Mastering Phase Noise Measurements (Part 1)

Application Note

Whether you are new to phase noise or have been measuring phase noise for years it is important to get a good understanding of the basics and to learn of new measurement techniques to improve your designs.

This series of application notes is broken up into three parts:

Part 1: Understanding the basics of phase noise: why it is important, how does it impact different applications, and what causes phase noise.

Note: This application is part one of a three part series. See the end of this application note to view the other two parts.

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2 Introduction

Phase noise is unintentional phase modulation on a signal that spreads the spectrum and degrades performance in many RF applications. Whether you are new to phase noise or have been measuring phase noise for years it is important to get a good understanding of the basics and to learn of new measurement techniques to improve your designs.

This series of application notes is broken up into three parts:

- **Part 1: Understanding the basics of phase noise: why it is important, how does it impact different applications, and what causes phase noise**
- Part 2: What are the different measurement techniques and their advantages/disadvantages: direct spectrum analyzer, phase detector, delay line discriminator and we introduce our new digital phase demodulator technique
- Part 3: How best to perform advanced measurements: additive phase noise, pulsed phase noise, and AM Noise

We will first cover part 1: Understanding the basics of phase noise

3 Understanding the Basics

Let’s first make sure that there is a good understanding of what phase noise is and where it comes from.

3.1 What is Phase Noise?

In a perfect world a signal would be an ideal sine wave, mathematically pure. If it were measured on a perfect oscilloscope it would look like a perfect sine wave, on a perfect spectrum analyzer it would look like a spectral line with no width and some amplitude (Figure 2-1a). It would have no phase noise or amplitude noise. This signal would be defined as

$$V(t) = A \sin(2\pi v t) \qquad (1)$$

where
A = nominal amplitude
v = nominal frequency

Unfortunately, perfect signals do not exist in the real world. There will always be some amount of noise on the amplitude part of the signal and with the phase or timing of the signal (Figure 2-1b). The effect of this noise is defined as

$$V(t) = [A + E(t)] \sin(2\pi v t + \varphi(t)) \qquad (2)$$

where
$E(t)$ = amplitude fluctuations
$\varphi(t)$ = phase fluctuations

Phase Noise is unintentional phase modulation that spreads the signal spectrum in the frequency domain. It’s equivalent in the time domain is jitter.

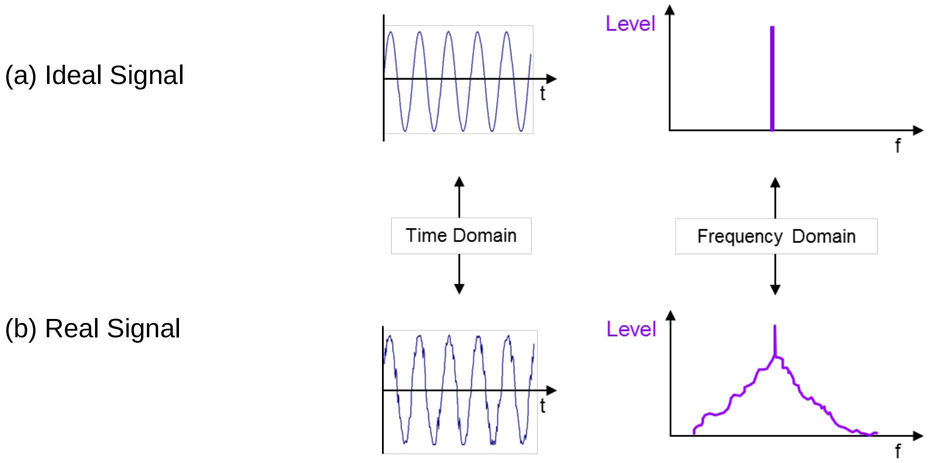


Fig. 2-1: Phase Noise is unintentional phase modulation that spreads the signal spectrum in the frequency domain and is equivalent to jitter in the time domain.

Phase noise is typically measured on a device that generates signals, basically an oscillator of some kind. This type of phase noise measurement is called absolute phase noise or 1 port phase noise (Figure 2-2a). Here the goal is to determine how much phase noise is actually produced by the device-under-test (DUT). A second fairly common measurement is additive phase noise. Often when adding a 2-port device, such as an amplifier or an up/down converter, there is interest to know how much phase noise that device adds to the signal (Figure 2-2b).

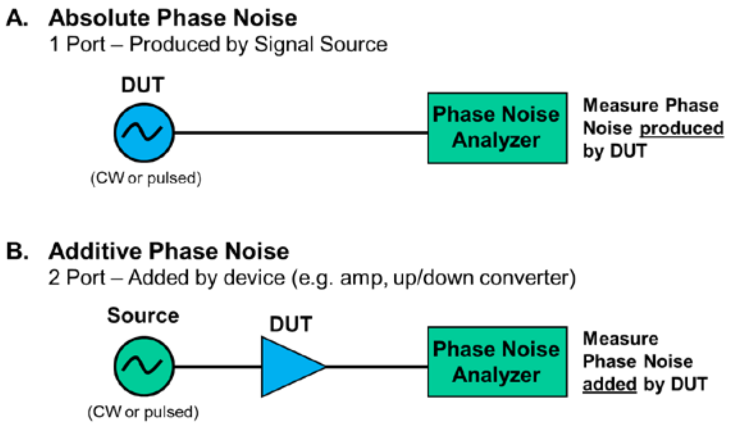


Fig. 2-2: Types of phase noise

3.2 Relationship to Jitter

Phase noise is a frequency domain phenomenon and its equivalent in the time domain is jitter. Jitter has historically been measured with an oscilloscope, which measures in the time domain. Oscilloscopes measure jitter directly and are very flexible in measuring time interval errors, period jitter, and offer different ways of expressing jitter (Figure 2-3).

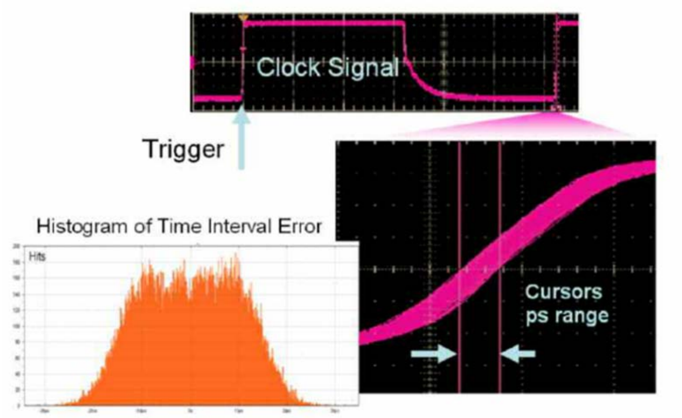


Fig. 2-3: Jitter is a time domain approach to phase noise.

There are two limitations with this time domain technique: sensitivity and cost. Oscilloscopes have a jitter floor they can't measure below, which is typically in the range of picoseconds for general scopes. There are very high-end oscilloscopes that can measure down to 100 femtoseconds of jitter. They can be very expensive, hundreds of thousands of dollars. Due to their high cost access is often limited if at all.

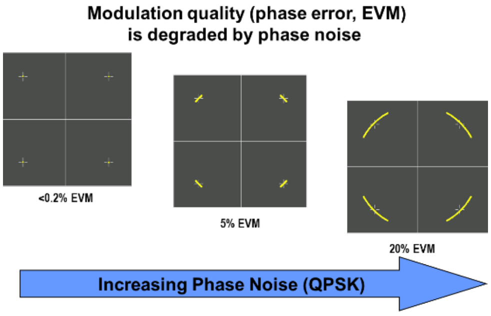
Fortunately, phase noise techniques can measure jitter with excellent sensitivity. Jitter measurements well below 10 femtoseconds (1 fs = 10-15 s) are possible, which is much more sensitive than a typical oscilloscope. To get this level of sensitivity the cost of a phase noise analyzer is almost two orders of magnitude lower. It is relatively easy to measure jitter under 10 femtoseconds with a phase noise analyzer.

Another advantage is that phase noise plots make it easy to distinguish random and deterministic jitter, which is difficult using an oscilloscope. One limitation of the phase noise analyzer is that it can only look at clocks or data streams that have a regular pattern. It does not work with random data stream.

3.3 Why is Phase Noise Important?

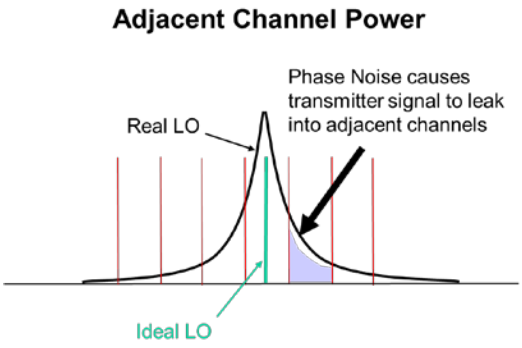
Phase noise matters in a wide variety of applications. It's commonly thought of in terms of modulators and transmitters, but it's also important in receivers. Phase noise can have a significant impact on digital systems, as well as radar systems. The following are a few specific examples.

3.3.1 Digital Modulation Systems



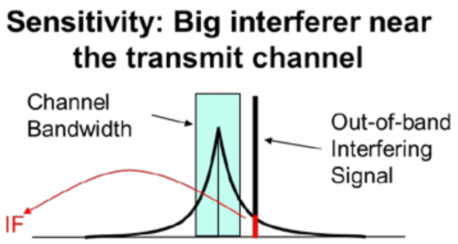
For digital modulation systems, transmitter phase noise can be a limiting factor on modulation quality. Different levels of EVM from increased phase noise will degrade the signal and spread the symbols. In this example a 20% EVM will push the limits of what a QPSK system can handle. This error would be introduced by the transmitter; it is important to recognize that these errors will carry across the channel and the receiver, where there will be further degradation to the signal. Minimizing transmitter phase noise can be critical to a design's success.

3.3.2 Communication System Transmitters



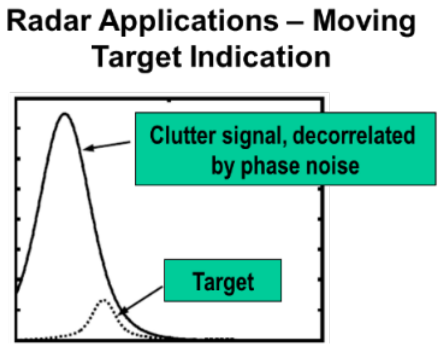
In communication systems, in addition to a transmitter degrading modulation quality, phase noise also spreads the spectrum out. This can result in leakage into adjacent channels. Most communication standards have defined limits on how much signal is allowed to leak into adjacent channels.

3.3.3 Receivers



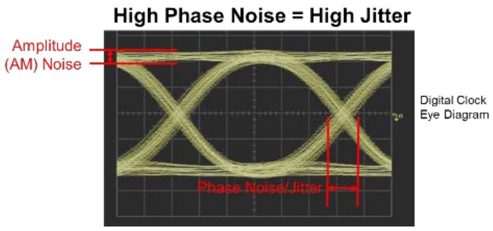
While it is obvious in transmitters, the importance of phase noise is often overlooked in receivers. The phase noise of the local oscillator (LO) inside the receiver needs to be factored into the overall system design. If the phase noise of the LO increases the signal width, even out-of-channel inferring signals can map into the intermediate frequency (IF) and reduce the overall sensitivity of the receiver.

3.3.4 Radar



Radar systems try to receive very faint reflections off of their targets. Often times there may be close-in-clutter that creates a really large reflection. If the width of that reflection is degraded enough by the increased phase noise of the LO inside the radar, it will actually mask the target.

3.3.5 Digital Systems



In the digital world, phase noise is commonly called jitter. It is important to note that jitter is a limiting factor on the quality of an eye diagram. When the jitter gets high, it can cause bit errors and reduce or limit the sustainable data rate. This is becoming increasingly important as the speed of digital systems increase.

3.4 Quantifying Phase Noise

Phase noise is usually expressed as L(f) and is commonly pronounced “script L of f”. A few years ago, the IEEE redefined phase noise to be one-half the spectral density of phase fluctuations, $S\varphi$ (f), or

$$L(f) = \tfrac{1}{2} S\varphi\,(f) \quad \text{IEEE STD 1139-2008} \qquad (3)$$

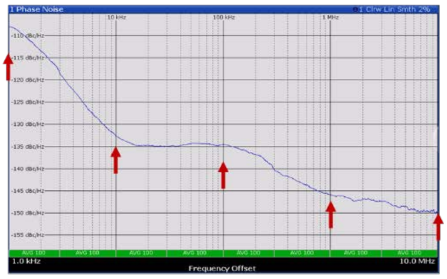
The old definition was defined as single sideband power due to phase fluctuations in a 1Hz bandwidth at a specified offset frequency, f, from the carrier. For users familiar with spectrum analyzer displays this was a bit more intuitive. In both cases it is specified in dBc/Hz.

In many cases it turns out that these two definitions are equivalent for normal, low-phase noise oscillators. The two diverge only when phase noise gets really high and the modulation index gets to where the sideband energy is pushed out into multiples of the sideband frequency.

An example phase noise plot is shown in Figure 2-4a. Typically, a plot goes from a start offset to a stop offset and those offset frequencies are on a log scale. So it's a log-log plot with dBc/Hz on the Y axis and offset frequency on the X axis. A second term, "spot noise," is the same as taking a marker and putting it on that plot to measure how many dBc/Hz are at that specific offset. Most phase noise analyzers provide a spot noise table, where specific offsets can be defined by the user (Figure 2-4b).

Units of dBc/Hz

A. Plot



B. Spot Noise

2 Spot Noise

Type	Offset Frequency [T1]	Phase Noise [T1]
Fixed	1.00 kHz	-107.89 dBc/Hz
Fixed	10.00 kHz	-132.72 dBc/Hz
Fixed	100.00 kHz	-134.53 dBc/Hz
Fixed	1.00 MHz	-145.83 dBc/Hz
Fixed	10.00 MHz	-149.60 dBc/Hz

Spot Noise offsets are user-definable (default to decade offsets)

Fig. 2-4: Quantifying phase noise.

In addition to measuring the raw phase noise, many times there is interest in what is called "calculated residual noises". The following terms are based off the phase noise curve:

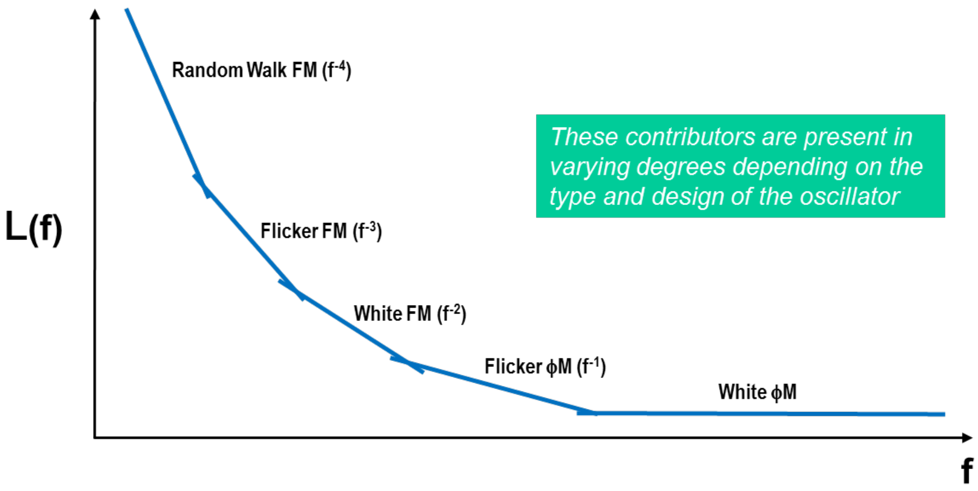
– Integrated Phase Noise	$\int \mathrm{L}(f)df$	(dBc)
– Residual PM	$\frac{180^{\circ}}{\pi}\sqrt{2\int \mathrm{L}(f)df}$	(deg or rad)
– Residual FM	$\sqrt{2\int f^{2}\mathrm{L}(f)df}$	(Hz)
– Jitter	$\frac{1}{2\pi f_{c}}\sqrt{2\int \mathrm{L}(f)df}$	(sec)

Note should be L(f)

3.5 Causes of Oscillator Phase Noise

So what causes phase noise? There are various contributors that, when put together, create the characteristic phase noise curves we are familiar with (Figure 2-5). These contributors are present in varying degrees depending on the type and design of the oscillator:

Random Walk:	Close to carrier, generally caused by environmental effects
Flicker FM:	Related to active oscillator physical resonance mechanism, power supply noise
White FM:	Related to passive resonator oscillators
Flicker φM:	Related to noisy amplifiers and multipliers
White φM:	Far from carrier, generally caused by broadband output amplifier noise



These contributors are present in varying degrees depending on the type and design of the oscillator

Fig. 2-5: Causes of oscillator phase noise.

4 Summary

Minimizing phase noise is critical to achieving the performance required by many of today’s RF applications. This application note Part 1 has provided a basic understanding on the fundamentals of phase noise. We showed how the residual parameters are calculated from raw phase noise data, including the integrated phase noise, residual PM, FM, and jitter.

Part 2 and 3 will look at several traditional measurement techniques and introduce a new technique using the R&S FSWP. While the traditional techniques have been used for years, they are hindered by cumbersome calibration and often require additional hardware. Our new digital phase demodulation technique provides really low-noise reference sources and achieves fast correlations with simple setups that deliver state-of-the-art sensitivity and speed.

Please follow this link for more information on the R&S®FSWP Phase Noise Analyzer and VCO Tester.

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