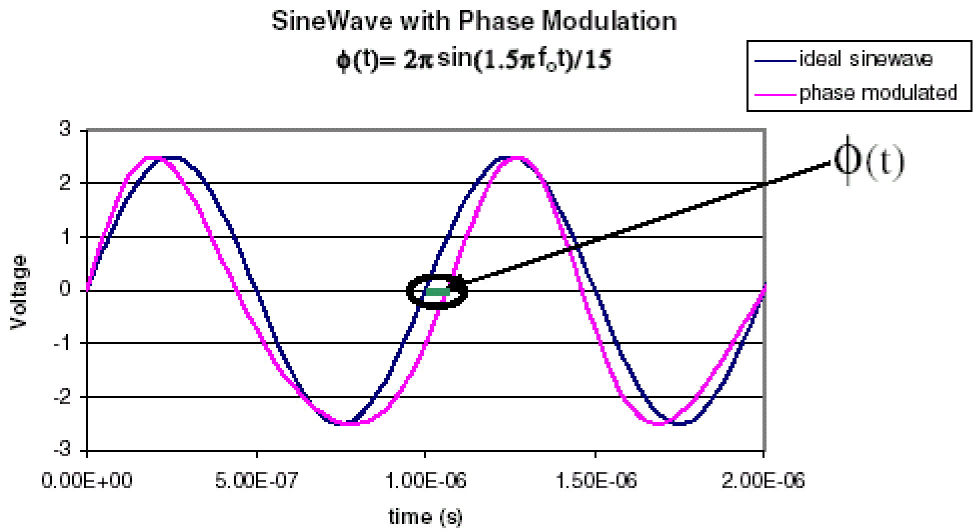

Figure 8

RALTRON ELECTRONICS CORP. ▪ 10651 N.W. 19th St ▪ Miami, Florida 33172 ▪ U.S.A.
phone: +001(305) 593-6033 ▪ fax: +001(305)594-3973 ▪ e-mail: sales@raltron.com ▪ internet: http://www.raltron.com

Phase noise, φ(t), can be defined as a measurement of the variation in the timing of the signal. Nonetheless, the results are showed in the frequency domain, *L(f).* The result, in Figure 9, is the relation of the noise power at unwanted frequencies to the total response power, distributed in a 1Hz bandwidth. The complete power on the oscillator would be centered at f=fo if the phase noise equals zero. Keep in mind that phase noise spreads some of the power of the oscillator to adjacent frequencies resulting in sidebands.

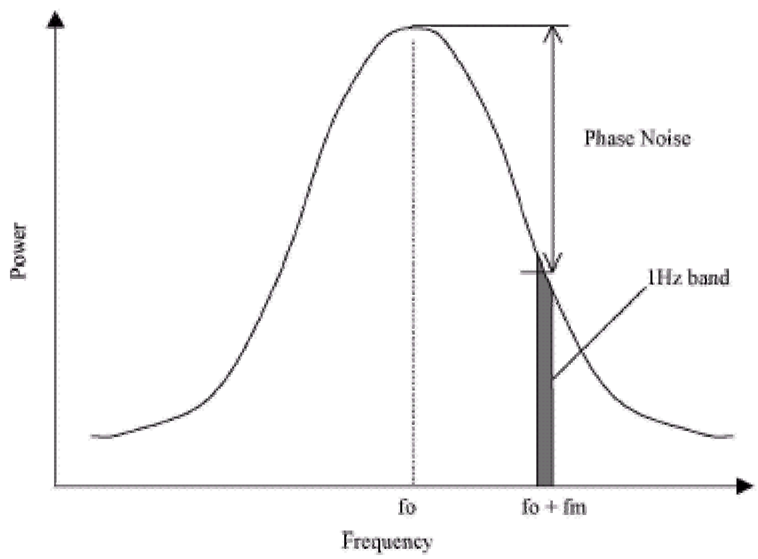

Figure 9 – Oscillator Power Spectrum

Phase noise is defined in dBc/Hz at a specific offset. The level in dB relative to the carrier is given in dBc. At any given offset, the oscillator's phase noise can be derived from the ratio of the total power of the carrier to the power in a 1-Hz bandwidth at the offset frequency. In figure 9, the ration of the total area of the power spectrum curve to the area of the rectangle with 1-Hz bandwidth at the offset fm (roughly the difference in height of the spectrum a the centre and at fm) is a representation of phase noise. The power spectrum of an oscillator with a noisy phase angle is the actual spectrum of the curve.

RALTRON ELECTRONICS CORP. ▪ 10651 N.W. 19th St ▪ Miami, Florida 33172 ▪ U.S.A.
phone: +001(305) 593-6033 ▪ fax: +001(305)594-3973 ▪ e-mail: sales@raltron.com ▪ internet: http://www.raltron.com

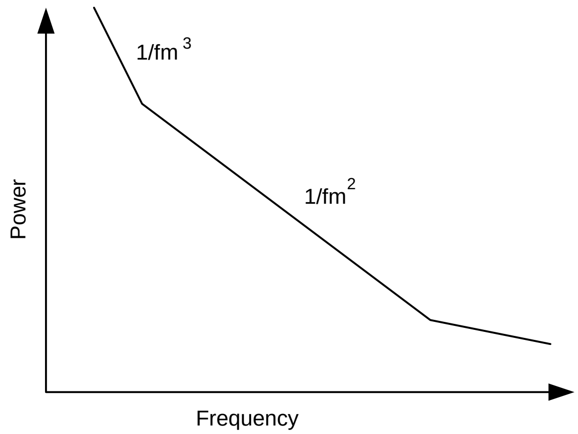

Figure 10 – Phase Fluctuation Spectral Density

The power spectrum of the oscillator is represented in Figure 9. The noisy phase angle term, called the spectral density of the phase fluctuations, is represented in figure 10. The measurement of the spectral density of phase variations, in Figure 10, is the same as the phase noise in dBc/Hz measured from the power spectrum, in Figure 9, for offsets very far from the carrier.

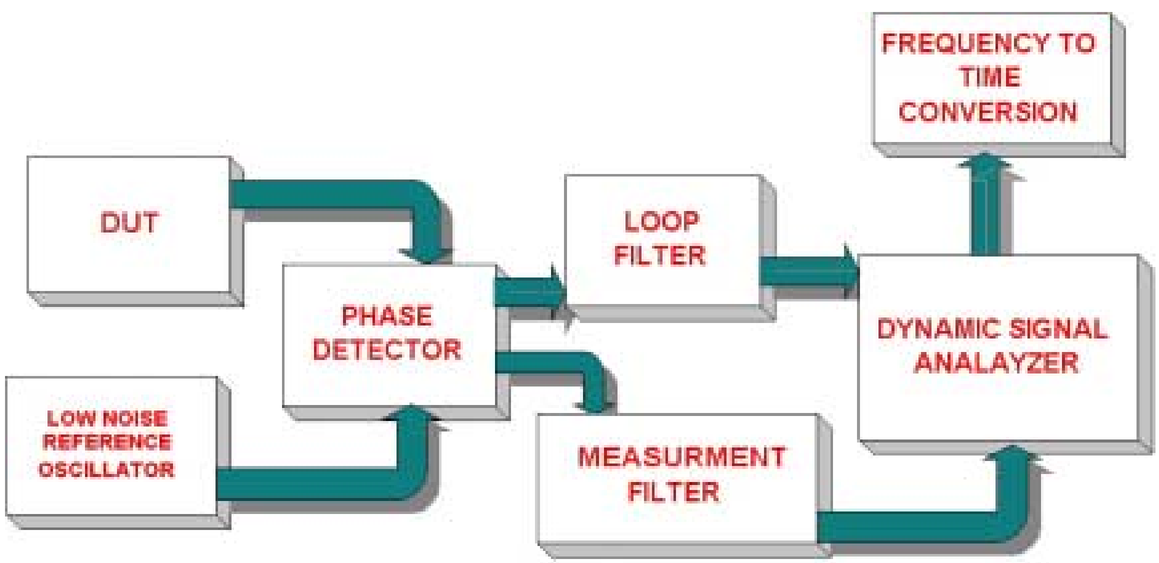

Figure 11

In Figure 11, an ovenized crystal oscillator (OCXO) is used as the reference clock which outputs a relatively close ideal sine wave as opposed to a VCXO. A VCXO is at the other side (DUT). To permit a definite comparison in frequency, with small changes to the control voltage of the VCXO, the frequency on the OCXO and VCXO should be very close. The output of the mixer calculates the small phase deviation between the two signals maintaining,

RALTRON ELECTRONICS CORP. ▪ 10651 N.W. 19th St ▪ Miami, Florida 33172 ▪ U.S.A.
phone: +001(305) 593-6033 ▪ fax: +001(305)594-3973 ▪ e-mail: sales@raltron.com ▪ internet: http://www.raltron.com

roughly, a 90° phase shift between the oscillator. $\varphi(t)$ is the measurement of the signal coming off the mixer after going through an amplifier and a low pass filter. Using a high resolution spectrum analyzer, the spectral density of $\varphi(t)$
is displayed in the frequency domain as $S_\varphi(f)$.

To plot the phase noise, the formula listed below is used

$S_\varphi(f) = 2L(f)$ *for* $\varphi \ll 1$ *radian*

To plot the dBc/Hz, the base 10 logarithm output from this equation is calculated.

For various communication applications, the phase noise is specified at the frequencies below for only the noise at these frequencies, away from, the carrier is of concern.

Hertz from Carrier	L(f) in dBc/Hz
10	-40
100	-70
1000	-100
10000	-120

This specification is graphed on Figure 12.

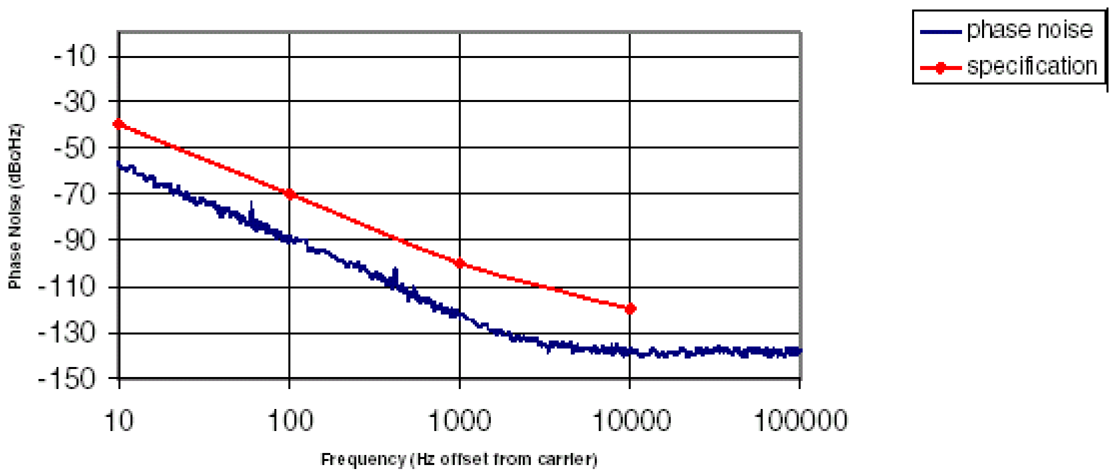

Figure 12 – Phase Noise

RALTRON ELECTRONICS CORP. ▪ 10651 N.W. 19th St ▪ Miami, Florida 33172 ▪ U.S.A.
phone: +001(305) 593-6033 ▪ fax: +001(305)594-3973 ▪ e-mail: sales@raltron.com ▪ internet: http://www.raltron.com

Noise floor should be monitored closely for random jitter in phase-locked loops (PLL), VCO's, crystal oscillators, and other clock signals. Analyzing the phase noise is very useful during the design stage or for troubleshooting when inspecting the noise floor. For this type of analysis, a frequency-domain phase measurement system is crucial. Techniques other than spectral evaluation do not offer a detailed insight into the design and system characteristics. A limitation of low level examination is to analyze jitter components under 200 MHz, way below the total bandwidth stipulated by several standards. Therefore, for bandwidth above 200 MHz other tools for analyzing jitter are needed.

A simple tool to convert Single Side Band (SSB) phase noise to jitter could be find at Raltron's web site: http://www.raltron.com/cust/tools/osc.asp

Phase Jitter – Phase Noise Integration

The overall noise power for a specified frequency range is more important than the shape of the curve (as shown in Figure 12) especially in communications applications. To accomplish this the time-domain signal must be examined in the frequency domain. Afterwards, it is reassembled in the time-domain into a root-mean-square (rms) value excluding unwanted frequencies. The rms value for $\varphi(t)$, expressed in dB, radians, unit intervals or seconds, is obtain by changing L(f) back to $S_\varphi(f)$ across the specified bandwidth. The portion of noise for the bandwidth in question is one standard deviation of phase jitter which is equivalent to the value in seconds. This is represented by the area under the curve from 500 Hz to 10 KHz in Figure 13.

The limits of integration are:
Minimum frequency = 500 Hz
Maximum frequency = 10 KHz
Total area under the integral = 2.63264E-09
φ_{rms} (radians) = 5.13093E-05
t_{rms} (s) = 5.25085E-14

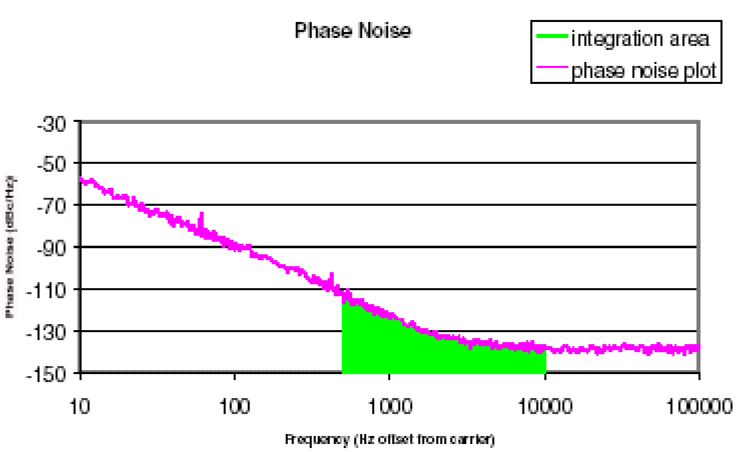

Figure 13 – Phase Noise Integration – Bandwidth 500 to 10KHz

RALTRON ELECTRONICS CORP. ▪ 10651 N.W. 19th St ▪ Miami, Florida 33172 ▪ U.S.A.
phone: +001(305) 593-6033 ▪ fax: +001(305)594-3973 ▪ e-mail: sales@raltron.com ▪ internet: http://www.raltron.com

Notice the considerable impact of the bandwidth on φ_{rms}. If the bandwidth is expanded from 10 Hz to10K Hz, as shown in Figure 14, t_{rms} is about 80 times larger.

The limits of integration are:
Minimum frequency = 10 Hz
Maximum frequency = 10 KHz
Total area under the integral = 1.70512E-05
φ_{rms} (radians) = 0.004129311
t_{rms} (s) = 4.22583E-12

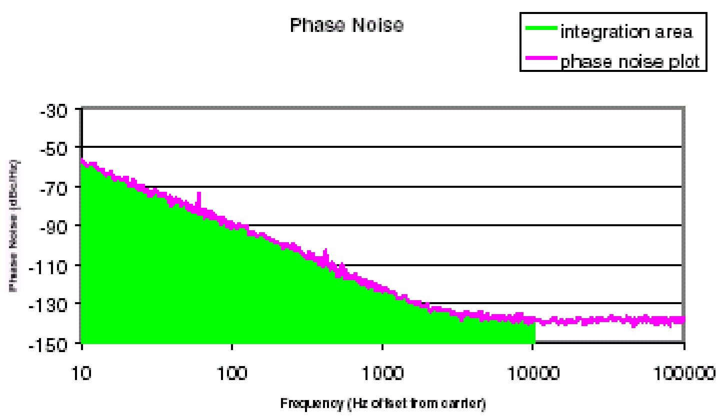

Figure 14 – Same graph as Figure 13 – Bandwidth changed to 10 to 10KHz

Converting Phase Noise to Jitter

Noise measurement can be used to extract jitter since both represent the same abnormality. At the following example the oscillator noise plot, Figure H, spreads from 12 KHz to 10 MHz. The power spectral density function in dBc is the sideband noise propagation given by the *L(f)* plot. As the associated levels of phase noise (modulation) are reflected by jitter, the power level of the carrier is of no importance. The result of the integration *L*(f) across the specified bandwidth, 12 KHz to 10 MHz, is the overall noise power of the sidebands.

RALTRON ELECTRONICS CORP. ▪ 10651 N.W. 19th St ▪ Miami, Florida 33172 ▪ U.S.A.
phone: +001(305) 593-6033 ▪ fax: +001(305)594-3973 ▪ e-mail: sales@raltron.com ▪ internet: http://www.raltron.com

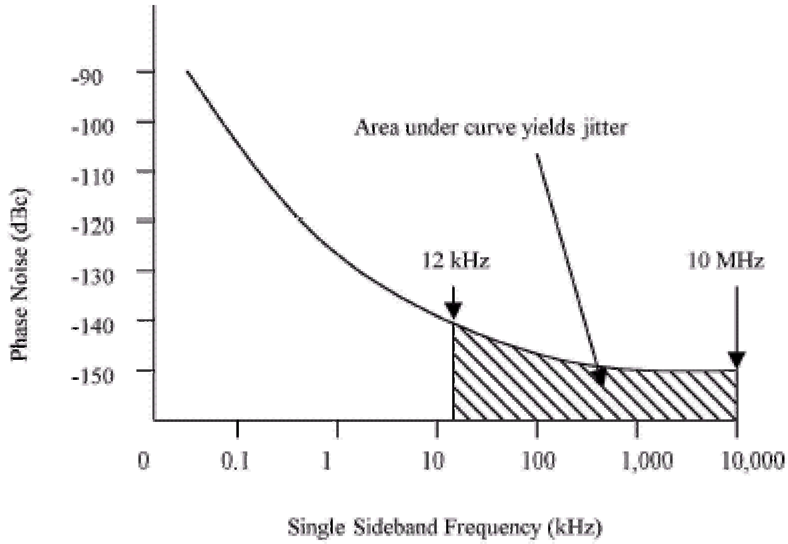

Figure 15 – Phase Noise plot

The RMS jitter can be derived by calculating the power level of the phase modulation in this band. Following is the integral of L(f) using 12 KHz and 10 MHz as the limits.

$$N = \text{Noise Power} = \int_{12KHz}^{10MHz} L(f)\, df$$

The RMS jitter caused by the noise power can be calculated using the following equation:

RMS Phase Jitter (radians) = $SQR(10^{N/10} * 2)$

The result can be denoted in unit interval (UI) or in time. Dividing the outcome of the above equation by the frequency of the carrier in radians returns a value in time (seconds).

RMSJitter (sec *s*) = Jitter(radians)/(2*π*fosc)

As an example, the RMS jitter value for a 312.5-MHz oscillator can be calculated using the noise power values plotted in Figure 15. Integrating the phase noise curve for the 12 kHz-to-20MHz interval yields a figure of -63 dBc:

$$N = Noise\ Power = \int_{12KHz}^{20MHz} L(f)\ df = -63dBc$$

The RMS phase jitter value in radians is therefore:

RMS Phase Jitter (radians) = SQR($10^{N/10}$**2)=*1415^{e-6} *Radians*

This jitter value in radians can be converted to RMS jitter in picoseconds:

RMSJitter = $1415^{e-6}/(2*\pi*10^{6})$= 0.72 ps (rms)

BY: Ronen Cohen
Raltron Electronics Corp.
Jan 15, 2005