WAVECREST Corporation

Phase Noise Measurement Using the *WAVECREST* Digital Timing System

Application Note No. 130

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Introduction

This application note will describe a method of using the Time Digitizer function in *WAVCREST*'s *Virtual Instruments*™ software along with *WAVECREST*'s Digital Time System (DTS) to measure the time jitter and calculate the phase noise spectrum. This method allows the DTS Time Digitizer to report both time jitter and phase noise simultaneously.

The sensitivity and spectral resolution of such a method will be discussed in as well as the phase noise measurement correlation between a DTS (using the Time Digitizer) and an RF Spectrum Analyzer.

The conclusion will state that, under certain conditions, the DTS Time Digitizer can accurately measure the two most important quantities on a high-speed signal: time jitter and phase noise.

Phase Noise Theory

Phase noise can be best illustrated by a sine wave of the form:

$$V(t) = V_0 \sin(2\pi f_0 t + \varphi_0(t)) \qquad (1),$$

where V(t) is the amplitude at a given time t, V_0 is the maximum amplitude, f_0 is the frequency of the carrier, and $\varphi_0(t)$ is the phase. If $\varphi_0(t)$ is random in nature, the waveform of V(t) will be shifting back and forth along the time axis, and this will create a time jitter. In this sense, the phase noise and timing jitter are related. It is important, therefore, to test for phase noise both in frequency and phase fluctuations of a given device. Phase noise is often used in specifications for a PLL clock chip.

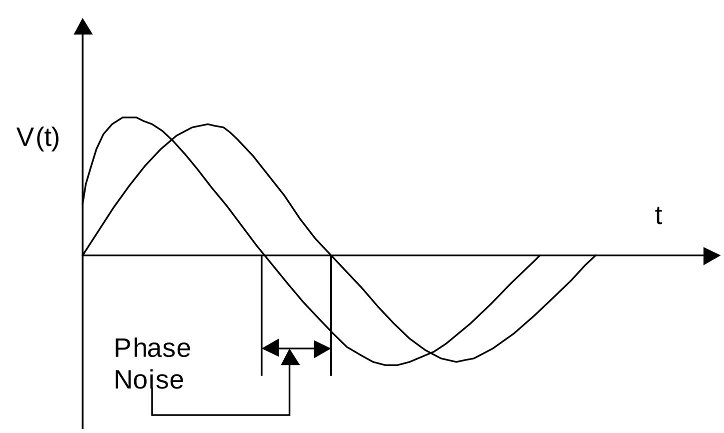

Figure 1. Illustration of phase noise.

In the frequency-domain, phase noise appears as sidebands offset from the carrier frequency. Figure 2 shows the phase noise in frequency-domain.

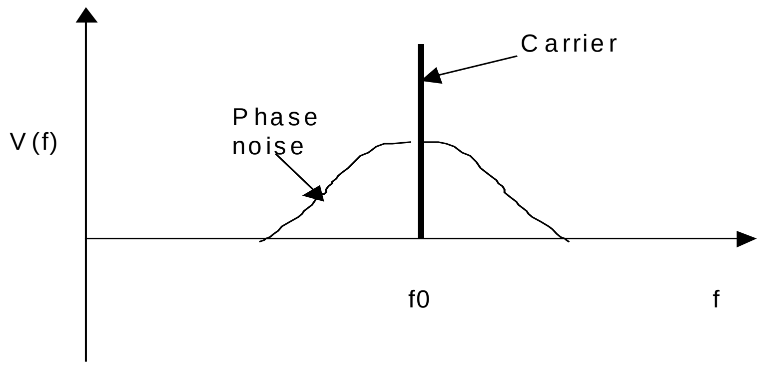

Figure 2. Spectrum of a sine wave with phase noise.

The phase noise frequency is normally specified at a particular frequency from the carrier, i.e., $f_m = f - f_0$, where f is the frequency referenced to zero. Phase noise magnitude is normally specified relative to the power of the carrier on a per Hz basis. The exact equation for calculating phase noise in dBc/Hz (dBc means power in decibel below the carrier) is given by the following equation:

$$L(f_m) = 10\log_{10}((P_n(f_m)/P_0)/B_n) \qquad (2),$$

where $P_n(f_m)$ is the noise power (in watts) at the offset frequency f_m, P_0 is the power of the carrier ($f_m = 0$), and B_n (in Hertz) is the noise bandwidth.

Sometimes, phase noise is also expressed in rad^2/Hz. This is equation (2) without $10\log_{10}$ (or decibel).

Phase Noise Measurements

Phase noise may be measured either with a frequency-domain based sweeping spectrum analyzer or a time-domain based single-shot instrument, such as the *WAVECREST* DTS system. The following is a basic introduction of each instrument, including its strengths and weaknesses, for making phase noise measurements.

Phase Noise Measurement Using A Sweeping Spectrum Analyzer

With a spectrum analyzer, the input is fed to an adjustable filter, composed of a mixer and an IF (intermediate frequency) filter, that extracts the incoming signal at a particular frequency.

The detector then measures the amplitude of the signal at that frequency and sends the value to the display. This process sweeps over the input signal bandwidth, a resolution bandwidth defined by the user, to give a complete frequency spectrum of the input signal.

A basic instrument block diagram for the spectrum analyzer is show in Figure 3.

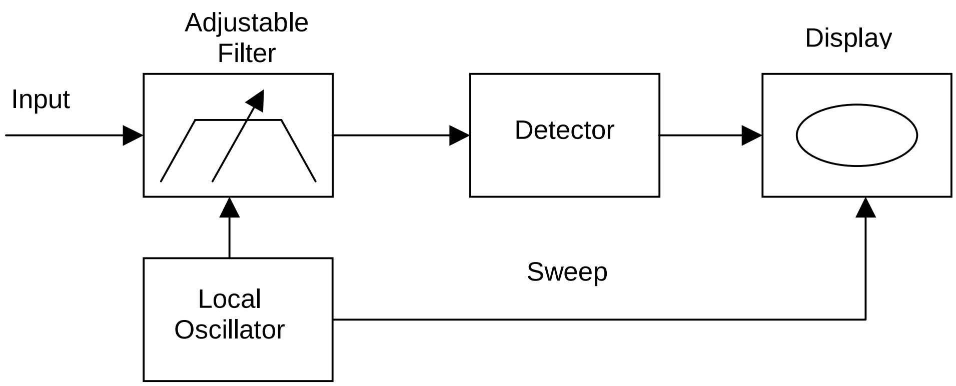

Figure 3. Sweeping Spectrum Analyzer.

In order to measure the noise at a certain level, the instrumental noise level must be smaller than the noise level of the input signal. The noise floor of a Spectrum Analyzer depends on the resolution bandwidth. The smaller the resolution bandwidth, the lower the analyzer noise floor, and vice versa. However, reducing the resolution bandwidth results in longer sweeping time. Errors in amplitude and frequency can occur if the sweeping process is too fast, since the IF filter will not have enough time to respond to an input signal.

A correction must be applied to equation (2) when considering the hardware design structure of a sweeping Spectrum Analyzer.

1. Since the IF filter of a spectrum analyzer is designed to be swept quickly, the shape of the filter is not very steep. This causes the 3dB bandwidth to be smaller than the actual bandwidth, by ~15-20% [1],[2]. To get a correct bandwidth, a correction factor of 1.2 must be applied to the 3dB bandwidth. (see equation (3))

2. A Spectrum Analyzer is designed to measure sinusoids, and can introduce an error when it is used to measure random noise. The amplifier after the IF filter is a logarithmic one that is optimized for spectrum line detection. The random noise measured is generally smaller than what its suppose to be. In general, a 2.5dBc/Hz correction needs to be applied to equation (2) in order to get a correct phase noise

measurement in dBc/Hz. In addition, when the noise level to be measured is close to the internal noise level of the instrument, errors can be induced. At 5dB above the instrument noise floor, a 1.65dB error can occur.

When considering statements 1) and 2), the following equation is developed and is required to convert the spectrum analyzer output to dBc/Hz..

$$L(f_m) = 10\log_{10}((P_n(f_m)/P_0)/(1.2B_n)) + 2.5 \qquad (3).$$

Phase Noise Measurements Using The DTS Time Digitizer Function

Key DTS system elements include event counters, interpolators, and a reference clock. An in-coming signal is fed to channel input. The event counter counts *n* events between start and stop signals. The time length of *n* events is measured using interpolators. Interpolators provide fine time measurement resolution. For details of DTS systems, refer to reference [3].

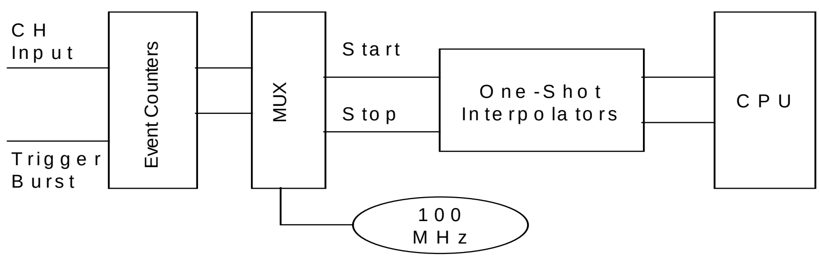

Figure 4. A schematic for DTS system architecture

Time Digitizer is a special function in *Virtual Instruments*™ (VI) software and is used as a real-time phase digitizer. It measures a burst of *n* input events and the associated time jitter. This gives one jitter measurement sample. To get a series of jitter measurement samples, this measurement is continued for a burst of samples and an FFT is applied to the time jitter series generating a jitter spectrum in the frequency-domain.

As in the case of the Spectrum Analyzer, the spectral resolution of the Time Digitizer function affects the FFT spectrum noise floor in a similar way. In other words, the smaller the spectral resolution, the lower the jitter noise floor and vice versa. For a given (fixed) maximum frequency (or Nyquist frequency in FFT spectrum), the larger the burst sample, the smaller the spectral resolution. The measurement time will, however, be longer if the spectral resolution is smaller. The Nyquist frequency is determined by the number of *n* events. The longer the *n* events measured, the longer the sampling interval, the smaller the Nyquist frequency and vice versa.

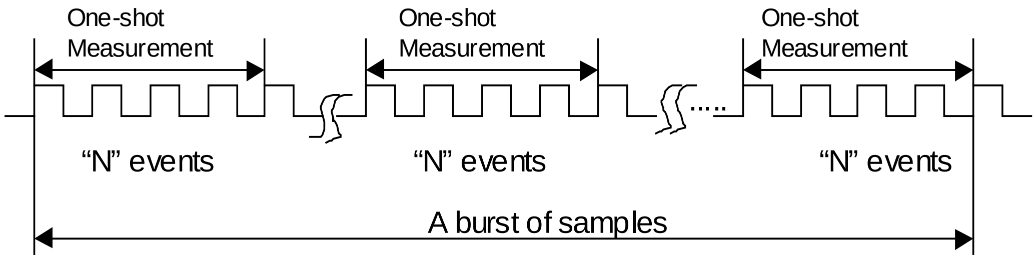

Figure 5.   A schematic of the Time Digitizer function.

A typical jitter noise spectrum measured by the DTS Time Digitizer function is displayed in Figure 6. The jitter (in ps) as a function of offset frequency f_m is shown. In addition, the user may specify an interested offset frequency to obtain phase noise in dBc/Hz at that frequency.

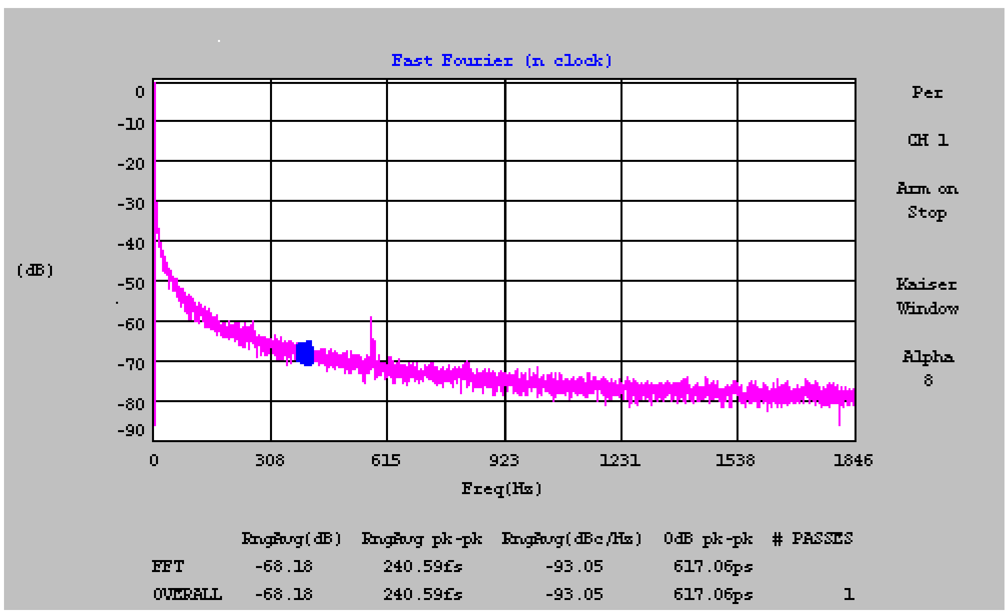

Figure 6. Time jitter spectrum as measured by the WAVECREST DTS 2075™ Time Digitizer. Phase noise at 400Hz offset frequency is shown.

Time Jitter to Phase Noise Conversion

The phase noise and time jitter can be related using the small amplitude perturbation theory. The total phase of the sine wave represented by equation (1) is:

$$\varphi = 2\pi f_0 t + \varphi_0(t) \qquad (4).$$

Taking the first-order derivative of equation (4), the following is obtained:

$$\Delta\varphi = 2\pi f_0 \Delta t + \Delta\varphi_0(t) \qquad (5).$$

Next, assume that f_0 does not change with time and that there is no frequency modulation. If the phase noise is random, then by average, $\Delta\varphi_0(t)$ is near zero and may be dropped from equation (5) to get:

$$\Delta\varphi = 2\pi f_0 \Delta t \qquad (6).$$

Here $\Delta\varphi$ represents phase noise, and Δt represents time jitter. The power of the phase noise averaged over a period (assuming a unit current) is then:

$$P_n = \frac{1}{2} V_0^2 (2\pi f_0)^2 \Delta t^2 \qquad (7).$$

The power of the carrier averaged over a period is $P_0 = \frac{1}{2} V_0^2$.

Using the definition of equation (2) to calculate phase noise in dBc/Hz, the following is obtained:

$$L(f_m) = 10\log_{10}((2\pi \ f_0 \Delta t(f_m))^2 / \Delta f) \qquad (8),$$

where Δf is the resolution bandwidth for the jitter FFT spectrum. We would like to emphasize that equation (8) relies on assumptions of: i.) phase noise is random; ii.) phase noise is narrow-band and small in magnitude. For broad-band signal and large phase noise, corrections to equation (8) are needed.

Equation (8) is very important since it unifies the phase noise with the time jitter. These two quantities were traditionally measured in two different domains, with different instruments. Equipped with these physical equations, a DTS system can measure both time jitter and phase noise spectrum. This was not formally possible when measuring with a single instrument.

A Correlation Study

As discussed, the theory developed in the previous section uses narrow-band and small phase noise assumptions, and therefore, has some limitations. In addition, DTS system is a time-domain based instrument and it is not designed to measure the phase noise in frequency-domain directly. It is therefore, very important to know how accurate the phase noise measured by a DTS compares with that measured by a Spectrum Analyzer.

Figure 7 shows the experimental setup for a correlation study. A 300MHz calibration sine signal on an HP Spectrum Analyzer (Model 8560E) is used as the input signal for both instruments.

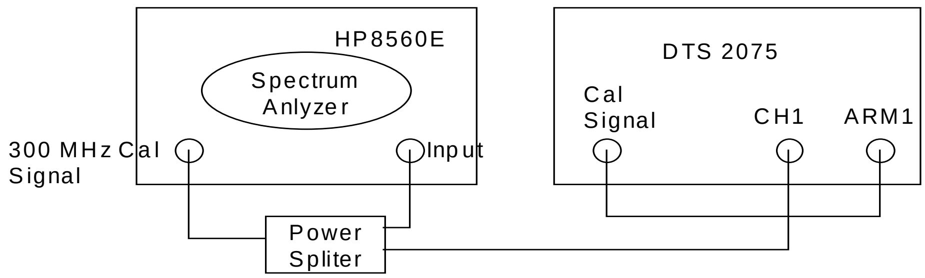

Figure 7. Experimental set up for RF Spectrum Analyzer and DTS 2075 to measure phase noise for a common input signal.

The experiment was repeated several times and it was found that the DTS results (using equation (8)) are consistent with the spectrum analyzer, within a few dBc/Hz, when the offset frequency f_m is < 500Hz. When f_m > 500Hz, Time Digitizer over-estimates the phase noise due to sensitivity limitations and narrow-band assumption violations. Corrections must be applied to equation (8) in order to get a correct phase noise measurement with equation (9) being more suitable for DTS phase noise measurement.

$$L(f_m) = 10\log_{10}((2\pi \ f_0\,\Delta t(f_m)\ )^7/\Delta f) + \beta \qquad if \qquad f_m > 500\,Hz \qquad (9).$$

$$L(f_m) = 10\log_{10}((2\pi \ f_0\,\Delta t(f_m)\ )^2/\Delta f) \qquad if \qquad f_m \le 500Hz$$

$$\beta = -50\log_{10}(2\pi f_0 \Delta t(f_m)\,|_{at\ \ f_m = 500\ Hz})$$

Using equation (9), the DTS-measured phase noise in dBc/Hz versus that measured by a Spectrum Analyzer are shown in Figure 8. It may be noted that they correlate well, to within ~90%.

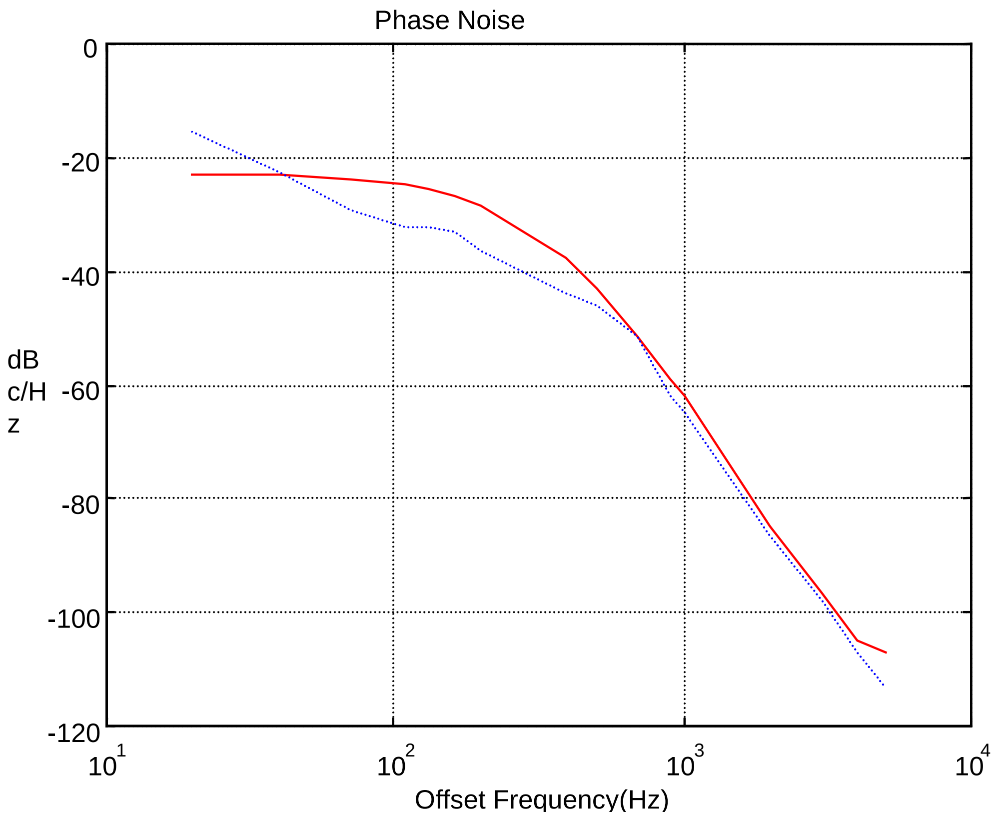

Figure 8. Phase noise measurement comparison. Solid (red) line is for HP8560E Spectrum Analyzer, and dotted (blue) line is for the DTS 2075.

Summary and Conclusion

WAVECREST Corp. has developed a theory that unifies phase noise and time jitter under the narrow-band and small phase noise amplitude assumptions. This theory has been incorporated into *Virtual Instruments*™ software so that the Time Digitizer function of DTS can give both time jitter and phase noise spectrum measurements simultaneously. Such instant jitter/noise measurements, in terms of time/power, provide critical information for PLL clock characterization, debug, and testing. It was concluded, through the correlation study, that the DTS-measured phase noise correlated to within 90 percent with that measured by a Spectrum Analyzer.

References

[1] R. White, "Spectrum & Network Measurements", PTR Pretentice Hall, 1993.
[2] HP seminar note, "RF & Microwave Phase Noise Measurement Seminar".
[3] Wavecrest Corporation, "DTS-2075 Product Specification, Rev 3.1", 1998

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