WAVECREST Corporation

JITTER TOLERANCE AND PERIODIC MEASUREMENT METHODOLOGIES AND CORRELATION STUDY

APPLICATION NOTE NO. 139

200139-00 REV A

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U.S. Patent Nos. 4,908,784 and 6,185,509, 6,194,925, 6,298,315 B1, 6,356,850 and 6,393,088; other United States and foreign patents pending.

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Jitter Tolerance and Periodic Jitter Measurements

Application Note 139

Introduction

When characterizing parts for jitter, it is common to measure jitter output of a transmitter and jitter tolerance of a receiver. When measuring jitter tolerance it is required to add various quantities of ISI, PJ and RJ to insure the receiver can tolerate data signals with significant jitter and still have a low BER. This Document focuses on methods for measuring PJ components using different types of measurement instruments including a Spectrum Analyzer, Sampling Oscilloscope, and a Time Interval Analyzer (*WAVECREST* SIA-3000). The results will be compared against the theoretically expected values over a wide PJ frequency and amplitude range.

Overview of Jitter Components [1]

Jitter is a period / frequency displacement of a signal from its ideal location. These displacements can occur in amplitude, phase or pulse width and are generally categorized as either deterministic or random in nature. Total jitter is the convolution of Deterministic Jitter (DJ) Probability Density Function (PDF) and Random Jitter (RJ) PDF[1] components. Deterministic Jitter is composed of Duty Cycle Distortion (DCD), Inter-Symbol Interference (ISI), and Periodic Jitter (PJ). DCD is caused when a data signal has a static duty-cycle error and/or this error varies with time. For example, DCD is caused by errors in the trigger threshold of a circuit and by coupling capacitors in the presence of low frequency content in the data signal. ISI is typically caused by a data path propagation delay that is a function of the past history of the data. DCD and ISI are also known as Data Dependent Jitter (DDJ). Periodic Jitter (PJ), the focus of this application note, is caused by one or more sine waves and their harmonics. It is typically the result of signal cross talk. Like all physical phenomena, some level of randomness-to-edge deviation occurs in all electronic signals. Random Jitter (RJ) is probabilistic in nature and is best modeled by a Gaussian function. Random Jitter is unbounded and therefore directly affects long-term reliability.

Measurement Techniques

Periodic Jitter (PJ) can be measured with a variety of different instruments. There are different techniques and equations for obtaining the PJ amplitudes from different instruments. The method for obtaining PJ amplitudes for a sampling oscilloscope, spectrum analyzer, and an SIA-3000 are described in the following sections.

Setup

The setup is shown in Figure 1. A square-wave signal generator is used as the clock source (1.5GHz) into the pattern generator. This generator has an internal maximum modulation of 1MHz so a second sign-wave signal generator is fed into the FM input on the square-wave signal generator and is used as an external modulation for frequencies above 1MHz. The square-wave signal generator also has a 3dB external FM frequency of 10MHz for its FM input. Frequencies at or near 10MHz won't correlate to the equations described in the section titled Spectrum Analyzers as they are attenuated

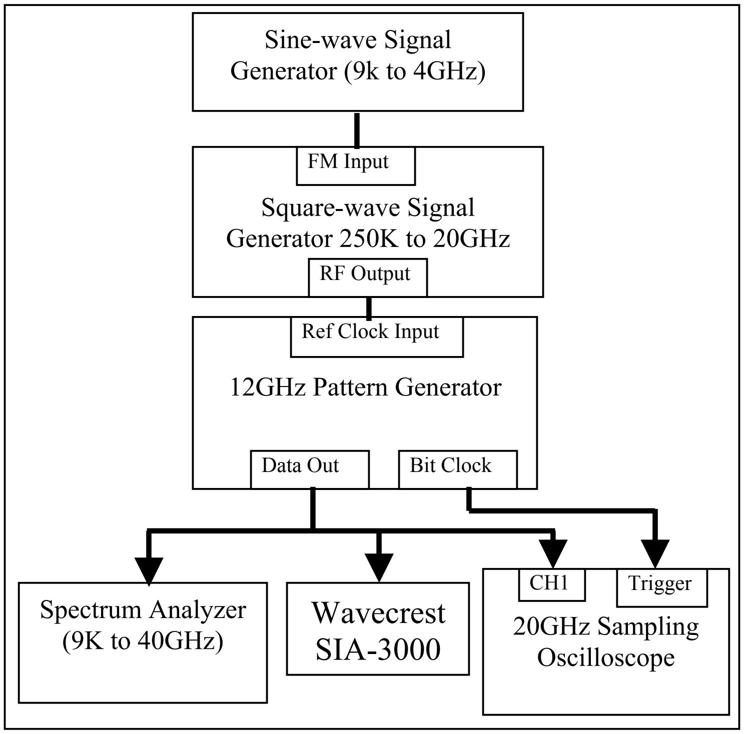
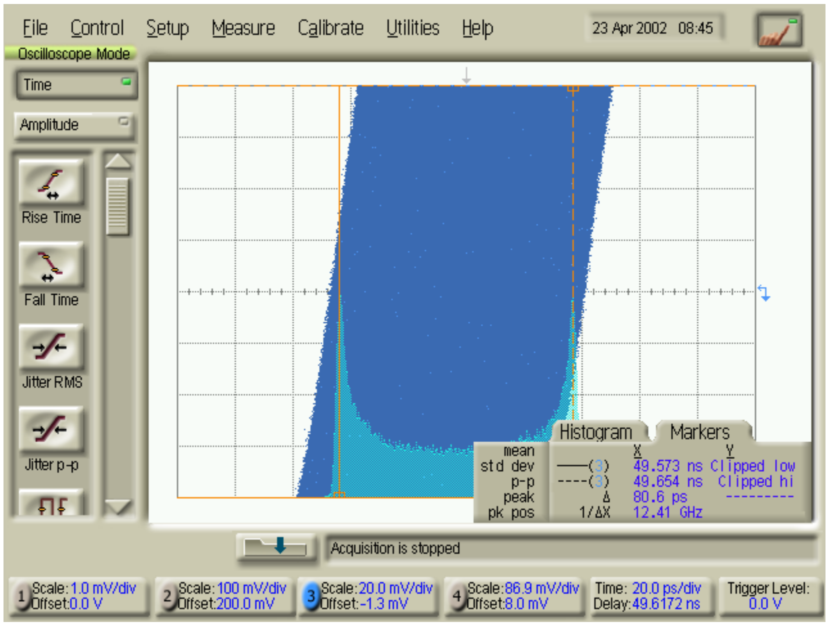


Figure 1 - Measurement Setup.

approximately 3dB. For frequencies above 10MHz, the sine-wave generator is power summed with the pattern generator output. However, in this case the equations in the Spectrum Analyzers section cannot be used, so the Sampling Oscilloscope PJ amplitudes are correlated to the SIA-3000 measurements.

Sampling Oscilloscope

Using the following method you can use a sampling oscilloscope to approximate PJ amplitudes. The setup is shown in figure 1. The bit clock from the BERT is used as the trigger on the sampling scope. The modulated data or clock signal is sent into the measurement channel. This will produce an Eye Diagram or in the case where the data is a clock, then you are able to view the modulated clock signal (Figure 2).



mean
std dev
p-p
peak
pk pos

	X	Y
——(3)	49.573 ns	Clipped low
----(3)	49.654 ns	Clipped hi
Δ	80.6 ps	---------
1/ΔX	12.41 GHz	

Acquisition is stopped

1 Scale: 1.0 mV/div Offset: 0.0 V
2 Scale: 100 mV/div Offset: 200.0 mV
3 Scale: 20.0 mV/div Offset: -1.3 mV
4 Scale: 86.9 mV/div Offset: 8.0 mV
Time: 20.0 ps/div Delay: 49.6172 ns
Trigger Level: 0.0 V

Figure 2 - Using a Sampling Oscilloscope's markers to estimate PJ Amplitude. The pk-pk PJ is 40.3ps.

To determine which span represents the largest pk-pk deviation, you must first determine which one corresponds to the worst-case modulation transition. Figure 3 shows the effect of a sinusoidal Phase Modulation (PM) on a clock or data signal. During the PM sine wave positive time, the modulation is lengthening the Resulting Jittered Clock periods. The accumulative affect of several longer than ideal periods is greatest at ½ of the modulation cycle. After this point, the negative side of the PM sine wave will be shortening the resulting clock periods and thus you will be moving closer to ideal. Notice that after one cycle of the modulation, the positive deviations equal the negative deviations, and you are now back to your ideal clock bit position. From this example, it becomes obvious that it is important to randomly acquiring data to insure that the instruments trigger is not synchronous with the jitter.

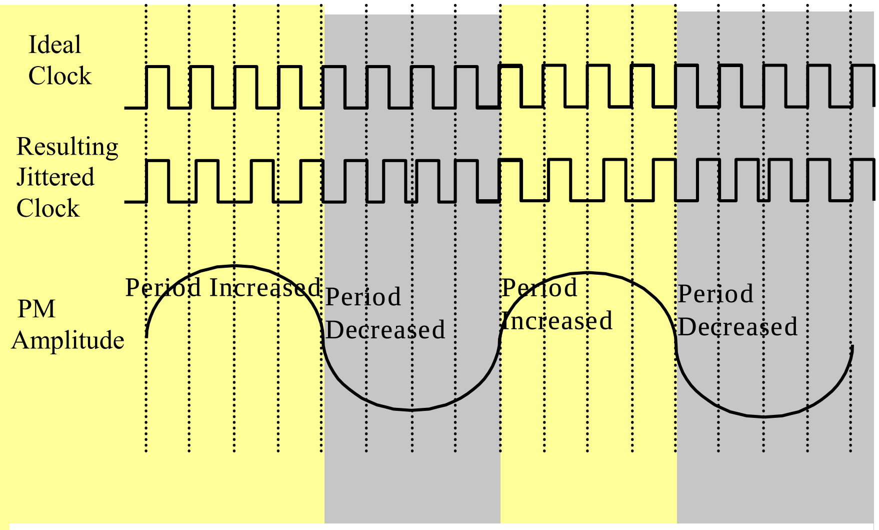


Figure 3 - Effect of a Periodic Sinusoidal Phase Modulation (PM) on a Clock.

To calculate the delay that corresponds to the maximum PJ on the sampling oscilloscope, determine the time interval that corresponds to on half the period of the modulation frequency (1/Fj*0.5). Remember that sampling oscilloscopes typically have a trigger delay of about 20ns. If the value is less than 20ns, you have to use odd multiples of this value to see the next point where you are half way through the modulation. For example, if Fj is 150MHz, then 1/Fj*0.5 is 3.333ns. This is less than

20ns. So we must look for the next repeat of the modulation. If we add one cycle or multiply this value times 3, we get 10ns. Multiplying by 7 gives a delay of 23.33ns. The data or clock transition closest to this delay will give you the best approximation of the maximum PJ accumulated amplitude. In this experiment, only clock edges where used to eliminate the effect of DCD+ISI from data patterns and get a better PJ estimate.

Once an edge with the largest accumulated PJ amplitude has been determined, measure the peak-to-peak (pk-pk) time deviation of the 50% voltage threshold with a 5-10mV range. Make sure that the left and right window borders are wide enough to contain the entire edge. Allow the histogram to accumulate enough points so you can see a good picture of the histogram. The histogram will have a “saddle” shape (as shown in Figure 2) corresponding to the probability density function (PDF) of a sine wave. If the modulation is a sine wave, the distance between the peaks is the magnitude of the modulation in both positive and negative deviation. Using the markers, you can estimate the PJ amplitude by placing the markers on the peaks of the saddle and dividing the delta by 2 (See Figure 2). NOTE: This is only valid when there is only one sine wave PJ modulation affecting the signal under test. When there are multiple PJ components, you will get some combination of these PJ amplitudes depending on their frequency ratios and individual amplitudes.

Spectrum Analyzers

Spectrum Analyzers can be used to measure PJ on Clock signals only. Also, the PJ amplitude must meet with the following requirement [2].

$$\beta = \frac{\Delta f}{f_j} << 0.5 \tag{1.1}$$

Where β is the ratio of peak deviation to modulation frequency, $\Delta\ f$ is the peak deviation of the modulation (sometimes called FM), f_j is the frequency or rate of the modulation. This is the case where the modulation is Narrow Band FM (NBFM). If β is greater than 0.5, a complicated solution using Bessel functions of the first kind are required. This is beyond the scope of this paper. For further information, see “Information Transmission, Modulation and Noise,” Fourth Edition, by Mischa Schartz [2].

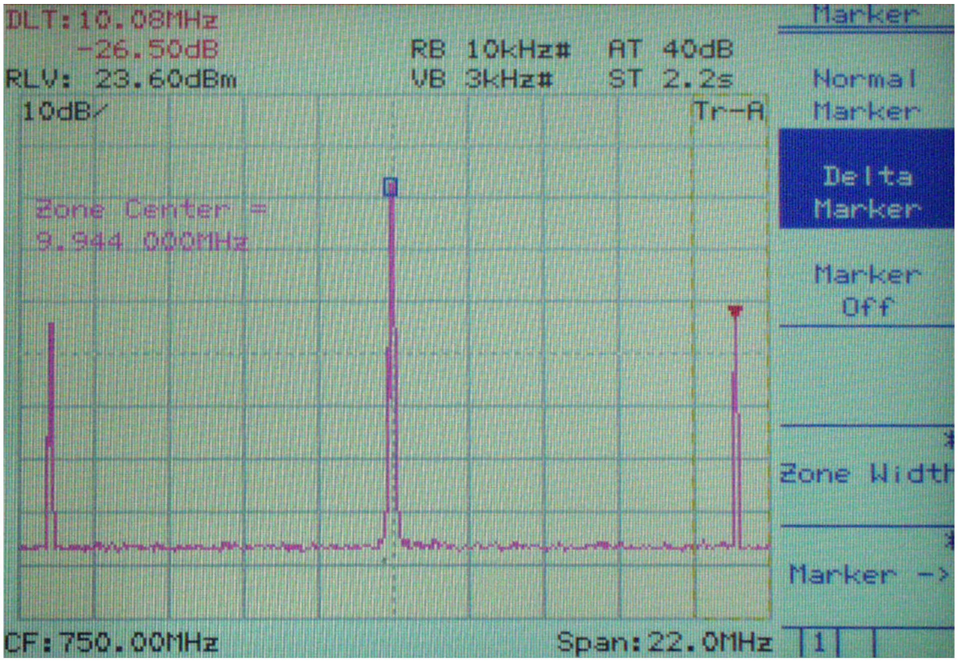
Equation 1.2 is used to determine RMS Phase Noise of a NBFM sideband.

$$\beta = 2 * \left[10^{\frac{Assb}{20}} \right] \tag{1.2}$$

Where Assb is the amplitude of the upper side band relative to the carrier in dB. Then, the peak cumulative jitter (J_{pk}) in seconds (s) is given by the following equation.

$$J_{pk} = \frac{\beta}{2 * \pi * f_o} \tag{1.3}$$

The peak-to-peak jitter ($J_{pk\text{-}pk}$) is given by equation 1.4.



DLT:10.08MHz
-26.50dB
RLV: 23.60dBm
RB 10kHz# AT 40dB
VB 3kHz# ST 2.2s
Zone Center =
9.944 000MHz
CF:750.00MHz
Span:22.0MHz

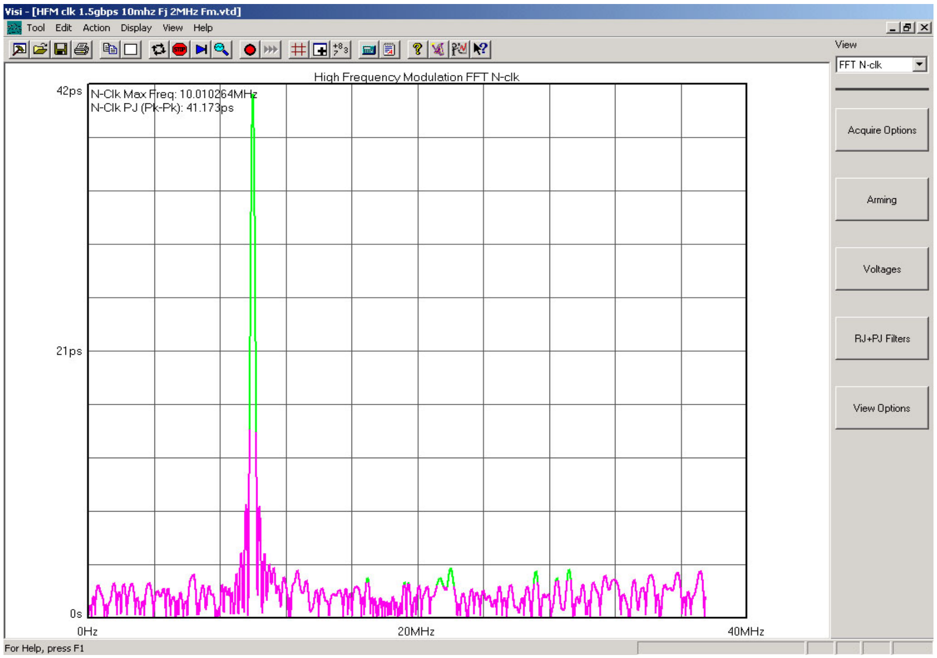
Figure 4 - Sideband Amplitude measurement on a Spectrum Analyzer. The setup is a 1.5Gb/s 1010 data (750MHz clock) with a 10MHz PJ. The SSB Delta is –26.50dB.

$$J_{pk-pk} = J_{pk} * 2 \qquad (1.4)$$

$J_{pk\text{-}pk}$ is the amplitude of a single sine wave modulation in seconds. Figure 4 shows a screen image of this measurement on a Spectrum Analyzer (SpecAn).

SIA-3000

The *WAVECREST* SIA-3000 can directly measure PJ amplitude and frequency on both clock and data signals. For clock signals you just send the signal into the SIA-3000 and measure it with either the Low Frequency Modulation (LFM) tool or the High Frequency Modulation (HFM) tool. Figure 5 shows an example plot. For data signals, you send the data into a measurement channel and a pattern marker into another channel and use the Known Pattern With Marker (KPWM) tool. If a pattern marker isn't available, *WAVECREST* supplies an internally



Visi - [HFM clk 1.5gbps 10mhz Fj 2MHz Fm.vtd]

View: FFT N-clk

N-Clk Max Freq: 10.010264MHz
N-Clk PJ (Pk-Pk): 41.173ps

For Help, press F1

Figure 5 - *WAVECREST* SIA-3000 **HFM tool showing a 41.173ps PJ at 10MHz.**

generated marker. Figure 6 shows how the *WAVECREST* tools measure PJ. A histogram of 1 period measurement is made (Top 2 Plots). The 1-sigma or standard deviation of this histogram is then plotted (Lower Left Plot). Then the process is repeated for 2 periods, 3 periods, etc. A patented AutoCorrelation routine is run on the resulting 1-sigma plot and then an FFT is done to convert to the frequency domain. The resulting FFT (Lower Right Plot) shows all of the PJ amplitudes and frequencies present on the signal being measured. All of these measurements are done randomly (eliminating any possible synchronization to the PJ frequency) with a hardware resolution of 200 femtoseconds (1 femtosecond is 10^{-15} seconds). See the Wavecrest SIA-3000 Specification for more information. [3]

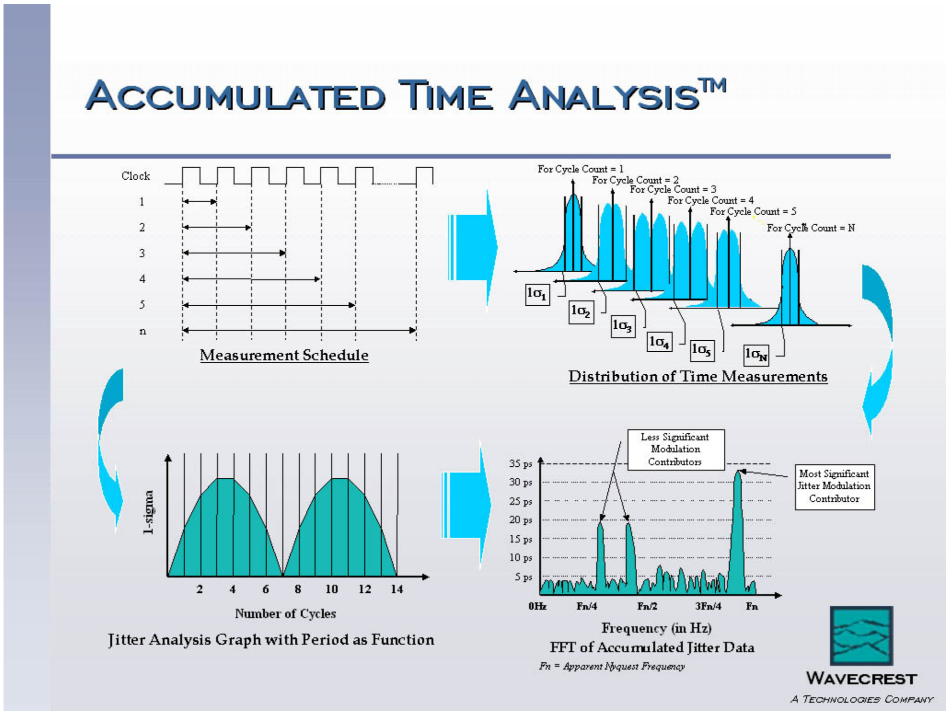


Figure 6 - Wavecrest SIA-3000 PJ measurement technique.

Theoretical Expected Value for Experimental Setup

When using a signal generator as shown in Figure 1, equation 1.5 can be used to convert the Δf or FM amplitude into Unit Intervals (UI) of jitter [2].

$$UI_{jitter}(peak - peak) = \frac{\Delta f}{f_j * \pi} \tag{1.5}$$

Since 1 UI=1/BitRate, the jitter in seconds is given by the following equation.

$$J_{pk-pk} = \frac{\Delta f}{BitRate * f_j * \pi} \tag{1.6}$$

This value can then be used for correlation to the PJ peak-to-peak values acquired by the other measurements techniques.

Measurement Results

Table 1 shows the results of the correlation to the expected mathematically derived values from the sine-wave generators settings. A 1010 data pattern was used for all measurements except for the SIA 3000 Known Pattern With Marker (KPWM) data mode. For this case, a PRBS 2^7-1 data pattern was used. Since the data is 1010 for the other setup, the Wavecrest SIA-3000 CLK High Frequency Modulation tool (HFM) is also used. These results are for the range of PJ frequencies from 30kHz up to 10MHz (3db point of the square-wave generator). The amplitudes used were the highest amplitude that the Sampling Scope could generate. Also, several low amplitude PJ modulations are included.

PJ Setup			*WAVECREST* SIA-3000					PJ Correlation Error %				
f_j	Δf	Theoretical Calculation	KPWM CLK like data	KPWM 2^7-1 data	CLK HFM	Spec. Analyzer	Sampling Scope	KPWM CLK Error	KPWM Data Error	CLK Error	Spec. An. Error	Scope Error
30kHz	2MHz	1.41E-08	1.42E-08	1.42E-08	1.42E-08	WBFM	Freq Low	0.45%	0.35%	0.14%	NA	NA
30kHz	100Hz	7.07E-13	Too Small	Too Small	7.05E-13	6.987E-13	Freq Low	NA	NA	0.33%	1.33%	NA
100kHz	2MHz	4.24E-09	4.31E-09	4.22E-09	4.22E-09	WBFM	Freq Low	1.55%	0.47%	0.49%	NA	NA
100kHz	50kHz	1.06E-10	1.06E-10	1.08E-10	1.06E-10	1.056E-10	Freq Low	0.53%	1.44%	0.45%	0.56%	NA
1MHz	2MHz	4.24E-10	4.24E-10	4.26E-10	4.20E-10	WBFM	Freq Low	0.02%	0.48%	1.08%	NA	NA
10MHz	2MHz	4.24E-11	4.10E-11	4.14E-11	4.12E-11	4.016E-11	4.03E-11	3.40%	2.52%	2.99%	5.48%	5.05%
10MHz	100kHz	2.12E-12	2.11E-12	2.11E-12	2.12E-12	1.933E-12	2.02E-12	0.47%	0.66%	0.19%	9.00%	4.81%

Table 1: Correlation results and percent error from expected value.

The results show very good correlation between all measurements. Note that for the last two 10MHz cases, all of the instruments measured a lower value than calculated. This is due to the 3dB attenuation of the FM input to the square-wave signal generator. Figure 7 shows a plot of these correlation error values.

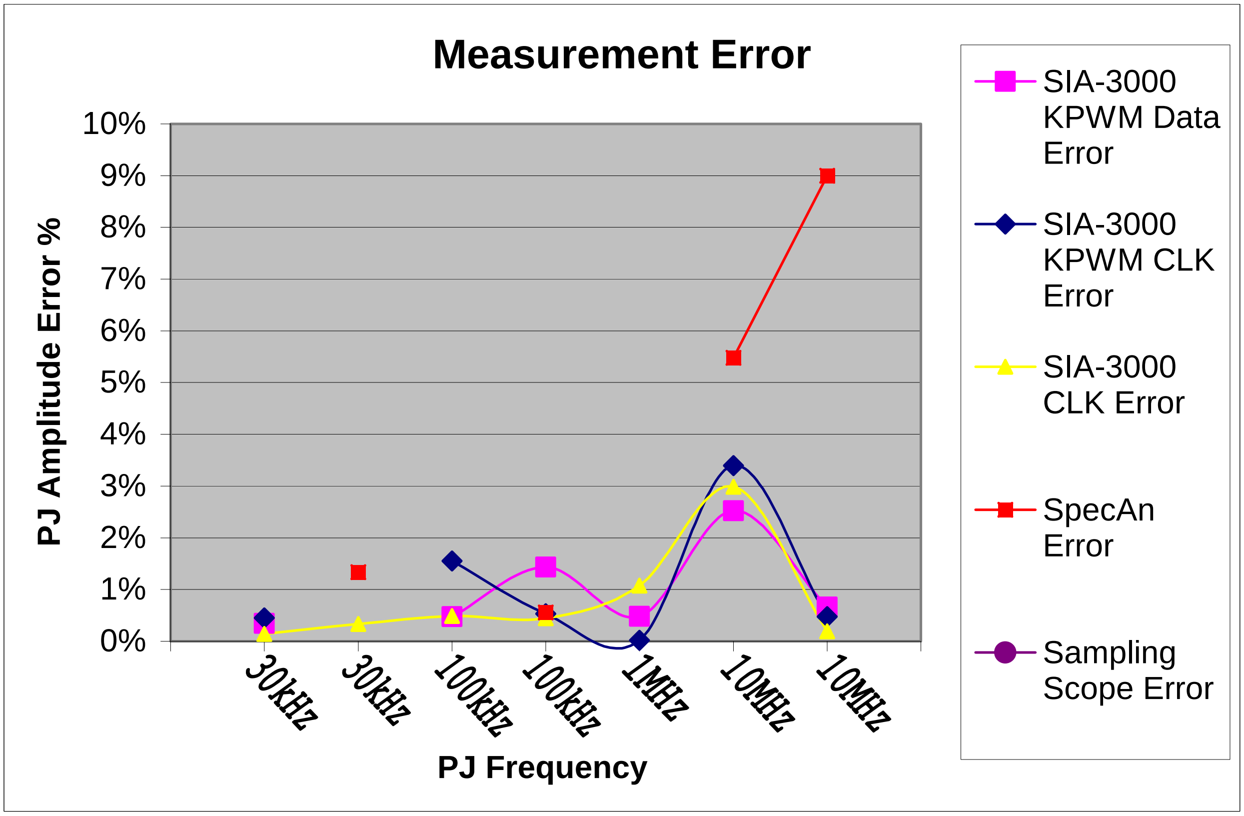


Figure 7 - Correlation error between measurements with respect to the expected values for different instruments.

Table 2 shows the correlation between the Sampling Oscilloscope and the SIA-3000 for high frequency PJ. The –3dB point of the square-wave signal generator is 10MHz so the PJ is power summed directly into the data stream. Since there are no correlated settings that can be used to measure against, the measurements of the Sampling Oscilloscope are compared to the *WAVECREST* SIA-3000 tools. Figure 8 shows a plot of these results.

	Wavecrest SIA-3000		
PJ Frequency fj (Hz)	KPWM CLK like data (s)	Clk HFM (s)	Sampling Scope (s)
1.000E+07	1.473E-10	1.530E-10	1.535E-10
1.000E+08	4.907E-10	4.918E-10	4.930E-10
1.500E+08	1.661E-10	1.660E-10	1.606E-10
2.000E+08	2.026E-10	2.095E-10	1.993E-10
7.000E+08	2.063E-10	2.066E-10	1.900E-10

Table 2: High Frequency PJ measurements.

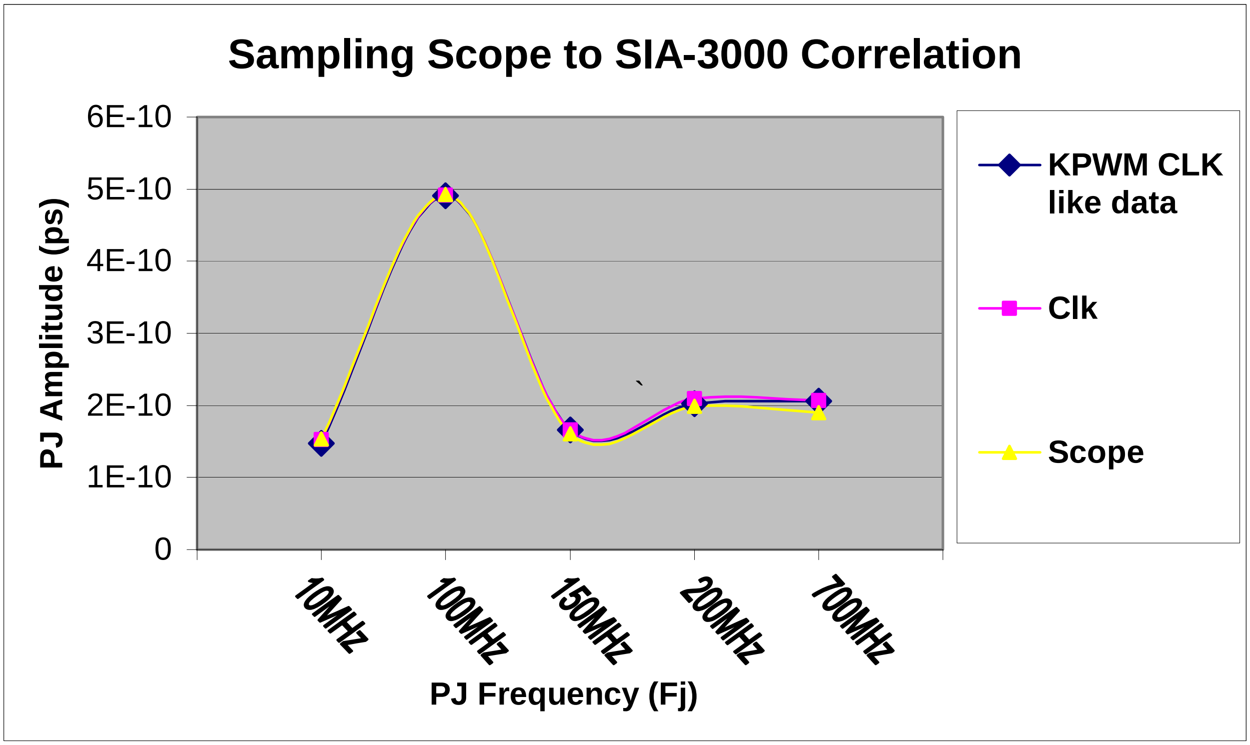


Figure 8 - Correlation of high frequency PJ values.

Each instrument is capable of providing accurate measurements for specific PJ amplitude and frequency ranges. Figure 9 shows this graphically. Repetitive Sampling Oscilloscopes can't measure PJ with amplitude ≥ about 0.8 UI because the eye will be closed and you won't be able to differentiate between adjacent edge transitions. Sampling Oscilloscopes cannot measure low frequency PJ (< 100 to 200KHz) due to their time base drift. Typically, the lowest frequency PJ that can be measured is about 200kHz for very high amplitude PJ. Also, it cannot measure any PJ components with amplitude lower than its wideband noise floor. This is about 1ps for most scopes and about 200fs for the low jitter time base options. It is not possible to obtain the frequency (f_j) of the modulation and very difficult to measure PJ without knowing the PJ frequency as described in section I. For Spectrum Analyzers, the narrow band FM model is only valid when $\beta << 0.5$. This equates to PJ's with amplitudes less than about 0.5UI. The minimum detectable amplitude needs to be above the instruments noise floor, which is about 100fs for the Spectrum Analyzer used in this experiment. Also, the Spectrum Analyzer is unable to measure PJ below its low-end bandwidth, which is 7 kHz for this instrument.

The SIA-3000 is the only instrument that is capable of measuring PJ amplitude (in ps) and frequency PJ (in Hz) over a wide frequency and amplitude range. It can also measure amplitudes down to less than 10 attoseconds (1 attosecond is 10^{-18} seconds) of single cycle jitter for lower frequency jitter components[4] and less than 75 femtoseconds of cumulative amplitude. The only limit to the maximum PJ amplitude that the SIA-3000 can measure is the theoretical adjacent cycle maximum deviation. For example, a 750MHz clock has a period of 1.333ns. A modulation at one half this frequency or 375MHz cannot have an amplitude greater than 1.333ns or it would have to generate a period of 2.666ns and one of zero seconds (Grey dashed area in Figure 9, "Theoretical/Hardware Limit"). In addition, the SIA-3000 has a minimum pulse width of 166.67ps.

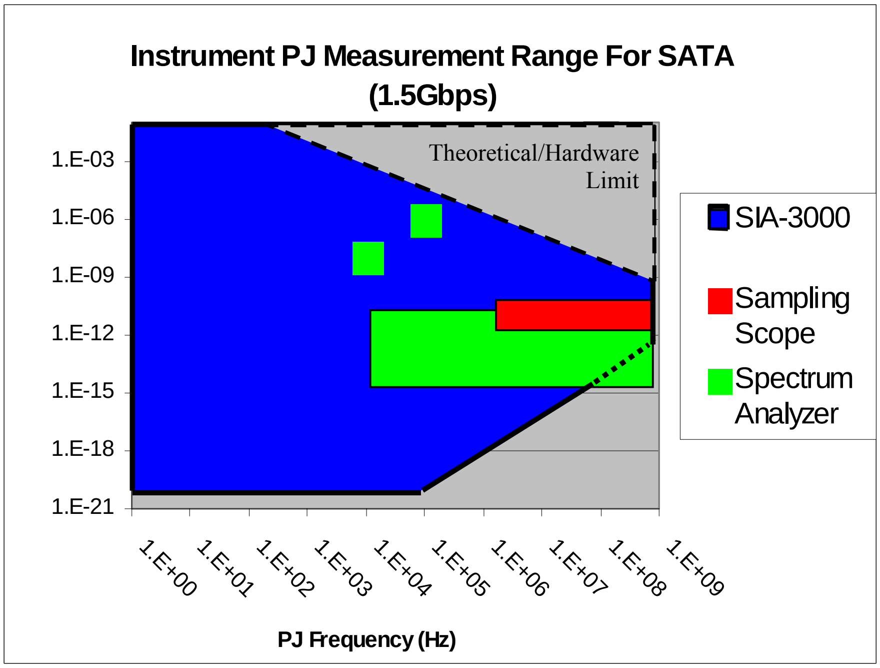


Figure 9 - PJ measurement regions for different instruments.

Conclusion

This paper has described a variety of techniques for measuring PJ and has compared the results with expected values. The measurement data was shown to validate the correlation of the various techniques to the expected values. The Sampling Oscilloscope is useful over a narrow PJ frequency (about 250kHz and up) and amplitude (about 1ps to 0.8 UI) band but can only be used when there is a single PJ component and its frequency is known. The spectrum analyzer covers a wider range of frequencies (7 kHz and up) but is limited to amplitudes less than 0.5 UI and can't measure PJ on differential signals or on data. The SIA-3000 can measure PJ amplitudes (in ps) for differential data and clock signals without any prior knowledge of the setup. In addition, the SIA-3000 can measure and display the frequency and amplitude of single or multiple PJ modulations over a very wide frequency and amplitude range thereby providing a very useful instrument for measuring jitter generation and jitter tolerance.

Footnotes:

[1] National committee for information technology standardization (NCITS), "Fibre Channel Methodologies for Jitter Specification-2", Rev 0.0, April 11, 2000.

[2] Mischa Schartz, "Information Transmission, Modulation, and Noise," Fourth Edition, May 1990.

[3] *WAVECREST* SIA-3000 Specification, 2002.

[4] Craig Emmerich, Application Note 137, "Measuring Low Frequency Attosecond jitter with the *WAVECREST* SIA-3000," May 2002.

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